Particuology 12 (2014) 33–39

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Investigation of grain mass flow in a mixed flow dryer

Fabian Weigler*, Jochen Mellmann

Department of Post-harvest Technology, Leibniz Institute for Agricultural Engineering Potsdam-Bornim, Potsdam 14469, Germany

ARTICLE INFO

Article history:
Received 30 November 2012
Received in revised form 22 March 2013
Accepted 10 April 2013

Keywords:
Mixed-flow dryer
Grain mass flow
Discrete element method

ABSTRACT

The numerical modeling of grain drying is a topic of great relevance to post-harvest engineering. The required type of drying process depends on the quantity of grain to be dried and the required quality of the grain. The choice of the drying system depends on the operating parameters of the drying process. The granular flow pattern of the material exerts a significant influence on the drying process. Post-harvest drying of grain is essential for better storage, handling, and processing. Therefore, it is important to know the material behavior that controls the particle flow patterns of grain in the drying equipment to guarantee the product quality and to optimize the drying process conditions. The discrete element method (DEM) was applied to investigate the particle flow pattern of wheat through a mixed-flow dryer (MFD) without airflow, and the findings were compared with experimental results in this work. The investigations were performed using dry wheat with 14 wb% moisture content.

1. Introduction

Drying is widely applied in agriculture to preserve large mass flows of grain, corn, and other coarse granular products. For continuous drying, mixed-flow dryers (MFDs) are widely used. MFDs consist of a vertical drying shaft, inside which duct-shaped elements are arranged homogenously to distribute the drying air. The drying air flow is controlled by the staggered inlet and outlet air ducts. The humidified material is loaded from the top of the dryer and flows vertically downwards by gravity. A discharge device at the bottom of the dryer regulates the product mass flow rate.

Design elements that are unfavorably constructed or arranged can cause broad residence time distributions, locally different drying conditions, and inhomogeneous drying. Consequently, a considerable part of the grain is over-dried in practice. This effect was investigated by Mellmann et al. (2011), in which the authors measured the grain moisture content and the temperature distributions at the dryer outlet. The measurements showed that the grain moisture content and the grain temperature distributions significantly fluctuated at the cross-section, which resulted from the effects of the air duct arrangement. This non-essential dehydration caused high specific energy consumption, which led to quality and economic losses.

Although the MFD has been studied by many researchers (Bruce, 1984; Cao, Yang, & Liu, 2007; Giner, Bruce, & Mortimore, 1998; Klinger, 1977), the granular flow pattern in the vertical dryer shaft has not been sufficiently considered in dryer modeling. In general, relatively few works have studied and mathematically modeled the individual processes. The grain flow through laboratory MFDs with different forms of air ducts was studied by Klinger (1977) using colored grains for visualization. However, only qualitative results were obtained from these experiments.

Most research papers published on mixed-flow drying have focused on the methods to increase the dryer performance and to preserve product quality, e.g., by improving the dryer control. Bruce (1984) modeled the MFD as a series of concurrent and counter-current elements. This model was successfully employed to predict the general dryer behavior and the influence of the operating variables on the dryer performance.

More recently, the number of papers related to basic research on MFD has increased. Cao et al. (2007) used a simulation model to investigate the effect of the structural and operating parameters on the performance and the energy consumption of a mixed-flow grain dryer. The conducted simulations were based on a two-dimensional dryer model, which was previously developed by Liu (1993). The authors emphasized the effect of the structural parameters such as the size and shape of the air ducts, the spacing between the air ducts, the number of rows of air ducts, and the column height. One of their observations was that the small air ducts were more efficient than the large air ducts. Kocsis et al. (2008) reported on experimental observations concerning the influence of air ducts and side walls on the grain flow. The particle velocity and the mass flow distributions were measured at an MFD test station, which was equipped with a transparent acrylic glass front wall.

* Corresponding author. Tel.: +49 331 5699336; fax: +49 331 5699846.
E-mail address: fweigler@atb-potsdam.de (F. Weigler).

http://dx.doi.org/10.1016/j.partic.2013.04.004

As demonstrated, the particle flow through the center of the dryer was faster than at the side walls. A two-dimensional model based on the discrete element method (DEM) was developed to simulate the particle movement in MFDs (Iroba, Weigler, Mellmann, Metzger, & Tsotsas, 2011). The obtained results showed that two flow regions existed in the MFDs: the near-wall region with a low particle velocity and the central region with a high particle velocity. The comparison between the simulated results and the experimental results revealed that the DEM could adequately predict the main features of particle flow. Based on the particle trajectory analysis, Iroba, Mellmann, Weigler, Metzger, and Tsotsas (2011) demonstrated that the half air ducts positioned at the side walls of the dryer created obstructions to the free flow of grains. However, all of these simulations used a spherical particle structure.

The present paper aims to study the particle flow of dry wheat through a MFD without airflow using experimental investigation and numerical modeling. Therefore, the model of Iroba, Weigler, et al. (2011) was advanced using a multi-sphere model to imitate the real particle structure. Although the air flow through the bed was not the focus of this work, this issue should be considered in future works. Particle flow experiments were conducted to validate the simulations.

2. DEM and simulation conditions

In this work, the granular flow behavior of wheat in a conventionally designed MFD was investigated using the DEM. The commercial software Particle Flow Code PFC^{2D} was applied for this purpose (Itasca Consulting Group, 2004). DEM was used to study the mechanical behavior of discretely divided structures, and it observed the bed not as a continuum but as individual particles on both microscopic and macroscopic scales.

DEM was introduced by Cundall (1971) and was first applied to soils by Cundall and Strack (1979) to compute the particle flow numerically via an explicit time-stepping integration scheme with suitable boundary and initial conditions. The calculation in PFC^{2D} consisted of repeated application of the law of motion to each particle, of a force–displacement law to each contact, and constant updating of wall positions (Itasca Consulting Group, 2004). The inter-particle force models were also applied to the interaction between a particle and the wall. The corresponding material properties were used to describe the behavior of the wall. The transaction in each time step was determined for each particle. The particle equations of motion for translation and rotation were solved numerically.

The equations of motion can be expressed as two vector equations: one equation relates the resultant force to the translational motion; the other equation relates the resultant moment to the rotational motion. The translational motion of the center of mass is described in terms of its position x_i, velocity $\dot{x}_i$, and acceleration $\ddot{x}_i$. The rotational motion of the particle is described in terms of its angular velocity ω_i and angular acceleration $\dot{\omega}_i$. The equation for translational motion can be written in the vector form

$$F_i = m(\ddot{x}_i - g_i), \quad (1)$$

where F_i is the resultant force, m is the total mass of the particle, and g_i is the body force acceleration vector (e.g., gravity loading).

For either a spherical or a disk-shaped particle of radius R, Euler's equation of motion can be simplified and referred to in the global-axis system as

$$M = I\omega = \beta m R^2 \dot{\omega}, \quad (2)$$

for a rotational motion with $\beta = 2/5$ for spherical particles, where I is the principal moment of inertia of the particle, and $\dot{\omega}_i$ is the angular accelerations about the principal axes.

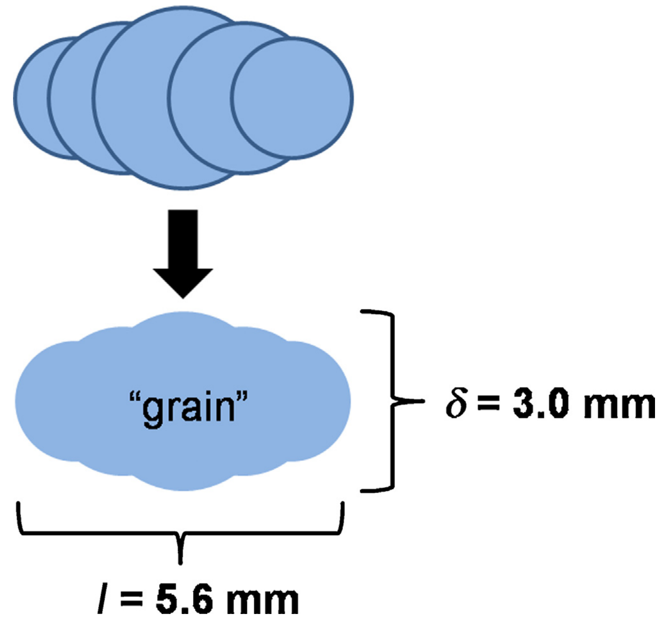

Fig. 1. Simulated grain shape: ellipsoidal clump.

The equations of motion, represented by Eqs. (1) and (2), were integrated using a centered finite-difference procedure that involved a time step of Δt. The quantities $\dot{x}_i$ and ω_i were computed at the mid-intervals of $t \pm n\Delta t/2$, while the quantities x_i, $\ddot{x}_i$, $\dot{\omega}_i$, F_i, and M_3 were computed at the primary intervals of $t \pm n\Delta t$.

Finally, the velocities were used to update the position of the particle center as

$$x_i(t + \Delta t) = x_i(t) + \dot{x}_i(t + \Delta t/2)\Delta t. \quad (3)$$

The values of $F_i(t+\Delta t)$ and $M_3(t+\Delta t)$, which would be used in the next cycle, were obtained using the force–displacement law.

After determining the forces, the moments and the resultant displacements, the new positions of the particles were calculated. The new contacts after the next time step followed from the new positions. Hence, new particle forces and moments could be calculated.

To simulate the flow patterns of particles such as grains, the particle bed can be simulated with a simplified particle structure such as a sphere. In the commercial DEM software PFC^{2D}, a sphere is the commonly used geometric shape, but the actual shape of wheat is nearly ellipsoidal. However, an ellipsoid is not possible to generate in PFC^{2D}. The main advantage of using spheres is the lower computation time in comparison with the real structures; in addition, the non-spherical particles require more advanced algorithms and are more difficult to model (Luding, 2008). The main disadvantage of using spheres is that the flow patterns of the real particle shape cannot be described. Therefore, the authors adopted a multi-sphere model to compose ellipsoidal particles. To generate an ellipsoidal structure from the spheres, several spheres must be symmetrically connected in a row. However, with an increasing number of particles, the elliptical shape increases, the mechanical time step of a discrete simulation decreases, and the computational time increases. Therefore, to replicate an ellipsoidal wheat grain and to save computational time, different arrangements and numbers of spheres were checked in the particle flow simulations to find the optimal number of spheres, which were 5 spheres. To describe the real particle behavior in our numerical model, clumps of 5 connected spheres were formed. Each clump was 5.6 mm long and 3.0 mm high (see Fig. 1). The clumps were assumed to have