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Experimental study and discrete element method modeling of temperature distributions in rapeseed stored in a model bin

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ABSTRACT

Rapeseed is one of the major sources of vegetable oil. Improving processing and storage conditions is very important in order to get high quality product. Rapeseed stored in silos is at constant risk of deterioration of quality. The self-heating phenomenon is the main reason for deterioration during storage. Therefore, the aim of the present work was to describe the temperature distribution during this phenomenon and determine whether the self-heating area in a silo could be predicted. The discrete element method (DEM) was used to predict temperature distributions in rapeseed in a cylindrical storage bin and to describe the self-heating process of rapeseed. Model validation was carried out by comparing the results of the model with experimentally measured grain temperatures at different points in a model silo. The predicted and measured temperatures were found to be in good agreement. DEM may be useful for predicting temperature distributions in a silo and can describe the self-heating phenomenon.

1. Introduction

The self-heating phenomenon is a well-known reason for the deterioration of the quality of freshly harvested seeds. Some factors that influence self-heating are high moisture content, a high temperature of the harvested seeds and excessive metabolic activity of insects living in the crop (Mills, 1989; Jia et al., 2001; Arbogast et al., 2004: Ramirez et al., 2010). Self-heating is a destructive process (Gawrysiak-Witulska et al., 2011) that is, unfortunately, rather common in practice during the storage of grain and seeds. The physical consequences of self-heating include the formation of an area of increased temperature, caking of the seeds, and cessation of the outflow of the material from the silo.

One method to reduce the risk of deterioration of stored grain is to monitor the temperature in the silo and to provide aeration when necessary. The ability to detect this phenomenon depends on the thermal diffusivity of the bulk material. For example, rapeseed, according to the studies of Moysey et al. (1977), has a poor thermal diffusivity, ranging from 8.7×10^{-8} to 10.14×10^{-8} m^2/s (the thermal diffusivities of some other bulk materials, according to ASAE (2008), are as follows: corn, 10.22×10^{-8} m^2/s; rice, 10.99×10^{-8} m^2/s; and hard wheat, 11.5×10^{-8} m^2/s). On the one hand, this is an advantage because precooled seeds hold their low temperature for a long time; on the other hand, it is a drawback because of the low level of heat transmission. The poor migration of heat accelerates the dynamics of the development of self-heating and makes self-heating difficult to detect and locate (Ileleji et al., 2006). Heat transmission between seeds may occur in three ways: by seed-to-seed contact, by convection of the air in the intergranular spaces, and by radiation between the surfaces of particles or across voids (Vargas and McCarthy, 2001). Unless there is forced air movement in a particular direction, the temperature field in the case of heat exchange by convection is governed by the gravitational field, heated air tending to move upwards. Two important determinants of convectional heat exchange in seeds are the bulk density of the medium and the moisture content. The density is influenced by the method by which the container was filled (Horabik and Rusinek, 2001), the moisture content of the seeds (Wiącek and Molenda, 2011), and the geometry and the structure of the seeds (Łukaszuk et al., 2009). Lower porosity causes a higher resistance to airflow, but it increases heat transfer (and therefore the thermal conductivity) by contact. Some authors (e.g., Smith and Sokhansanj, 1990; Iguaz et al., 2004) claim that heat transmission by seed-to-seed contact dominates in small-grain cereals such as wheat, rice, and rapeseed, whereas the effect of convection is more important for larger particles such as apples and potatoes. According to Muramatsu et al. (2007), the thermal conductivity of brown rice kernels increases linearly with an increase in the moisture content; similar results were obtained for cumin seed by Singh and Goswami (2000).

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In practice, the safe storage of seeds requires their ventilation (Rusinek et al., 2012). Safety and measurement equipment is used to control the conditions of storage, and the condition monitoring is usually based upon measurements of the temperature in the intergranular space (Jia et al., 2001). For the storage of dry matter, ISO 4112:1990 (ISO, 1990) recommends that temperature sensors should be arranged geometrically in a silo in the shape of a grid. The present work is centered on the description of temperature increases that indicate self-heating.

Testing destructive phenomena such as self-heating in laboratory experiments is demanding of time and resources. However, the development of computer technology and numerical algorithms in recent decades provides us with an opportunity to devise a more convenient alternative. Numerical modeling of heat transfer inside a mass of material is usually based on assumptions of continuum behavior and homogeneity, using, for example, the finite element method or computational fluid dynamics (a basic description of such models can be found, for example, in Wang and Sun, 2003). Recently, there have been a number of numerical simulations of heat transfer, pressure distributions, and airflows in grain silos (Xu and Burfoot, 1999; Jia et al., 2000a,b; Moran et al., 2006; Juan et al., 2006; Chourasia and Goswami, 2007). However, although such approaches may give accurate time-averaged results, they do not take account of interparticle interactions in the granular bed, nor of the behavior of distinct particles (Chaudhuri et al., 2006).

In recent years, one of the more popular approaches for dealing with granular media has been the discrete (or distinct) element method (DEM). This was originally proposed by Cundall and Strack (1979), but has been extensively developed and used over the last 20 years. The DEM was originally developed to simulate the mechanical response of a granular bed. However, it can easily be extended to study other physical properties such as heat transfer (Li and Mason, 2000; Chaudhuri et al., 2006; Kwapinska et al., 2008; Nguyen et al., 2009).

In the work reported here, the DEM software package LIGGGHTS, developed by Kloss et al. (2012) was used. The aim was to evaluate the potential application of DEM to predicting phenomena such as self-heating. The objectives of this study were as follows.

- to determine the progress of the self-heating phenomenon with time and to find out whether, and if so how fast, a grid of temperature sensors situated in the bed can detect an area of self-heating;
- to adapt the DEM model to predict the temperature distribution in a rapeseed storage bin and to describe the self-heating phenomenon; and
- to validate the simulation model based on experimental data.

2. Methods

2.1. Measuring system

The system was composed of 20 sensors. Each sensor measured the temperature and relative humidity (r.h.) of the air in the intergranular space. The temperature and r.h. values were transmitted over single wires to a control module. All data – sensor numbers, temperature and r.h. values, measurement numbers, and additional information – were archived in the memory of the control module. After the test, control module was connected to the PC to copy the data. Each of the humidity and temperature sensors was built into a square plastic box with a size of 10 × 10 × 15 mm. The casing had 1 mm diameter holes in it, sufficient to ensure a free flow of air. This paper presents the results of the temperature measurements only.

2.2. Model silo

A measurement station was developed for the study presented here, composed of a model cylindrical silo with a capacity of 3.85 m^3 (~2500 kg), which was filled with winter rapeseed of the variety Suzy. A cylindrical container with a height H and diameter D of 1.7 m (so that $H/D = 1$) was constructed from steel sheeting. The surface of the seedbed was covered with plywood. The container was filled centrally, directly from a screw conveyor. The sensors were placed every 0.15 m in one plane in both vertical and horizontal directions.

In the first test (Fig. 1a), the sensor network was adjusted so as to place the intersection of the horizontal and vertical axes at the center of the model container, where the most rapid progression of the heating phenomenon might be expected to occur. In this experiment, the silo was filled with three layers of seeds, each 0.5 m high: the first layer, at the bottom, had a moisture content of 7% (w.b.), the second layer had a moisture content of 12.7%, and the last layer, at the top, had a moisture content of 7% again. The moisture content of the seeds was determined by oven drying at 103 ± 1 °C for 72 h (ASAE, 2006).

The second test (Fig. 1b) was performed with an internal heat source. An electric heater (0.17 kW, 230 V, consisting of a heating mat 0.8 m long and 0.5 m wide, which generated a maximum temperature of 40 °C) was installed at the bottom of the container. The temperature of the heater was increased in accordance with the typical progression of self-heating: for the first six days, the increase was about 1 °C per day, and for subsequent days, 2 °C per day. A digital programmer and temperature sensors in the bulk material were used to control the increase of the temperature in the silo. Three replications of the experiment were performed. Temperature in the laboratory was controlled at 21 °C.

2.3. Numerical DEM simulation

The DEM algorithm is based on four main steps, namely:

- detection of particle–particle and particle–wall contacts;
- application of forces (contact, gravity, etc.) to each particle;
- constructing and solving a set of differential equations based on Newton's second law of motion for every particle;
- updating the particle parameters (e.g., positions and velocities) after a time step and repeating the whole cycle.

In the most basic form of the three-dimensional DEM, the system of equations in the third step consists of three equations for the spatial coordinates and three for the rotational coordinates. However, this system can easily be extended with additional equations, describing other particle properties transferred during contact, for example charge and temperature.

The mathematical model used in the present work for calculating the contact forces between colliding particles was based on Hertz's theory, extended with a tangential force based on the work of Mindlin and Deresiewicz (see, e.g., Di Renzo and Di Maio, 2004). In the case of a static bed discussed here the normal component of the contact force is calculated as follows:

$$N = \frac{4}{3}E^* \sqrt{R^*}\delta_{i-j}^{3/2}, \quad (1)$$

where the reduced parameters representing the Young's modulus E^*, and particle radius R^* are calculated as follows:

$$\frac{1}{E^*} = \frac{\left(1-\nu_i^2\right)}{E_i} + \frac{\left(1-\nu_j^2\right)}{E_j}, \quad (2)$$