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Discrete particle simulation of food grain drying in a fluidised bed

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ABSTRACT

Drying is a common practice for post-harvest processing of food grains. Fluidised beds are often adopted for this purpose. It is of importance to understand the fluidised bed drying process for improving its energy efficiency. This work establishes a numerical drying model based on the combined approach of computational fluid dynamics and discrete element method for describing heat and mass transfer in the gas-solid flow system. Water evaporation is modelled in resemblance to a chemical reaction, thereby requiring fewer model parameters. The model is first described in detail. Then it is tested by comparing model predictions with those experimental data of corn kernel from the literature. General drying characteristics including grain and air moisture contents are reproduced qualitatively. The predicted drying rate curves are quantitatively comparable with those of experimental data. Finally, the effects of inlet air velocity and temperature are examined. The model predictions confirm that the drying rate increases with both the inlet air velocity and temperature. However, the drying product quality, here represented by the standard deviation of grain moisture distribution, increases with increasing air velocity or decreasing air temperature. This grain scale model would be useful to the design and control of the drying process.

1. Introduction

Drying is a common practice in food processing, mainly to prevent post-harvest deterioration, to restrict microbial growth and spoilage and to reduce handling costs [1]. It is one of the most important and frequently used unit operations in a variety of industrial applications e.g. food, pharmaceutical, wood processing and so on [2]. In practice, drying requires a high energy input because of the high latent heat of water evaporation. To improve energy efficiency, many novel drying techniques have been introduced. Meanwhile, most of the existing drying techniques are continuously being re-visited, optimised or integrated to minimise energy requirement and to improve product quality. Among them, fluidisation is an important mode in drying of food grains due to its intensive mixing of solids and high efficiency in heat and mass transfer [3].

Experimental approaches are traditionally used to investigate drying processes. However, the costs for experiments are very high. As an alternative way, computational approaches can be used with relatively low costs either to optimise the existing processes or to develop a new procedure, allowing detailed investigation of complex drying mechanisms [4]. Several advanced computational methods were established for drying. Computational fluid dynamics (CFD) is the most used one and it is a powerful tool for its capacity of in-depth analysis of flow, mass transfer and heat exchange in multi-component systems [5–7]. However, it is difficult for CFD to consider the discrete nature of grains [8].

In recent years, the discrete element method (DEM) is increasingly used to study granular flows in different systems [8,9]. In such DEM models, the motion of each grain is described by Newton's laws of motion and it is able to consider the forces due to gravity, grain-grain and grain-wall interactions, capillary bridges or an electrostatic field [10]. When the effect of an interstitial fluid is significant such as in fluidised beds, DEM models can be combined with CFD to investigate coupled gas-solid flows and heat and mass transfer therein [8].

The main advantage of the combined CFD-DEM approaches is to generate detailed grain scale information, including grain trajectory and the forces acting on individual grains. Many studies demonstrated that the CFD-DEM approach is effective to examine the flow and heat transfer in fluidised systems (see, for example, [10–15]). The fluidised bed drying involves simultaneous heat and mass transfer to evaporate and remove water from grains to a drying medium [2]. Hence the CFD-DEM approach is suitable for modeling the drying process by incorporating suitable heat and mass transfer models [16,17]. To date, such a CFD-DEM model has not been developed with the simple drying model requiring fewer model parameters [18–21].

This work aims to develop and test a new model for food grain drying in a fluidised bed. First, a detailed description of the model is given. Then, the model is tested by comparing the predictions with literature data in terms of drying kinetics. Last, the effects of pertinent operation parameters on the drying rate and the probability mass function of

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grain moisture content are discussed. It will be demonstrated that the CFD-DEM approach is useful for understanding the drying process and hence for improving product quality.

2. Model description

The gas-solid flow system for drying of food grains is considered here as a coupled system of a continuum gas phase for the drying medium (hot air in this work) and a discrete solid phase for food grains (called as particles hereafter).

2.1. Governing equations for the discrete solid phase

The solid phase is described by the DEM, originally proposed by Cundall and Strack [22]. A particle is considered to have two types of motion: translational and rotational. The particle may interact with its neighbouring particles and/or walls in moving, through which the momentum and energy are exchanged. The motion of a particle is determined by Newton's laws of motion. At time t, the governing equations for the translational and rotational motion of particle i with radius R_i, mass m_i and moment of inertia I_i can be written as:

$$m_i\, d\boldsymbol{v}_i/dt = \Sigma_j\left(\mathbf{f}_{e,ij} + \mathbf{f}_{d,ij}\right) + \mathbf{f}_{pf,i} + m_i\mathbf{g}, \tag{1}$$

and

$$I_i d\boldsymbol{w}_i/dt = \Sigma_j\left(\mathbf{T}_{t,ij} + \mathbf{T}_{r,ij}\right), \tag{2}$$

where $\boldsymbol{v}_i$ and $\boldsymbol{\omega}_i$ are the translational and rotational velocities of the particle. $\mathbf{f}_{pf,i}$ and $m_i\mathbf{g}$ are the particle-fluid interaction force and the gravitational force. The other forces involved are the elastic force $\mathbf{f}_{e,ij}$ and the viscous damping force $\mathbf{f}_{d,ij}$. The torque acting on particle i due to particle j includes two components: $\mathbf{T}_{t,ij}$ which is generated by the tangential force and causes particle i to rotate, and $\mathbf{T}_{r,ij}$ which, commonly known as the rolling friction torque, is generated by asymmetric normal contact forces and slows down the relative rotation between contacting particles [23,24]. If particle i undergoes multiple interactions, the individual interaction forces and torques are summed up for all particles interacting with particle i. Note that the water in the studied range of moisture content is mainly in the form of absorbed water and there is no liquid bridge. Hence no capillary force and agglomeration are considered and they might become important for high moisture contents. Most of the equations for determining the forces and torques have been well established as reviewed by Zhu et al. [10]. The equations of the forces and torques for the present study are well documented in the previous studies [25] and given in Table 1 for completeness.

Heat exchange occurs by convection heat transfer with surrounding fluid, conduction heat transfer to neighbouring particles or walls and radiative heat transfer to the environment. The governing equation of the energy balance for particle i can be written as:

$$m_i c_{p,i} dT_i/dt = \sum\nolimits_j \dot{Q}_{i,j} + \dot{Q}_{i,f} + \dot{Q}_{i,rad} + \dot{Q}_{i,wall} + \dot{Q}_{i,dry}, \tag{3}$$

where $\dot{Q}_{i,j}$, $\dot{Q}_{i,f}$ and $\dot{Q}_{i,rad}$ are the heat exchange rates by conduction, convection and radiation respectively. $\dot{Q}_{i,wall}$ and $\dot{Q}_{i,dry}$ represent the conduction heat exchange rate between the particle and wall and the heat for drying, respectively. $c_{p,i}$ is the particle heat capacity. Eq. (3) has been established on the basis of heat balance at a particle scale [26,27]. The equations to calculate heat exchange rates in Eq. (3) are listed in Table 2 [13,26].

The heat of drying from a particle can be expressed as a function of the moisture content of the particle and its variation, given by [28]:

$$\dot{Q}_{i,dry} = h_{fg}\left[1 + a\exp\left(bY_{i,H_2O}\right)\right] \cdot S_{i,H_2O}. \tag{4}$$

Table 1
Equations to calculate forces and torques on particle i.

Force or torque	Equation
Normal elastic force, $\mathbf{f}_{en,ij}$	$-\frac{4}{3}E^*\sqrt{R^*}\delta_n^{3/2}\mathbf{n}$
Normal damping force, $\mathbf{f}_{dn,ij}$	$-C_n\left(6m_{ij}E^*\sqrt{R^*\delta_n}\right)^{1/2}\mathbf{V}_{n,ij}$
Tangential elastic force, $\mathbf{f}_{et,ij}$	$-\mu_s\lvert\mathbf{f}_{en,ij}\rvert\left(1-(1-\delta/\delta_{t,\ max})^{3/2}\right)\hat{\boldsymbol{\delta}}_t$
Tangential damping force, $\mathbf{f}_{dt,ij}$	$-C_t\left(6\mu_s m_{ij}\lvert\mathbf{f}_{en,ij}\rvert\sqrt{1-\delta_t/\delta_{t,\ max}}/\delta_{t,\ max}\right)^{1/2}\mathbf{v}_{t,ij}$
Coulomb friction force, $\mathbf{f}_{t,ij}$	$-\mu_s\lvert\mathbf{f}_{en,ij}\rvert\hat{\boldsymbol{\delta}}_t$
Torque by tangential forces, $\mathbf{T}_{t,ij}$	$\mathbf{R}_{ij}\times(\mathbf{f}_{et,ij}+\mathbf{f}_{dt,ij})$
Rolling friction torque, $\mathbf{T}_{r,ij}$	$\mu_{r,ij}\lvert\mathbf{f}_{en,ij}\rvert\hat{\boldsymbol{\omega}}_{ij}^n$
Particle-fluid drag force, $\mathbf{f}_{d,i}$	$0.125C_{d0,i}\rho_f\pi d_{pi}^2\varepsilon_i^2\lvert\mathrm{u}_i-\mathrm{v}_i\rvert(\mathrm{u}_i-\mathrm{v}_i)\varepsilon_i^{-\beta}$

where $1/m_{ij} = 1/m_i + 1/m_j$, $1/R^* = 1/R_i + 1/R_j$, $E^* = E/[2(1-v^2)]$, $\hat{\boldsymbol{\omega}}_{ij}^n = \boldsymbol{\omega}_{ij}^n/\lvert\boldsymbol{\omega}_{ij}^n\rvert$, $\delta_t = \lvert\boldsymbol{\delta}_t\rvert$, $\hat{\boldsymbol{\delta}}_t = \boldsymbol{\delta}_t/\lvert\boldsymbol{\delta}_t\rvert$, $\mathbf{R}_{ij} = R_i(\mathbf{r}_j-\mathbf{r}_i)/(R_i + R_j)$, $\delta_{t,max} = \mu_s\delta_n(2-v)/(2(1-v))$, $\mathbf{v}_{ij} = \mathbf{v}_j-\mathbf{v}_i + \boldsymbol{\omega}_j \times \mathbf{R}_j-\boldsymbol{\omega}_i \times \mathbf{R}_i$, $\mathbf{v}_{n,ij} = (\mathbf{v}_{ij}\cdot\mathbf{n})\cdot\mathbf{n}$, $\mathbf{v}_{t,ij} = (\mathbf{v}_{ij} \times \mathbf{n}) \times \mathbf{n}$, $\varepsilon_i = 1-\sum_{i=1}^{k_v}V_i/\Delta V$, $\beta = 2.65(\varepsilon+1)-(5.3-3.5\varepsilon)\varepsilon^2\exp[-(1.5-\log_{10}\mathrm{Re}_i)^2/2]$, $C_{d0,i} = (0.63+4.8/\mathrm{Re}_i^{0.5})^2$, $\mathrm{Re}_i = \rho_f d_{pi}\varepsilon_i\lvert\mathrm{u}_i-\mathrm{v}_i\rvert/\mu_f$.
Note that tangential forces ($\mathbf{f}_{et,ij} + \mathbf{f}_{dt,ij}$) should be replaced by $\mathbf{f}_{t,ij}$ when $\delta_t \geq \delta_{t,max}$.

where h_{fg} is the latent heat of vaporisation of free water (KJ/Kg). The coefficients a and b for the grain are determined as 3.2 and −21.7 [29].

The moisture content is described as a chemical component in the particle and the conservation equation is written as:

$$m_i dY_{i,H_2O}/dt = S_{i,H_2O}, \tag{5}$$

where Y_{i,H_2O} is the mass fraction of moisture in particle i and S_{i,H_2O} is the exchanged moisture with surrounding drying medium.

The water evaporation model, developed by Chen and co-workers in resemblance to a chemical reaction [19], is adopted for the drying of spherical food particles since it requires fewer model parameters. Note that this work for the first time combined the CFD-DEM approach and the simple water evaporation model for the drying process. Hence the drying rate can be expressed as:

$$S_{i,H_2O} = -h_m A\left(\rho_{v,s}-\rho_{v,\infty}\right), \tag{6}$$

where $\rho_{v,s}$ and $\rho_{v,\infty}$ represent the vapour concentrations at the particle-medium interface and in the drying medium (kg/m^3), respectively. h_m is the mass transfer coefficient (m/s) and A is the surface area (m^2). h_m can be determined by the established Sherwood number (Sh). For a spherical particle, $Sh = 2 + 0.6\mathrm{Re}^{1/2}Sc^{1/3}$, where Re and Sc are the Reynolds and the Schmidt numbers, respectively.

The vapour concentration at the particle-medium interface can be obtained from the saturated vapour concentration according to the following equation [20]:

$$\rho_{v,s} = \ exp\left(-\Delta E_v/RT\right)\rho_{v,sat}(T_s), \tag{7}$$

where ΔE_v is the relative activation energy of evaporation, depending on the moisture content. T is the temperature of the particle being

Table 2
Heat transfer modes and the equations for determining heat exchange rates.

Heat transfer mode	Equation for heat exchange rate
Convection	$\dot{Q}_{i,f} = (2.0 + a\ \mathrm{Re}_i^b\ \mathrm{Pr}^{1/3})k_f A_i \Delta T/d_{pi}$
	$\dot{Q}_{f,wall} = 0.037\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{1/3}k_f A_w \Delta T/L$
Conduction	$\dot{Q}_{i,j} = (T_j-T_i)\int_{r_{sij}}^{r_{sf}} 2\pi\cdot r\left(\left(\sqrt{R_i^2-r^2}-r(R_i^2+H)/r_{ij}\right)\cdot(1/k_{pi}+1/k_{pj}) +2[(R_i^2+H)-\sqrt{R_i^2-r^2}]/k_f\right)^{-1}dr$
	$\dot{Q}_{i,j} = 4r_c(T_j-T_i)/(1/k_{pi}+1/k_{pj})$
	$\dot{Q}_{i,j} = c(T_j-T_i)\pi r_c^2 t_c^{-1/2}/((\rho_{pi}c_{pi}k_{pi})^{-1/2}+(\rho_{pj}c_{pj}k_{pj})^{-1/2})$
Radiation	$\dot{Q}_{i,rad} = \sigma e A_i(T_{local,i}^4-T_i^4)$, $\dot{Q}_{f,rad} = \sigma e_f A_f(T_{local,i}^4-T_f^4)$
	where $T_{local,i} = \varepsilon_f T_{f,\Omega}+(1-\varepsilon_f)\sum_{j=1}^{k_\Omega}T_j(j\neq i)/k_\Omega$