Investigation of mass flow properties of particles in Silo Dryers

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Abstract — The most relevant question of the mixing systems used in silo dryers is the mixing efficiency of screw augers. The aim of design is that the construction stirs the granular assembly on an optimal level i.e. mixing should be uniform and the mixed amount should as much as possible. Although the mixing process appears unsophisticated, it is a very complex phenomenon. Engineers and researchers work on this field, use mostly experimental data for designing and development because there not too much is known about what happens around the rotating mixing screw. In our prior work, the mixing efficiency and effective radius were determined [3]. In the present article, we investigate the mixing process with a mass flow rate, which determined with cylindrical volumes along the vertical axis. To model this phenomenon, we used the EDEM Academic 2.7. discrete element software.

Keywords — silo dryer discrete element method, granular material

1. INTRODUCTION

In case of convectonal dryers, the flowing air is responsible for the product’s drying. Due to it’s dehydationability, hot air is used. The product which flow against the drying air is actuated by gravity. In the thin layer dryers the required drying rate appears before the loadout system and it can causes over drying rate. To increase the drying efficiency, the thick layer dryers were worked up (belt and band dryers). In the most cases, these dryers are used where the temperature and the velocity of drying air are low (herbs and leafy vegetables). For most of the listed dryers, the motion of the grain is unidirectional, and the relative (mixed) motion inside the granular assembly is not significant. This fact would be disadvantageous, if the moisture distribution of the granular assembly is not homogeneous. To reduce this inhomogenity and reach uniform, good efficiency drying rate, mixing systems are used. Mixing is a common task in agricultural and pharmaceutical industry. Design of mixing process and operation is very difficult, being largely based on judgment rather than science [1]. The guidelines for the selection of particle mixers are still not fully developed and predictions of the mixture quality after mixing operations are still not possible [2]. There are cases, when the mixing process can only be performed by using open mixing screws, for example in case of silos or silo dryers. During mixing – in most of the cases – we would like to reach the optimal level of mixing during the shortest possible time.

![Fig. 1 Parts of mixing system](image-url)
In the other hand, excessive mixing could worsen the quality of the mixed material and the mixture quality also. Because of these contradictory criteria, it is a difficult challenge for the practicing engineers to find the optimal mixing intensity. A good example of this is the case of the drying of agricultural crop products, by using silo dryers, where a thick layer of granular material stored in silos must be dried by using the inflow of hot air from below. Without the constant mixing of wet and dry layers of material, such kind of uneven distribution of dry and wet grains can take form, which results over or under dried granular material, and at the end, loss of revenue. To reduce the possibility of such losses, there are mixing screws inside such silos (Fig.1.), which are designed to cease all of such inhomogeneity.

The number of such screws, the geometry and kinematical parameters of their operation are determined by using experimental investigations, but little is known about what happens around the rotating mixing screw and because of this, there are no clear guidelines for planning of them [3]. The mixing process usually consists of 3 different motions. The mixing augers have linear motion on the console, the console is rotating about the silo’s vertical axis and the augers are rotating about their own axis, therefore the motion of the mixing system is complex. It subserves the air flow by scarifying the grains. The adequate temperature drying air comes the drying chamber through the ventilation flooring. The dried material can be wiped out with a screw conveyor.

II. DISCRETE ELEMENT METHOD

The discrete element method (DEM) is a new numerical method for computing the motion and effect of a large number of small particles. According Bagi’s definition, the discrete element model consists of separate, finite sized bodies (“discrete elements”) each of them being able to displace independently of each other; the displacements of the elements can be large (i.e. not infinitesimally small) the elements can come into contact with each other and loose contact, and these changes of the topology are automatically detected during the calculations [4]. By the use of DEM, the model problem is solved by applying and solving the equation of motion on each singular particle of the bulk material assembly [5]. For modeling the mechanical behavior of the particulate material, the EDEM discrete element software was used which is high performance DEM simulation software for solve complex problems in design, prototyping or optimizing equipment that handles granular materials. This software was first introduced nearly a decade ago, but also the software and also the method still continuously developing. To model mixing of wheat Hertz-Mindlin no slip contact model (Fig.1.) was used and micromechanical parameters were used for describe of interaction between particles and walls.

![Fig. 2 A Simplified Hertz-Mindlin no slip contact model [5].](image)

- **Poisson’s ratio (ν):** defined as ratio of transverse contraction strain to longitudinal extension strain in direction of
- **Stretching force.**
- **Shear modulus (G):** defined as ratio of shear stress to shear strain, where the shear stress is the components of stress at a point that act parallel to the plane in which they lie and shear strain is the components of a strain at a point that produce changes in shape of a body without a volumetric change.
- **Density (ρ):** defined as “weight” per unit volume.
- **Coefficient of restitution (C_r):** ratio of speed of separation to speed of approach in a collision.
- **Coefficient of static friction (μ_s).**
- **Coefficient of rolling friction (μ_r).**

Coefficient of restitution, static friction coefficient and rolling friction coefficient should to define between particles and also between walls and particles [33]. Hertz-Mindlin no slip contact model uses a spring-dashpot model to describe interactions (Fig. 6). This contact model is elastic non-linear and takes into account viscous and frictional damping.

In the discrete element model the simulation evaluates the contact forces according to the “Hertz-Mindlin no slip” contact model: the material and interaction parameters have their effect on the normal and tangential forces. This forces and moments acting between the interacting grain particles in the form of the following equations.
The normal force:

\[ F_n = \frac{4}{3} E_0 \delta^3 R_0 - 2 \frac{5}{6} \ln C_e \sqrt{2 \frac{G_0 R_0^5 \delta \sqrt{m_0 v_{rel}^2}}{E_0}} \]

Where \( C_e \) is the coefficient of restitution, \( E_0 \) is the equivalent Young modulus of the two interacting particles; \( \delta \) is the overlap between these two particles. \( R_0 \) is the equivalent radius, \( m_0 \) is the equivalent mass and \( v_{rel} \) is the normal component of the relative velocity of the particles.

The tangential force is:

\[ F_t = -8G_0 \sqrt{R_0} \delta \delta_t - 2 \frac{5}{6} \ln C_e \sqrt{2 \frac{G_0 R_0^5 \delta \sqrt{m_0 v_{rel}^2}}{E_0}} \]

Where \( G_0 \) is the equivalent shear modulus of the two interacting particles, \( \delta \) is the tangential overlap between the two particles and \( v_{rel} \) is the tangential component of the relative velocity of the particles. The tangential overlap is the tangential displacement of the contact point up to the point at which the contact ends or the particle begins to roll or slip. The tangential overlap represents the tangential deformation of a particle. The tangential force is limited by Coulomb friction \( \mu_S F_n \), where \( \mu_S \) is the coefficient of static friction.

The moment from rolling friction is:

\[ M_r = -\mu_r F_n R_i \omega_i \]

Where \( R_i \) is the distance of the contact point from the center of the \( i \)th particle and \( \omega_i \) is the unit angular velocity vector, which is a dimensionless quantity representing only the direction of rotation of the \( i \)th particle. \( \mu_r \) is the coefficient of rolling friction. The tangential force also has moment on the particle:

\[ M_i = F_t R_i \]

During the simulations, the linear- and angular momentum theorem is used to write the equation of motion for all the individual particles resulting multiple number of differential equations to be solved in a sufficiently large number of time steps. The used time step has a great impact on the stability of the numerical model. EDEM applies the Rayleigh-type time step.

\[ T_e = (0.163 h^3 + 0.8766) \pi R \left( \frac{p_e}{G_p} \right)^{\frac{1}{2}} \]

III. DISCRETE ELEMENT SIMULATIONS

In our work, the micromechanical parameters and the particle model of wheat by Keppler et al. [6] were used. Micromechanical parameters with index \( w \) apply to walls, parameters with index \( p \) apply to particles (Table 1). Particle model has been created as clump of three spheres, having radiuses 3 mm and 2.5 mm respectively. Distance between center of spheres on edges was 2 mm (Fig. 2.). The mass of one particle was 0.238 g, principal moments of inertia of one particle were 1.43x10-9 kgm² and 8.015x10-10 kgm² [25].

![Fig. 3 Wheat particle model by Keppler et al. [6]](image1)

![Fig. 4 The geometrical model of the mixing system](image2)

To reduce the computational time, a volume was defined and investigated (Fig. 3.). The wall of the volume was defined as a frictionless material. The mixing screw has 120 mm leaf diameter and 85 mm pitch. The circular velocity is 300 r/min. The first step in simulation was created the randomly generated particle assembly, and then the particles were allowed to fall under gravity. During mixing process the particles was mixed by a steel screw auger.
The second step was the mixing of particles. When the particles reached a static state (kinetic energy of the bulk is about zero) then the mixing process was started, and all of particles were mixed. The filling process took 1.7 s in all cases, under this time the bulk reached in all cases a static state. The process took about 6 s. The number of particles was nearly 137600. The total mass of the mixed material was about 33 kg. The time step in case of all simulations was 25% of critical time, the Rayleigh time. The Rayleigh time is taken by an energy wave to transverse the smallest element in the particular system. Time step must be so short, that the disturbance of particle’s motion could only propagate to the nearest neighbors [20, 35, 36]. The final time step value was $\Delta t = 4.21 \times 10^{-5}$ s. The grid size in all simulation was $3.75 R_{\text{min}}$, where $R_{\text{min}}$ is the minimal radius of particles. The simulation was repeated three times. To follow the particle motion, coloured layers were defined within the assembly. The steps of the simulation process can be seen on Fig. 4.

Mass flow analysis enables the calculation of the rate of mass flow in a certain volume within the simulation. The volume (a cylinder) is created and placed it within the model domain. The calculation for mass flow rate for a single time step is:

$$\dot{m} = \frac{\sum (m_i (v_i \cdot \hat{l}))}{L}$$

- $\dot{m}$ = magnitude of the mass flow rate
- $m_i$ = the mass of particle $i$ in the selection bin
- $v_i$ = the velocity of particle $i$ in the selection bin as a vector
- $\hat{l}$ = the length of the cylinder as a unit vector

The first step is to set the mass flow sensor’s properties to define its size, shape, and initial position. For cylinders, set the number of sides to determine how many polygons are used to approximate the circumference of the cylinder. Fewer polygons are faster to process, but at the expense of accuracy. For each particle its mass is multiplied by the dot product of its velocity and the unit vector of the cylinder from start to end. Each of these per particle values are then summed and divided by the length of the volume. The length of the bin is the distance from the start point to the end point of the cylinder. Cylinder volumes with 0.5 m radius, 0.05 m height and 50 polygons were used in each simulation. 10 volumes were placed in vertical direction (Fig. 5.)

Based on results of simulations the mass flow was determined in each cylindrical volume at 4-5-6 sec. The simulation was repeated three times. The following figures show the results of the mass flow calculations.
IV. CONCLUSION

In our prior work we proved that combination of three types of motion means the mixing effect of the screw. The screw transports the particles upwards. Through the cylindrical surface around the screw there is an influx of particles to the free spaces created by the rotating screw, at a given distance from the screw, there is a downwards motion of particles. In this paper we investigated the mass flow properties of particles in silo dyers. It can be found that the highest mass flow evolved in the 2nd zone and in the further zones it is reduced. These results provide helps for the future investigations, where the heat flow will be taken into consideration.

REFERENCES