SZENT ISTVÁN UNIVERSITY

ANALYSIS OF PARTICLE MOVEMENT CONDITIONS OF OPEN MIXING SCREWS

Thesis of PhD Work

Attila Varga

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Leader: Prof. Dr. István Farkas, DSc
Faculty of Mechanical Engineering
Szent István University
Gödöllő, Hungary

Supervisor: Dr. László Fenyvesi, PhD
Faculty of Mechanical Engineering
Szent István University
Gödöllő, Hungary

Co-Supervisor: Dr. István Keppler, PhD
Institute of Mechanics and Machinery
Faculty of Mechanical Engineering
Szent István University
Gödöllő, Hungary

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affirmation of Head of school	affirmation of Supervisor

TABLE OF CONTEST

NOMENCLATURE

d	leaf diamater	$[mm]$
C_r	coefficient of restitution	$[-]$
G	shear modulus	$[Pa]$
h	pitch of the mixing screw	$[mm]$
R	leaf radius	$[mm]$
R_{eff}	effective radius	$[m]$
V	mixed volume	$[m^3]$

Greek letters:

Δt	time step	$[sec]$
μ_0	coefficient of static friction	$[-]$
μ_r	coefficient of rolling friction	$[-]$
ν	Poisson-ratio	$[-]$
ρ	density	$\left[\frac{kg}{m^3}\right]$

1. INTRODUCTION, OBJECTIVES

In the first section the actuality and aims of my work are described.

1.1. Actuality and importance of the topic

In many areas of engineering practice, problems arising from the particular mechanical behavior of granular materials can be encountered. The granular material assemblies behave in a similar way to solids under certain conditions (they are capable of retaining strength, retaining their shape), however in other circumstances the same assembly of granules, which have been previously modeled as solids, exhibit similar properties to the liquid This duality may make it difficult to describe the mechanical behavior of the granules, and in some cases none of the models can be applied (e.g. discharge of silos). For this reason, technologies that have a significant role in grain assemblies. (e.g. construction, agriculture, pharmaceutical industry, etc.) are often experimentally determined / selected for a particular process or device. In many cases, the selection or definition method is not appropriate, which can cause a number of technological problems. In case of drying of grains, it is especially important to use the right technology, because of the very high operating costs, quantity of the material as well as high quality requirements.

A group of industrial dryers is made up of thick-layered grain dryers. For the thick layer dryers, the biggest problem is that at the end of the process the moisture content of the material will not be homogeneous. In order to reduce inhomogeneity, grain-mixing devices may be used. This solution has not been applied to most silo dryers, although it has proven that improve the homogeneity of the moisture distribution of the drying material.

The most important questions of the design of the mixing systems are how much mixing sprouts during the mixing process how much time to travel and how much material to move during the time. In the case of mixers and conveyors in the field of industry and agriculture, it is very important to specify precisely the geometrical characteristics and the operating settings. If these parameters are selected incorrectly, the performance will not be adequate either. The transport process itself seems simple, but modeling the process is a difficult and complex task. Researchers and engineers working in this field rely heavily on empirical data in design and development because they do not have accurate information on the material flow processes in the mixing screws.

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1.2. Objectives and aims

The subject of my research is the examination of the grain flow processes about the mixing screws. In my dissertation, I present a discrete element model validated by experimental investigations, with which engineers can get reliable results.

Aims in connection with discrete element modeling:

- Creating a model that describes the actual mixing process with acceptable precision, and the time and energy requirements remain moderate.
- Based on the flow chart obtained in the discrete element simulations, the definition of the functions describing the boundaries of the mixed domain.

Since there is no such an index-number of the efficiency of the open mixing screws to compare different geometries and angular velocities, my research aims in the field of open mixing screws:

- Defining and quantifying the mixing efficiency of open mixing screws to compare simulations with different speeds.
- Determination of mixing efficiency in a function of parameters influencing the mixing by sensitivity test.

2. MATERIAL AND METHOD

In this chapter, I present the modeling and experimental methods used to achieve my research goals.

2.1. Experimental apparatus

The first step to determine the particle motion around the mixing screws was to design an experimental apparatus which can represent the motions in the industrial dryers.

The experimental investigations were done at the laboratory of Mechanics and Technical Drawings Department. The wall of a mixing apparatus is a transparent cylinder having 450 mm diameter and 3 mm of wall thickness. The top of the cylinder is open. In the center of the cylinder there is the mixing screw, having a V-belt drive connection to an electric motor. Although the wall of the cylinder is transparent, the particle motion around the rotating mixer cannot be seen because of the cylindrical configuration and because of the rotating screw.

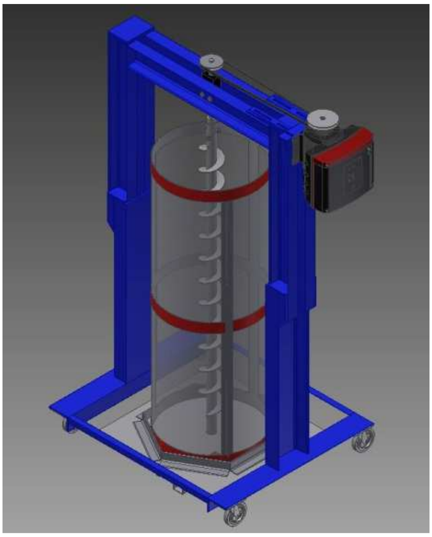


Fig. 1. 3D model of the mixing apparatus

2.2. Method of measurements

One layer of painted wheat was also placed around the middle of the particle assembly. After ten rotations of the screw (with angular velocity 15 Rad/s), the rotation has been stopped, and the sampler tubes were pushed from above into the mixed assembly in different distances from the rotating mixing screw

The vertical displacement of the colored grain layer has been measured by evaluating the decrease of the thickness of the top non colored layer from the original thickness of this layer placed above the colored one in the beginning of the measurement. Because of the cylindrical symmetry of the problem, it was possible to determine the whole vertical displacement field by this way. The results of this measurement made it possible to verify the usability of DEM. The model of the mixing apparatus has been created by using DEM, and analyzed the displacement field after the same number of rotation.

2.3. Modifiaction of the experimental apparatus

In addition to the measurement procedure outlined in the previous subchapter, I used another method to validate my discrete element model. The disadvantage of the cylindrical container is that it is not possible to see what is happening in the immediate vicinity of a screw. To solve this problem, I placed a plexiglass box in place of the cylindrical plexiglass, the width of which was equal to the diameter of the mixing screw (Fig. 2). When selecting the dimensions of the box, care should be taken to ensure that the resting and moving parts are well separated during the mixing process. Based on preliminary calculations, I chose the length of the box to 570 mm. In connection with the modified equipment, the most important question was how much the material would behave the same as in the cylinder plexiglass.

Fig. 2. The modified experimental apparatus

The tests showed that the mixing process in the box is very similar to mixing in a cylindrical tube (Fig. 3).

Fig. 3. The distinction of the resting and moving zones

During the mixing, it seemed clear that the resting and moving parts were clearly distinct from each other.

2.4. Determination of strength of the wheat particles

When determining the optimum speed of the mixing screws, the forces between the particles are also great importance in addition to the amount of the mixed material. If the forces acting between the particles exceed the limit for breaking the particles over a given speed, the material quality may be significantly reduced. In order to be able to investigate later whether the particles were damaged at speed, I had to first determine the force needed to break a particle. The strength tests were performed using an INSTRON 5581 universal material tester.

2.5. Discrete element modeling of a mixing process

To modeling the mechanical behaviour of the granular assamblies discrete element modeling technique was used. The simulations were done with the EDEM discrete element system.

2.5.1. Contact and particle model

For modeling the mechanical behavior of the particulate material the Hertz-Mindlin contact model has been used. The wheat particle model has been created as the clump of three spheres, having radiuses 3 mm for the central and 2.5 mm for the two smaller side parts, respectively. The sizes of the wheat partilce can be seen in Fig. 4. The weight of one particle was 0.238 gr. The moment of inertia were $1.434 \cdot 10^{-9}$ kgm^{2}and $8.015 \cdot 10^{-10}$ kgm^2. In the DEM simulations the micromechanical parameters in Table 1. were used.

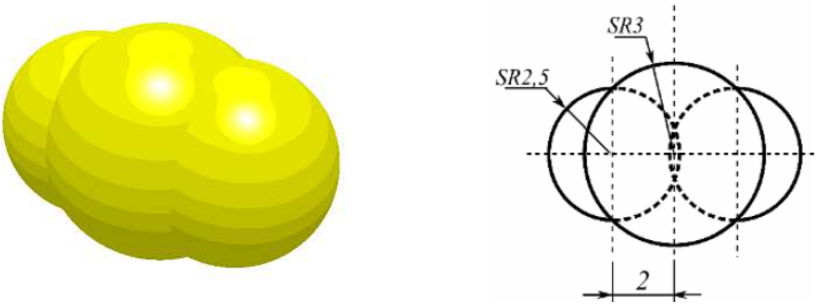


Fig. 4. DEM model of a wheat particle

Table 1. Micromechanical parameters of wheat and steel

Micromechanical parameters	**Wheat**	**Steel**
Poisson-ratio, v	0.4	0.3
Shear modulus, G, Pa	$3.58 \cdot 10^9$	$8 \cdot 10^8$
Density, ρ, kg/m^3	1460	7500
Impact coefficient, C_r	Wheat: 0.5	-
	Steel: 0.6	Wheat: 0.5
Friction coefficient, μ_0	Wheat: 0.3	-
	Steel: 0.25	Wheat: 0.25
Rolling friction coefficient, μ_r, m	Wheat: 0.01	-
	Steel: 0.01	Wheat: 0.01

2.5.2. Description of a simulation process

During the simulations, the geometry and speed of the mixing screws were changed. Initially, the dimensions of the model were the same as those of the experimental equipment. Due to the large volume of plexiglass and the large number of particles in it, a running time was more than 2 weeks. For multiple runs, the data obtained during the calculation is impossible to store due to their size. That is why it was necessary to simplify the model.

My initial assumption was that the vertical movement of the particles has the greatest effect on the efficiency of the drying, so in the simulations only a "slice" of the plexiglass was examined.

In the first step of the simulation, randomly generated particles were deposited in the model space, which fall under the influence of gravity at the bottom of the model space. The mixing process was started when the system reached the equilibrium state. I could start mixing after the steady state. The "start time" moment was 1.7 s in any case, regardless of geometry. Measurements and simulations also showed that the grains form a tapered surface at the top of the set, which does not grow further after a time, reaches its maximum height, and a dynamic equilibrium is formed. The simulation process is shown in Fig. 5 and 6 from grain generation to dynamic state. Colors indicate the speed of particles. The time interval applied during the simulations was $\Delta t = 4.21 \cdot 10^{-5} sec.$

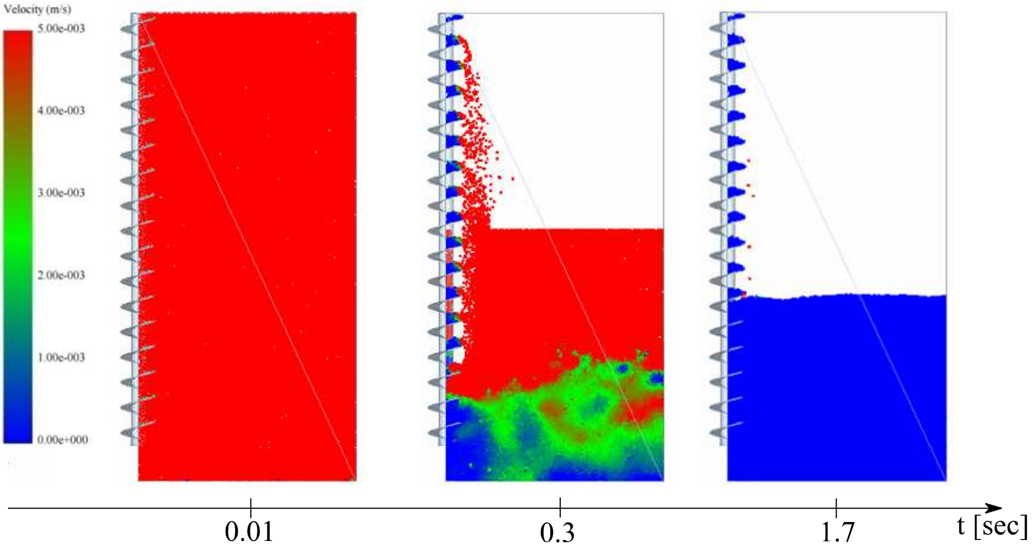


Fig. 5. Simulation of mixing process until steady state

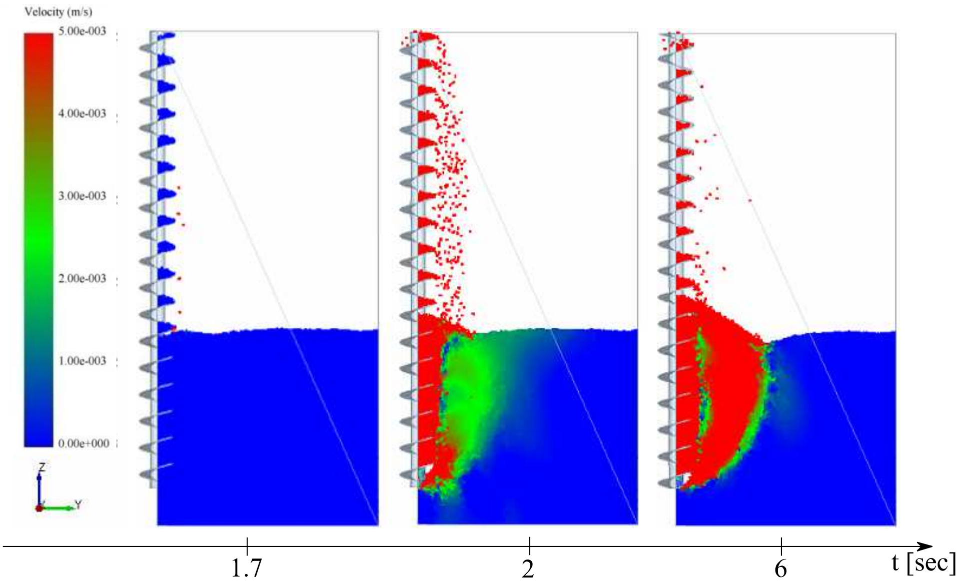


Fig. 6. Simulation of mixing process until dynamic state

The time needed to reach dynamic equilibrium could be determined experientially. For different geometries and speeds this time has changed. After the creation of the calibrated discrete element model of the mixing system, the next step was to solve the comparison of simulations with different geometries and speeds.

2.6. Quantifying of mixing efficiency

2.6.1. Definition of effevtive radius

None of the available literature can be used to determine the delivery or mixing performance of open vertically placed mixing screws. To determine the efficiency of mixing, concept of effective radius has been introduced. This is the distance from the longitudinal axis of the screws at which the vertical velocity of the particles equal to 20% of the maximum velocity along the radius. The 20% is an arbitrary recorded value that can be used to illustrate the effective radius.

2.6.2. Determination of the mixed volume

The performance of the mixing screws was determined by the effective radius at first However, if the speed is too low, the backflow is not yet formed and may affect the results. It is preferable to examine the displaced volume after reaching dynamic equilibrium. The particles are sifted at speed, moving and resting zones are well separated. Three functions can be added to the bounds of the moving zones, which can be easily mapped to the range (Fig. 7).

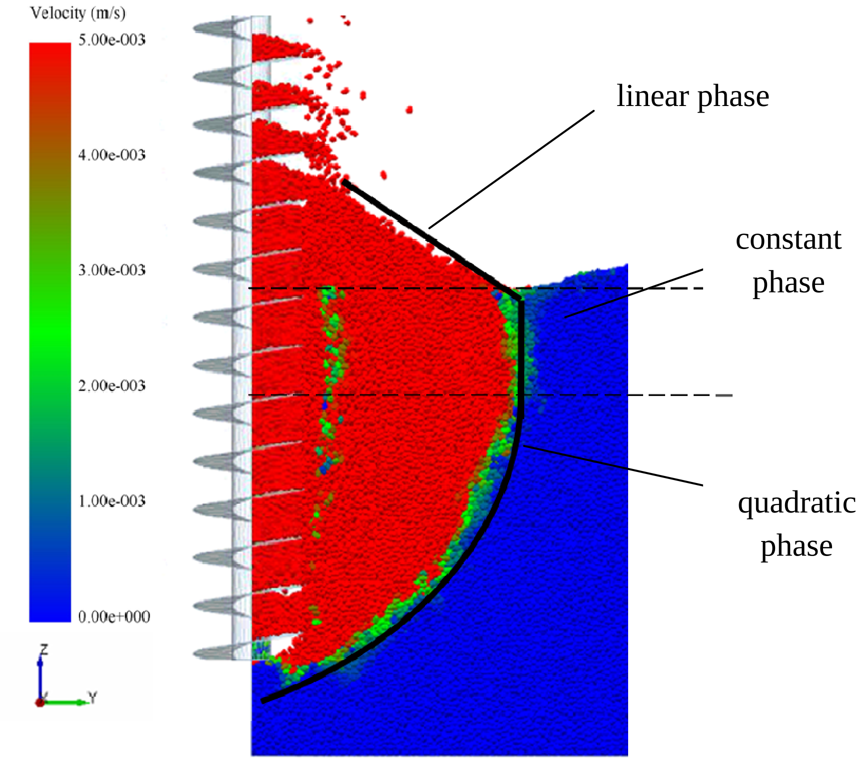


Fig. 7. Functions fitted to boundaries of the mixed domain

The functions are rotated about the vertical axis to obtain a rotating body whose volume will be the mixed volume. In all cases, the simulation time was set at least 6 sec. During that time, even at low speeds ($20\,rad/s > \omega > 0$), the final shape of the set will develop. The effects of the parameters influencing the size of these volumes were examined and, in the case of different grain geometries, the nature of the mixed domain was examined. Response surface method was used for the studies. The essence of the process is to describe the test parameter defining the phenomenon (which is the transmitted volume) as a function of selected factors (leaf diameter, thread pitch, angular velocity).

3. RESULTS

In this chapter, I present the new scientific results obtained during my research, which help to optimally operate the open mixers in the silos dryer.

3.1. Validation of discrete element model

The measurements presented in Chapter 2.2 have been used to validate my simplified model introduced in Chapter 2.5. In EDEM discrete element software, it is possible to color the particles and monitor their movement. The particles were colored after reaching equilibrium. The following figure shows the position of colored particles after 10 rotations (Fig. 8).

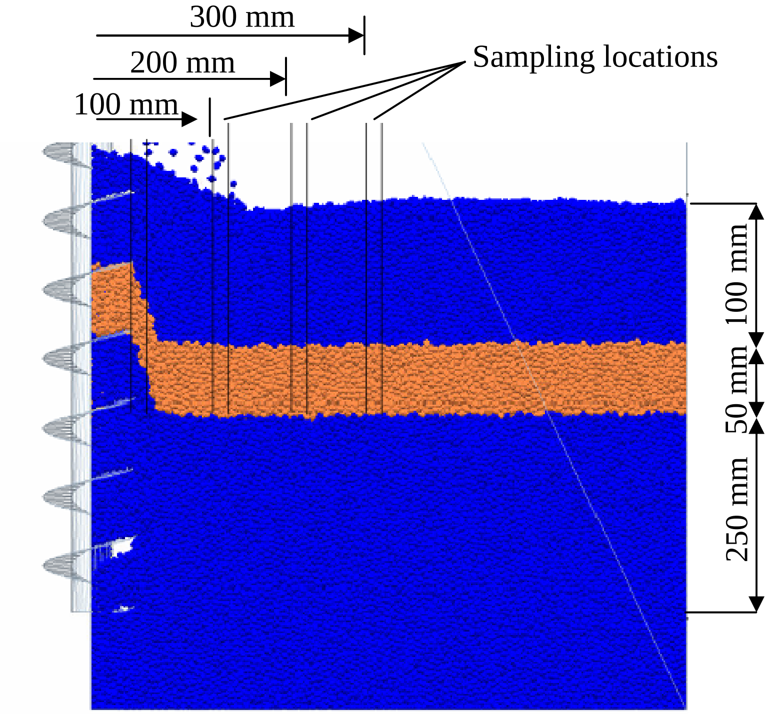


Fig. 8. The location of the particles after 10 rotations

The simulation results showed that beside the screw, the displacement of the particles (95mm) was almost identical to the measured values of the experimental tests (90-100mm). There was no shift in the rest of the assambly.

After this, I continued to rotate the screw to compare the flow images obtained with the DEM simulation with the flow image in a study of the Home-Grown Cereals Authority (HGCA) (Fig. 9).

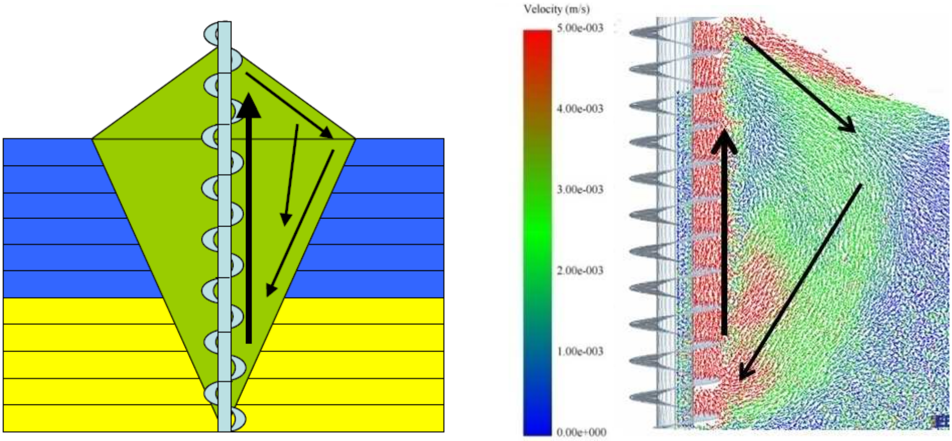


Fig. 9. The flow chart found in the literature and the simulations

In the simulation (right image), the velocity vectors of the particles are visible. In both figures, the arrows show the flow direction and their thickness represents the magnitude of the velocity. In the left figure, the yellow range indicates the set with the drying air, the blue being the cooler, humidest range. In both cases a backflow process can be observed. In my dissertation, I avoided the thermal effects, only the description of the grain movements was my goal.

In order to verify of the model, further tests were necessary. In the next step, I compared the displacement fields with the whole model, the simplified model, and the modified experimental device. When comparing the resulting flow chart with the grain flow conditions generated in the simplified model, it can be seen that the moving zone is nearly identical in both cases (Fig. 10).

The material flow processes generated during mixing with the modified experimental apparatus are well visible due to the size of the container box and the transparent plexiglass. Fig. 11 shows the position of the moving zone boundaries in the real process. Because of better visibility, the boundaries of the moving zone are marked with a blue line on the plexiglass plate.

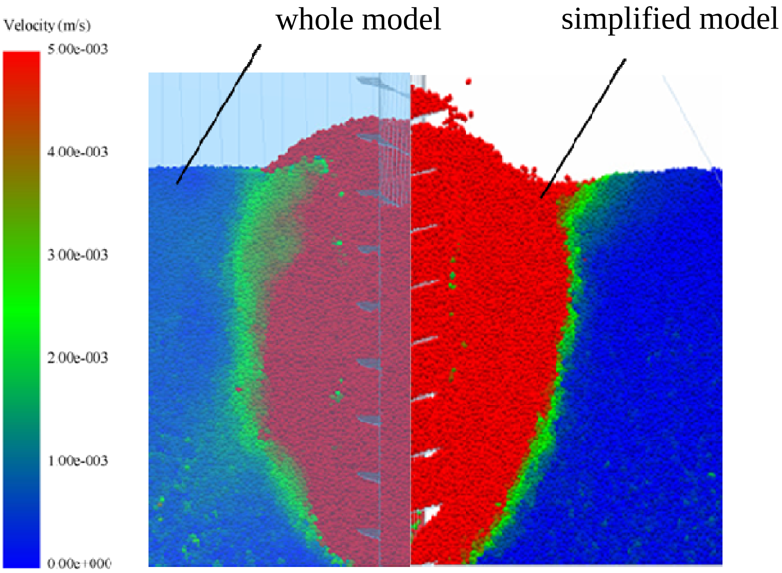


Fig. 10. Comparison of simulations

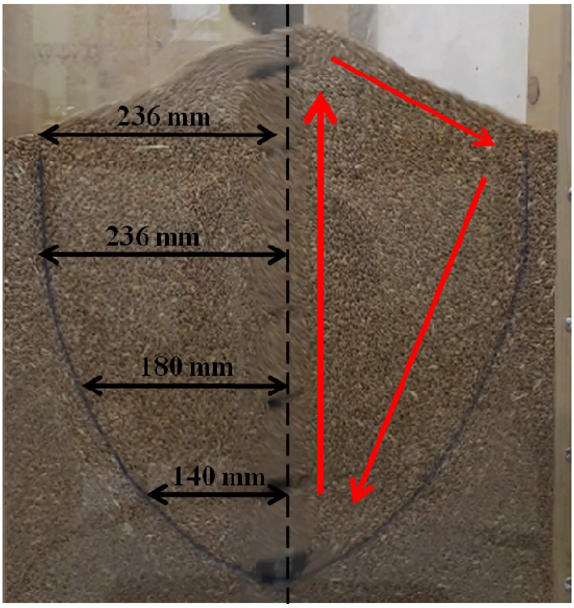


Fig. 11. The position of the moving zone formed during the experiment

When comparing the simulations and the experimental studies, I found that the motion of particles in the discrete element model is similar to reality and the results show good agreement (Fig. 12).

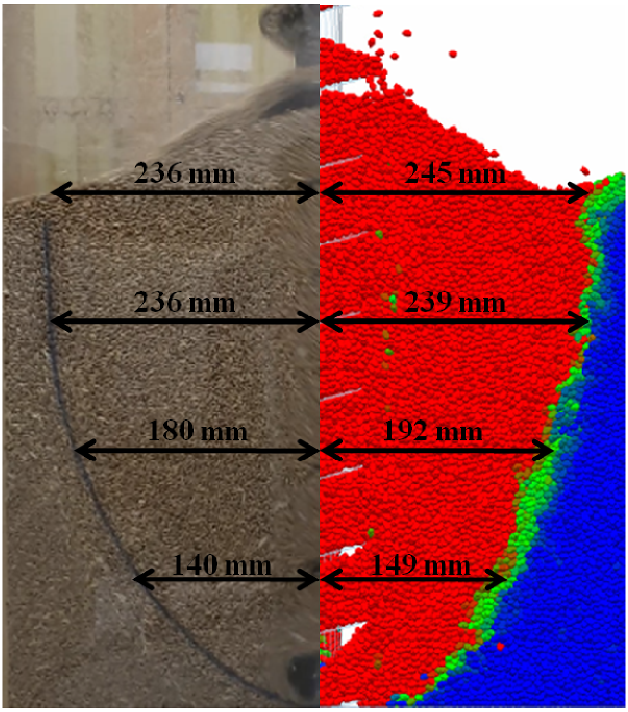


Fig. 12. Comparison of experimental testing and simulations

The discrete element model I built allows the determination of short-term (1-1.5 days) of grain movements around the mixing screws.

3.2. Determination of mixing efficiency with the effective radius

In the next step I tested the velocity distribution in the discrete element model at different angular velocities. The range of the test range was 5 rad/s and 45 rad/s. The simulations were done with triple repetition at each angular velocity. Mixing efficiency was defined as the quotient of the effective radius and the leaf radius. In the evaluation, I found that the results for the given repetitions show a small spread. In Fig. 13, it can be seen that increasing the speed increases mixing efficiency, but falls after a certain value has been reached. The dynamic equilibrium state does not occur at the speeds to the left of the red line mark. This means there is an optimum value beyond which there is no reason to increase the speed. In engineering practice, we can save energy by optimizing the speed.

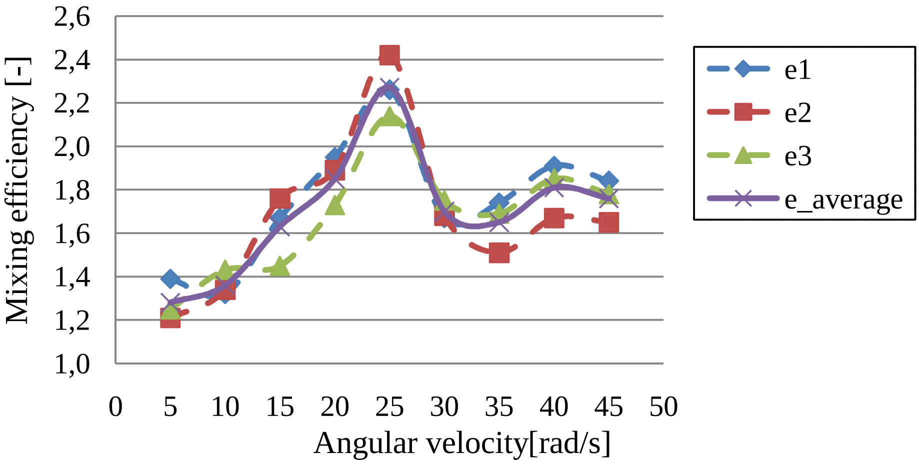


Fig. 13. The mixing efficiency will be maximized at a given angular velocity

I also examined the evolution of the contact force between the particles depending on the speeds. Increasing the speed increases the maximum contact forces between the particles (Fig. 14). I found that in the range of speeds I examined, the value of the forces from the particle-particle and particle-screw interaction (impact) did not reach the limit for breaking the particles (110-130 kN), however, the increase in contact forces and the number of collisions could be adversely affected the quality of the mixed crop.

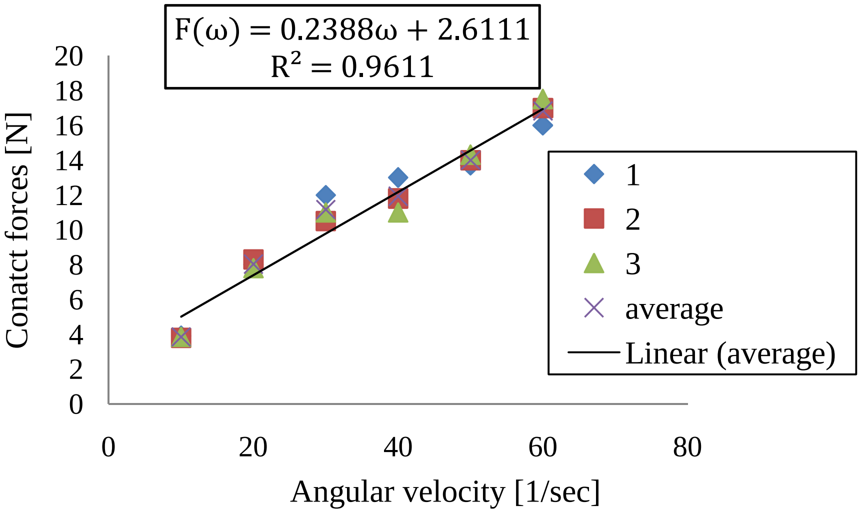


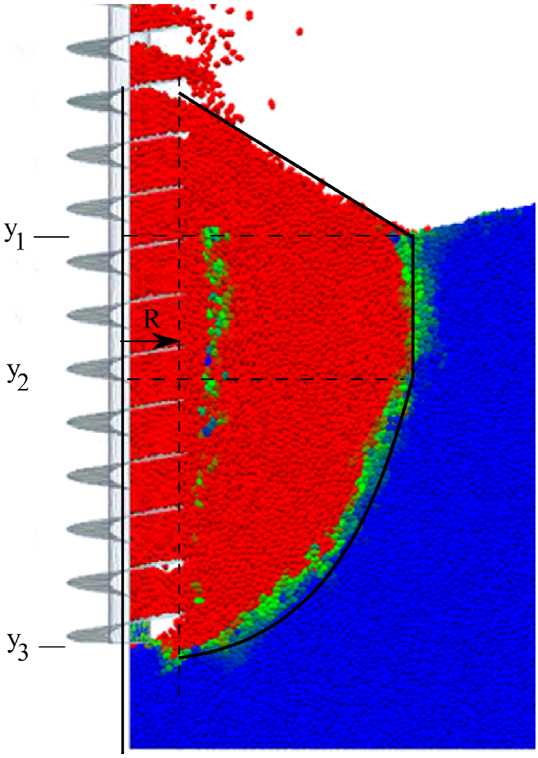
Fig. 14. Changes in contact forces in that range

3.3. Determination of mixing efficiency with the mixed volume

When examining the flow chart obtained in discrete element simulations, I found that the shape of the boundary of the mixed domain can be approximated by 3 functions. If these functions are known, the following mathematical operation can be used to determine the mixed volume:

$$V = \int_a^b 2\pi z\big(f(z) - g(z)\big)dz\,. \tag{1}$$

Sufficient if the linear and the quadratic functions are known. The integration boundaries were at the edge of the screw’s leaf and the boundary of the mixed volume. Fig. 15 shows the nature of the three functions.



$$R(y) = \begin{cases} A \cdot R + B & R\epsilon[0, y_1] \\ R_{eff} & R\epsilon[y_1, y_2] \\ C \cdot R^2 + D & R\epsilon[y_2, y_3] \end{cases}$$

Fig. 15 Functions describing the mixed domain

In addition to the 3 sphere-element, I also performed calculations with a smooth sphere element and two spherical elements. The smooth sphere has a diameter of 3mm. For the two spherical elements, the diameter of the spheres forming the grain was 2 mm and the distance between the two spheres was 1 mm. I have found that the nature of the mixed domain does not change, i.e., it is independent of the grain geometry, and in this way the mixing efficiency of the fixed-shaft screws can always be characterized by the mixed volume.

3.4. Determine the empirical function of the mixed volume

Based on the simulation results I had to determine the $V = V(d, h, \omega)$ relation, where:

- d – leaf diameter,
- h – pitch,
- ω - angular velocity.

The function was searched the range of d = 60~120 mm; h = 50~80 mm; ω = 50~300 rpm.

For the function to calculate the error limit for the entire test range, I first determined the variance for each experimental setting. Then I verified that the variance for each experimental setting belongs to the same theoretical variance. After the Fisher and Bartlett tests, I have found that the eight experimental variance analyzed does not have the same theoretical variance, so the phenomenon can not be described in the test range with linear function.

3.5. Determination the effect of mixing factors

In the previous chapter, it was found that the mixed volume can not be described by linear function of factors. There are three ways to continue investigations. Reducing factor count, higher degree (linear instead of quadratic) approximation, and crossover volume test with parameter sensitivity test. Among the listed options I chose the latter, that is, I examined the change of the mixed volume so that I left two of the three factors unchanged, and changed the third one. Fig. 16 shows the results at different speeds. The leaf diameter was 120 mm and the thread pitch was 85 mm. The diagram shows that (just like in the case of the effective radius) there is an optimum speed at which the screw mixes most of the material. The optimum speed here is 300 rpm = 31.42 rad/s. Above this value the screw no longer mixes more material.

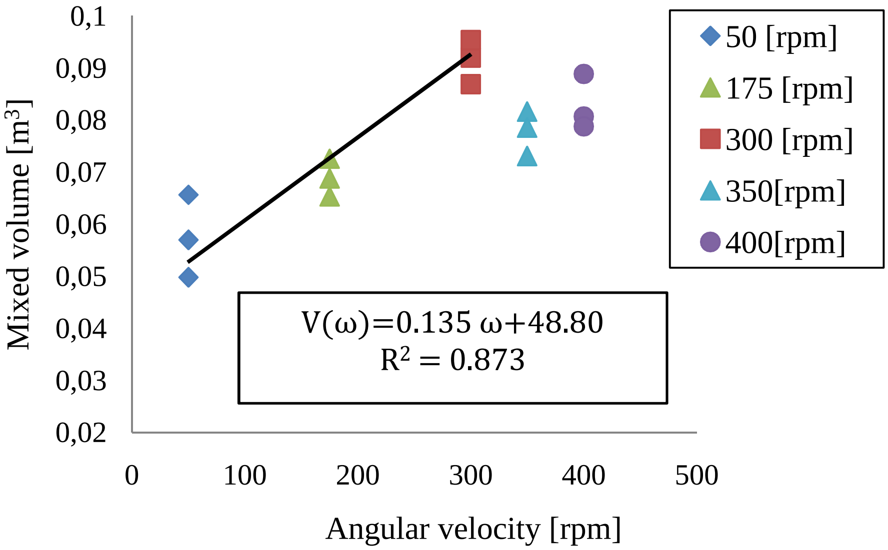


Fig. 16. Change in mixing efficiency (mixed volume) as a function of angular velocity

In the next step, I examined the effect of the leaf diameter of the screw. The speed was 300 rpm and the pitch was 50 mm. The results are shown in Fig. 17.

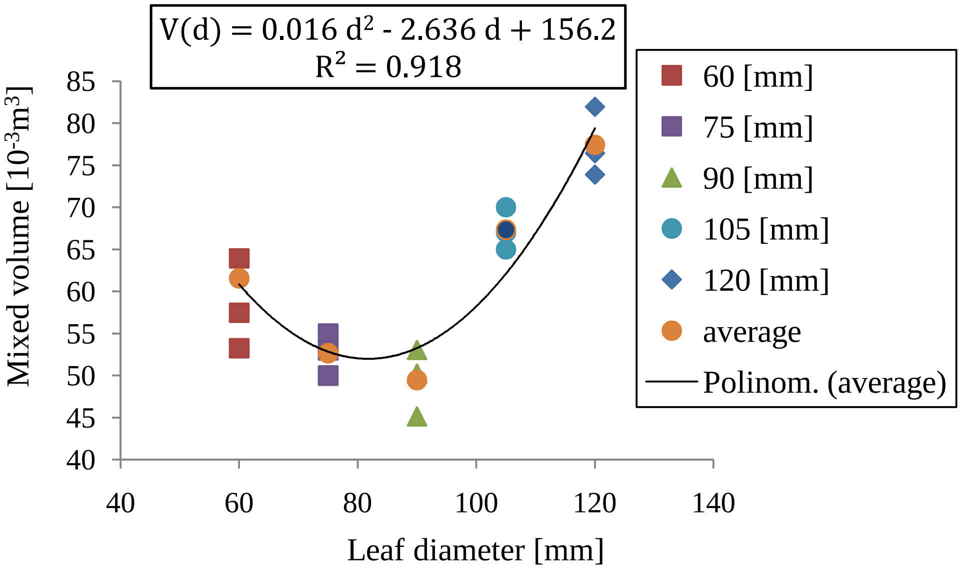


Fig. 17. Change in mixing efficiency (mixed volume) as a function of leaf diameter

4.NEW SCIENTIFIC RESULTS

1. Validation of discrete element model

With the help of experimental tests and simulations, I have proved that the discrete element model defined in my work describes the movement conditions around the mixing screws used in practice with the adaquate precision. With this new discrete element model, it is possible to achieve the results much faster (1-1.5 days) and more efficient than to look at the whole container (in the latter case the calculation time is nearly 3 weeks).

2. Determination of mixing efficiency with the effective radius

By introducing the effective radius, simulations run at different speeds can be compared. This is the distance from the longitudinal axis of the screws at which the vertical velocity of the particles equal to 20% of the maximum velocity along the radius:

$$v(x = R_{eff}) = 0.2 \cdot v_{max} \,.$$

Mixing efficiency expressed with the effective radius:

$$e = \frac{R_{eff}}{R} \,.$$

The results demonstrate that in the range of speeds I have studied - within the speed limits for technical practice - the mixing efficiency will be maximized at a given speed. Increasing the angular velocity does not improve mixing efficiency.

3. Increasing the angular velocity increases the contact forces between the particles

By calculations I proved that the change of the contact forces between the particles can be described by the

$$F(\omega) = 0.2388\,\omega + 2.611 \qquad \omega \in [10,60] \,,$$

function in the range I examined by the micromechanical paramaters in Table 11.

4. Determination of mixing efficiency with the mixed volume

During my work, I determined the grain flow conditions around the mixing screws with different grain geometry and velocities. When examining the flow chart obtained in discrete element simulations, I found that the mixed domain consists of three segments and the edge of the segments can be approximated by the following three functions:

$$R(y) = \begin{cases} A \cdot R + B & R\epsilon[0, y_1] \\ R_{eff} & R\epsilon[y_1, y_2] \\ C \cdot R^2 + D & R\epsilon[y_2, y_3]. \end{cases}$$

The results demonstrate that the shape of the mixed domain does not depend on speed or grain geometry. By rotating the mixed domain around the vertical axis, the mixed volume is obtained. The mixing efficiency can also be characterized by the mixed volume.

5. Determination of the effect of mixing factors

With parameter sensitivity analysis, I found that the factors affecting the mixed volume significantly are the angular velocity and the leaf diameter of the screw. Increasing angular speed initially improves mixing efficiency, but after a given value, the screw is no longer able to mix more material.

The change in mixing efficiency in the given speed range (with leaf diameter: 120 mm and pitch: 85 mm) is described by the following function:

$$V(\omega) = 0.135\,\omega + 48.8 \quad \omega \in [50{,}300]\,.$$

The mixing efficiency can be described as a function of leaf diameter by

$$V(d) = 0.016\,d^2 - 2.636\,d + 156.2 \quad d \in [60{,}120]\,.$$

By increasing the leaf diameter, the mixing efficiency decreases to 90 mm and then increases to 90-120 mm.

The pitch increases the time elapsed until the dynamic equilibrium state is reached. Increasing the leaf diameter increases the amount of mixed volume so mixing efficiency increases. At a given speed, there is a "worst" leaf diameter selection because the efficiency here is minimal.

5. CONCLUSIONS AND SUGGESTIONS

In the case of mixers and conveyors in the field of industry and agriculture, it is very important to specify precisely the geometrical characteristics and the operating settings. If these parameters are selected incorrectly, the performance will not be adequate either. Researchers and engineers working in this area rely heavily on empirical data for design and development because they do not have accurate information on the material flow processes around the mixing screws.

One of the main areas of my research was the description of the flow conditions around the open mixing screws. By simulations and experimental studies, I proved that the vertical flow rate of the particles is by magnitude greater than the radial velocity. Therefore, it is not necessary to examine the whole container, it is enough to incorporate only one section of the container into the modeling. During my research, I have found that during the mixing process a moving and a resting zone is formed which are well separated from each other. Within the moving zone, a backflow process develops, the intensity of backflow does not change after a certain time and develops a so-called dynamic equilibrium state.

The second main area of the research was the quantification of mixing efficiency. Using the effective radius, I have determined that there is an optimum speed in the fixed axes of open mixers, that there is an optimum value beyond which the speed is no longer justified. I have also developed another method for quantifying the mixing efficiency. I have determined that the mixed domain can be described by three functions irrespective of grain geometry. The three limiting functions can be used to calculate the mixed volume, which can also be characterized by the efficiency of the mixing screw. I completed the complete response surface method. The mixed volume was the test parameter. I found that the mixed volume can not be described by linear functions of the factors. Subsequently, by parameter sensitivity analysis, I found that the factors influencing the mixed volume are the leaf diameter and speed of the screw. I have verified that at a given speed there is a "worst" leaf diameter selection, and increasing angular speed initially improves mixing efficiency, but after a given value, the screw is no longer able to mix more materials. The increasing of the pitch affects only the time elapsed until the dynamic equilibrium state.

6. SUMMARY

In case of the drying process of agricultural grains in silos the main problem is that the distribution of the moisture content is not homogeneous within the granular assembly. To reduce this effect mixing systems are used within the silos. In most of the cases the motion path and velocity of the screws are unchangeable. If the operational parameters are not set adequate then significantly additional costs could appears.

The aim of my research was to determine the particle-flow about the mixing screws. To reach this goal I studied the literature in every detail. After to map the deficiency of the literature and choose the suitable modeling technique, an experimental apparatus was built. To describe the mixing phenomenon discrete element method was used which is a fairly new proceeding to model the mechanical properties of bulk materials. I had to decrease the simulation time, therefore the container's size had to be reduced. In the case of size reduciton, attention must be paid that the original behavior of the bulk material does not change. After the modification of the experimental apparatus, it was proved that the vertical displacement has the largest influence over the mixing efficiency. Due to this statement, it was sufficient to examine the slice of the plexiglass cylinder.

To compare the simulations with different parameters the effective radius has been determined. It can be found there is an optimal screw rotation angular velocity above which there is no reason to operate the mixing apparatus, as the mixing efficiency does not increase with the increase of screw angular velocity, as the change in the efficiency of mixing becomes smaller and smaller by increasing the angular velocity and the causeless increase of screw angular velocity results higher compressive forces acting on the mixed particles.

I established that the mixed domain can be described with three functions and the shape of this volume does not depend on the particle's geometry. The mixed volume can be evaluated with the rotations of these functions about the vertical axis. The volume is affected by the following factors: leaf diameter and angular velocity of the screw. I proved that the pitch of the screw has no effect to mixed volume.

Summarizing it can be said, the new scientific results could help the design and operation processes of mixing systems and decrease the costs.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign language:

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