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Numerical study on the impact of particles filling pattern and screw parameters on the mixing uniformity of wheat grains in a screw mixer

S. Garneoui[a,*], I. Keppler[a], P. Korzenszky[a], M. S. Talafha[a]

[a] *Department of Mechanical Engineering, Hungarian University of Agriculture and Life Sciences, 2100 Gödöllő, Hungary*

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Abstract

The presence of moisture content in a silo makes the preservation of a grain stock challenging especially when dealing with a large stock. This made it as a major concern for engineers to preserve large crops of grains and avoid huge losses. By installing a screw inside of a silo, the moisture problem could be avoided by stirring the loaded granular bed alongside aeration, also it could be effective to mix different types of loaded materials. The present work has sought to develop predictive models of discrete element method for mixing uniformity assessment when mixing wheat granules in a hopper-bottom screw mixer. The different factors being investigated are: initial configuration of particles, screw rotational direction, screw pitch length, screw diameter and screw rotational velocity. Findings regarding bed homogeneity were calculated using the nearest neighbor's method. The best mixture was obtained when considering a side-wise filling type of particles ahead mixing and using a 20 mm screw diameter, 30 mm screw pitch and rotating the screw at 80 rpm speed.

Keywords: discrete element method, granular material, homogeneity index, screw mixer

1. Introduction

Mixing process has a crucial role to get the desired product quality in many industries, such as pharmaceutical [5], chemical [18] and metallurgical [7]. Stocking of wheat grains in silos is an ordinary task after harvesting, however the presence of moisture between grains in a silo could deteriorate the whole stock and leads to a huge loss. Typically, pumping hot air from the bottom of a silo is the used technique to remove the moisture, however when dealing with a large mass of material, moisture will slightly decrease, but an important amount remains present. For this concern, agitating the whole material with a screw would let the air to flow among the majority of particles, consequently the remained moisture will diminish. In addition, over-mixing costs money and time, therefore optimal mixing time should be pre-set to avoid these drawbacks.

Researchers studied the mixing of solid particles in various mechanisms. For example, Metcalf et al. [13] revealed using experiments that a screw feeder would be more efficient in terms of mixing quality by increasing the screw shaft diameter, increasing the screw flight diameter, decreasing the screw pitch, and decreasing the screw rotational speed. Uchida and Okamoto in [21] used the X-ray technique and they showed that a better mixture quality could be achieved by increasing the screw pitch. These contradictory results between the different experiments reveals that the appropriate selection of screw parameters depends on the particles

*Corresponding author. E-mail: seifeddine.g@gmail.com.
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mechanical properties. On the other hand, Peter et al. [15] used the Novosad theoretical model to measure the resulting horizontal force acting on a blade for individual blade immersion depths during mixing, yet many terms must be calculated ahead, which make this method complicated.

With the emergence of the numerical tools based on the discrete element method (DEM), the old experimental trial and error method which is costly and time consuming is no more appropriate. Numerical simulations are conducted instead to imitate a real process and obtain many information of vital importance that cannot be obtained using real experiments such as particles coordinates, particles velocities, forces acting between particles, etc., see [11, 17]. Ali et al. [9] evidenced that DEM simulations showed adequate rapprochement with real experiments in a paddle mixer, which appears to be a favorable tool to forecast particles dynamics. Boonkanokwong et al. [4] revealed using discrete element simulations that the mixture quality is at its maximum when using two or three blades in a bladed mixer instead of one or four blades.

In our previously conducted study that used a new screw design by adding ploughs mated to the screw and evaluating the mixture uniformity using the classic index of mixing so-called Lacey index [6]. We have seen that less volume would be available for filling grains, also changing the number of cells alters the Lacey index results. In this paper, we examined the effect of the following parameters: initial filling configuration of particles, screw rotational direction, screw pitch length, screw diameter and screw rotational speed on the mixture uniformity of wheat particles in a hopper-bottom screw mixer, and examining these parameters would help to improve the mixer performance. A bi-component mixture was performed firstly using EDEM® (discrete element software), then the mixing index based on the nearest neighbor's method [8] was employed to quantitatively evaluate the mixing rate.

2. The discrete element method

The discrete element method is a powerful numerical tool that could be used to study the movement of particles during a mixing process. DEM applications could be found in various domains such as geophysics [19], masonry [1], blending [2], etc. Interactions defined between the different types of materials allows to calculate the normal and tangential forces by iteration along the process. In each iteration, several steps must be accomplished in order to move to the next iteration; it starts with the detection of contact, then the calculation of the normal F_n and tangential F_t forces, which are calculated as follows

$$F_n = \frac{4}{3} E_0 \delta^{\frac{3}{2}} \sqrt{R_0} - 2\sqrt{\frac{5}{6}} \frac{\ln C_r}{\sqrt{\ln^2 C_r + \pi^2}} \sqrt{2E_0} \sqrt[4]{R_0 \delta} \sqrt{m}_0 v_{nrel}, \tag{1}$$

$$F_t = -8G_0 \sqrt{R_0 \delta_n} \delta_t - 2\sqrt{\frac{5}{6}} \frac{\ln C_r}{\sqrt{\ln^2 C_r + \pi^2}} \sqrt{2G_0} \sqrt[4]{R_0 \delta_n} \sqrt{m}_0 v_{trel}. \tag{2}$$

When two particles come into contact, their equivalent Young's modulus E_0 is calculated by the formula $1/E_0 = (1 - v_1^2)/E_1 + (1 - v_2^2)/E_2$. In (1)–(2), δ quantifies the overlapping between those two particles, C_r describes the rebounding of each particle after contact with another particle known as the coefficient of restitution (this coefficient should be defined in EDEM® pre-processor as the ratio of relative speed after collision to relative speed before collision), and v_{nrel} is the normal component of the relative velocity of particles. The equivalent shear modulus G_0 of two particles in contact is calculated by $1/G_0 = (1 - v_1)/G_1 + (1 - v_2)/G_2$. In (2), δ_n and δ_t describe the normal and tangential overlap between those particles, respectively, and v_{trel} is the tangential component of the relative velocity of particles. The first to last tangential contact between those particles upon slip or collision is the definition of the tangential overlap.

The dynamics of particles are computed iteratively through time to solve and update the differential equations. As it has been revealed, results would not converge without an appropriate setting of time-step, therefore it should be attentively pre-set [3]. Usually, Rayleigh time is used to estimate the maximum time-step for such a DEM simulation to run stably, it is calculated as

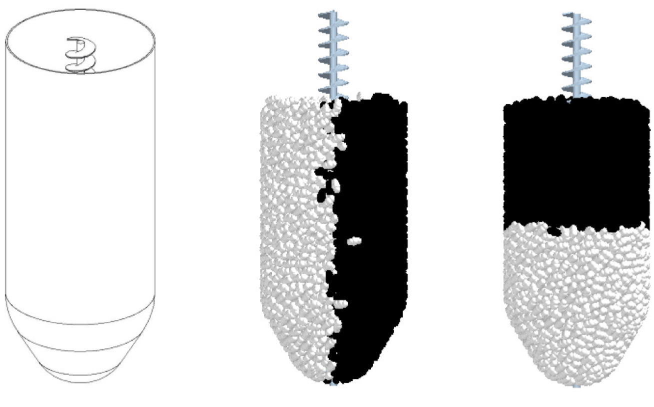
$$T_{\text{Rayleigh}} = \frac{\pi R \sqrt{\frac{\rho}{G}}}{0.163\,1 \upsilon + 0.876\,6}, \tag{3}$$

where R, ρ, G and υ are the average particle radius, particle density, particle shear stiffness and particle Poisson's ratio, respectively.

Based on previous conducted studies that utilized discrete element simulations, it would be better to choose a time-step below the Rayleigh time to avoid significant errors [11, 22]. In our simulations we fixed the time step at 40% of Rayleigh time for all the simulation scenarios.

3. Discrete element model

Fig. 1a shows the CAD model of the mixer imported into EDEM® discrete element software. The mixer has a screw positioned in the middle and was set in various rotational speeds after generating all particles inside the mixer under the effect of gravity. This mixer depicts a small prototype of a silo used for storing and conserving granular materials such as wheat, cement, etc. However this mixing operation is a convolute task because many operational and physical factors could have an impact on the homogeneity results.



(a) (b) (c)

Fig. 1. (a) 3D mixer design (b) side-by-side initial configuration (c) top-bottom initial configuration

The mixer frame has the diameter of 100 mm and length of 250 mm. While these dimensions were kept constant for all simulations, the screw rotational direction, the screw diameter and the screw pitch were varied (Fig. 2).

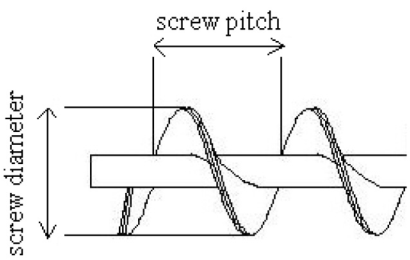


Fig. 2. Screw geometrical variables studied

All particles have the same shape and size, however two types of particles were created using different colours in order to discern the different mixing states throughout the mixing process, and find the relative mixing indices. Segregation state of the two types of particles were generated using different configurations as shows in Fig. 1b and 1c. This would let us examine the mixing uniformity from a totally segregated material. The authors of [16] revealed by shear tests that results drastically diverge between spherical and non-spherical particles in term of rolling, therefore, The shape of each particle was created as a straight three spheres connected together to approximately mimic the real shape of a wheat grain (Fig. 3), and a 70% fill fraction by volume were considered in all the numerical runs. This high filling level was intentionally identified as the flow of particles is more intense, which makes the mixing process more challenging. The micro-mechanical properties presented in Table 1 utilized in our study were taken from the literature [10]. Mixing a large number of particles is computationally expensive. The researchers in [15] revealed by discharging a bulk material on a flat surface that the angle of repose variance when using a shear moduli from 1×10^6 to 1×10^{11} Pa is trivial. Therefore, in our study we used a scaled-up value of the Young's moduli to speed-up simulations time.

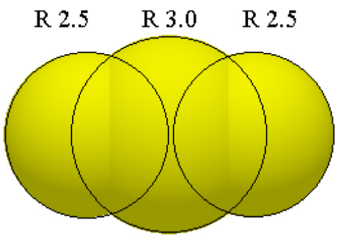


Fig. 3. Straight three spheres model of a wheat particle

Table 1. Micro-mechanical properties of the particle and the mixer [10]

Parameters	Wheat grain	Mixer wall
Poison ratio υ [–]	0.4	0.3
Shear modulus G [Pa]	5×10^{-6}	5×10^{-6}
Density ρ [kg/m^3]	1 460	7 500
Coefficient of restitution C_r [–]	0.5	0.6
Coefficient of friction μ_0 [–]	0.3	0.25
Coefficient of rolling friction μ_r [–]	0.01	0.01

4. Nearest neighbour's index

The mixing index is used to quantitatively evaluate a mixture state. A conventional method uses thief probes thrust in a mixed material bed, however this method lacks accuracy because without a proper number of sampling, we get wrong information, also we cannot know the mixing states along the process, because interrupting a mixing process for sampling would impact the material flow [3]. With the emergence of the numerical tools based on the discrete element method, we could know the mixing information at any time along the process. The mixing index varies between 0 and 1; 0 represents a totally unmixed material and vice-versa for 1.

In our study, we used the so-called nearest neighbor's method, it is a grid independent method means that we do not need to divide our system into cells, instead we extract the x, y and z coordinates of each particle, then we split the data by particle's type, and finally the index is calculated by the following equation

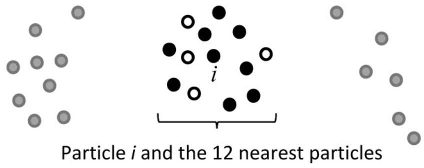


Fig. 4. Illustration of the nearest neighbor's method

$$M = \frac{1}{N_{\text{part}}} \sum_{N_{\text{part}}} \frac{2n_{\text{diff}}}{n_{nb}}, \tag{4}$$

where N_{part}, n_{diff} and n_{nb} are the total number of particles in the system, the number of different particles in terms of type and the number of neighbouring particles, respectively.

Fig. 4 presents a case study of the nearest neighbor's method. This method works as follows: it finds the 12 nearest particles to each particle by iteration then (4) is applied to find the index of each particle, and finally it gives the mean value of all these indices related to the whole material bed. For instance, as shown in Fig. 4, particle i in black has 4 white particles and 8 black particles in the vicinity, consequently the index of particle i is $M_i = (2 \times 4)/12 = 0.67$.

In our calculations, we developed a java script to automatically read the coordinates of all particles through a csv-file, and finally calculates the mixing index in a reasonable time.

5. Results and discussions

We assessed the impact of particle filling type, screw rotational direction, screw pitch length, screw diameter and screw rotational speed on the mixture quality by qualitative and quantitative analyses. EDEM® post-processor allows to see the mixture state not only through the mixer periphery but also in the middle of the material using the clipping function. In this way snapshots were captured along the process to qualitatively evaluate the mixture quality in every simulation. On the other hand, we applied the nearest neighbor's method to quantitatively evaluate the different mixtures. The design of numerical experiments is presented in Table 2.

Table 2. List of the conducted numerical simulations

Runs	Initial configuration of particles	Screw direction of rotation	Screw pitch length [mm]	Screw diameter [mm]	Screw rotational speed [rpm]
Run 1	Top-bottom	clockwise	10	10	60
Run 2	Side-by-side	anticlockwise	10	10	60
Run 3	Side-by-side	clockwise	10	10	60
Run 4	Side-by-side	clockwise	10	10	60
Run 5	Side-by-side	clockwise	20	10	60
Run 6	Side-by-side	clockwise	30	10	60
Run 7	Side-by-side	clockwise	40	10	60
Run 8	Side-by-side	clockwise	30	20	60
Run 9	Side-by-side	clockwise	30	20	40
Run 10	Side-by-side	clockwise	30	20	50
Run 11	Side-by-side	clockwise	30	20	70
Run 12	Side-by-side	clockwise	30	20	80

5.1. *Effect of particles initial configuration and screw rotational direction*

In this part, the first three simulations from Table 1 were conducted to investigate the impact of the initial filling pattern and screw rotational direction on the mixture uniformity. Two initial configurations of the particles illustrated in Fig. 1 were arranged before mixing. Filling one type of particles in the mixer, then filling the other type on the top is more practical, however it fails to attain a good mixture uniformity and changing the screw rotation in the opposite direction has almost no effect on the mixture uniformity (Fig. 5).

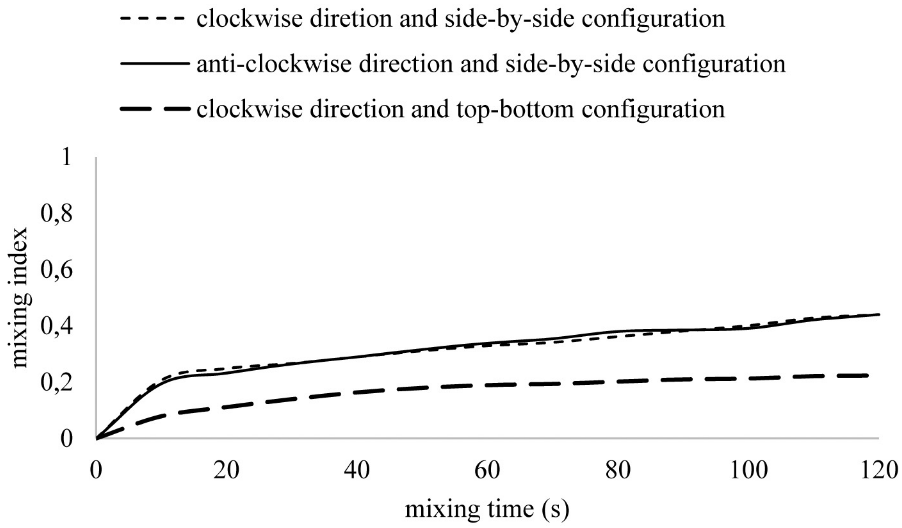


Fig. 5. Mixing index curves in term of screw direction of rotation

5.2. *Effect of the screw pitch*

Simulations 4 to 7 were carried out using a screw having the following pitch lengths: 10 mm, 20 mm, 30 mm, 40 mm and 50 mm, while the screw diameter and screw speed were maintained constant. Particles state from the mixer wall does not give an adequate information about the mixing quality, therefore, we clipped the system longitudinally along the z direction to have an insight into the particles state in the middle of the mixer. Snapshots were taken every 30 seconds mixing time for all the simulations (Fig. 6). Furthermore, we calculated the mixing rate every small period of mixing time along the process for every simulation shown in Fig. 7.

Snapshots of the internal structure of particles as well as the curves of the mixing indices reveals that the homogeneity is at its maximum when using a screw pitch length of 30 mm and the homogeneity is at its minimum when using a screw having a small screw pitch length. Also, increasing the length of the screw pitch above 30 mm adversely impacts the mixing quality as revealed when using a 40 mm and 50 mm screw pitches.

5.3. *Effect of screw diameter*

Taking into account results obtained from the previous section, we evinced the optimal length of the screw pitch. We furthered a simulation with this optimal value and having a bigger screw diameter in order to check the differences. As done before, we screened the internal structures and the evolution of the mixing indices curves. Distinctly, results showed that using a 20 mm screw diameter gives a better mixture quality.

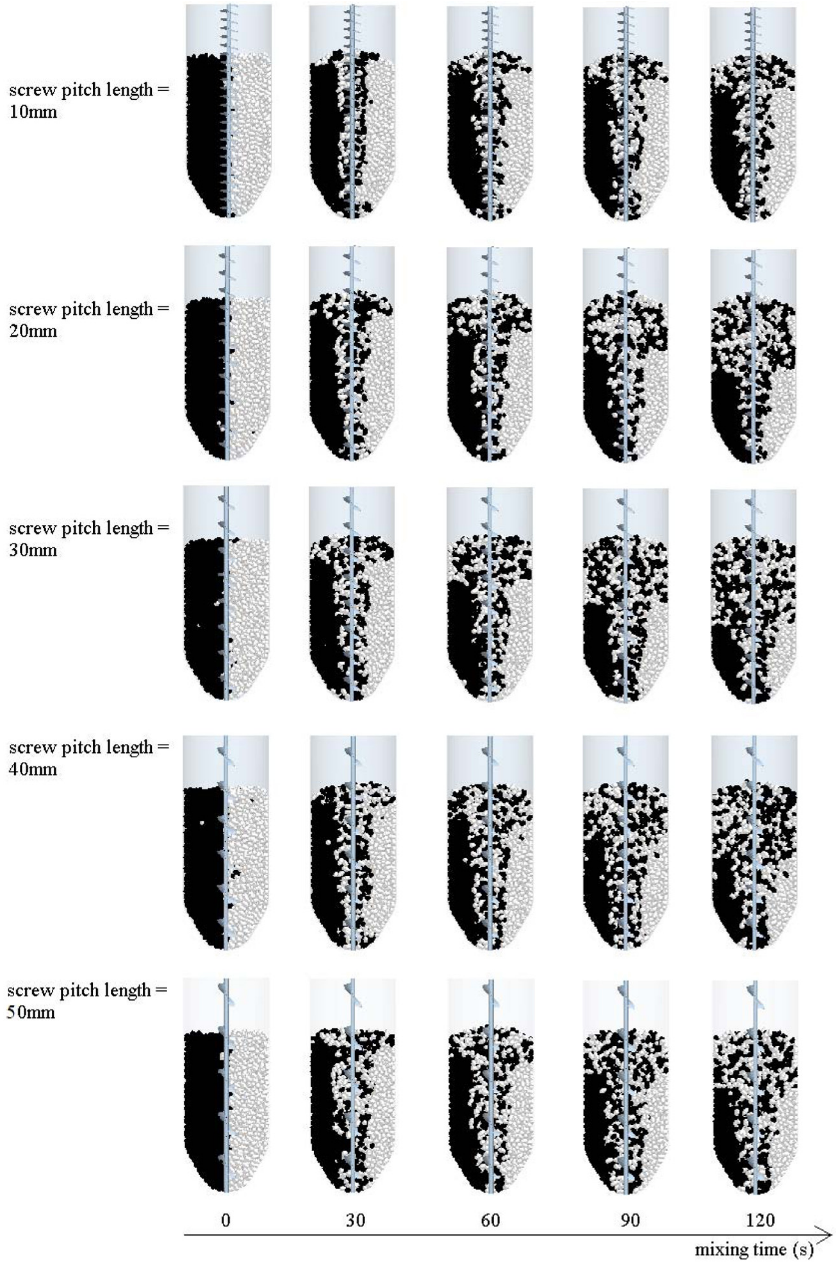


Fig. 6. Series of internal structures of the mixture along mixing time when using different screw pitch dimensions

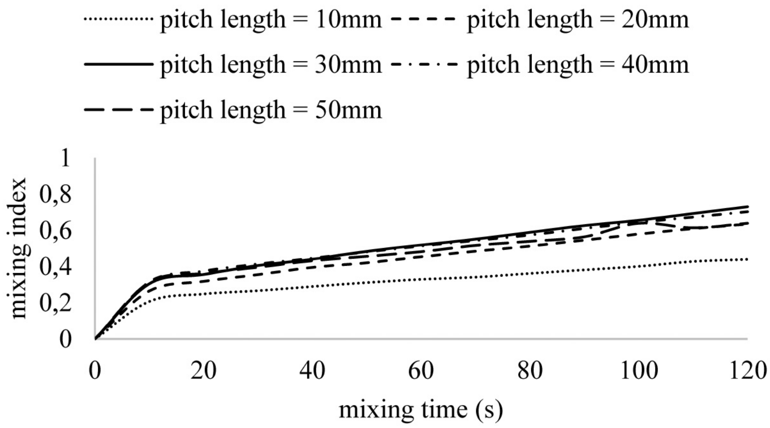


Fig. 7. Mixing index curves in term of screw pitch length

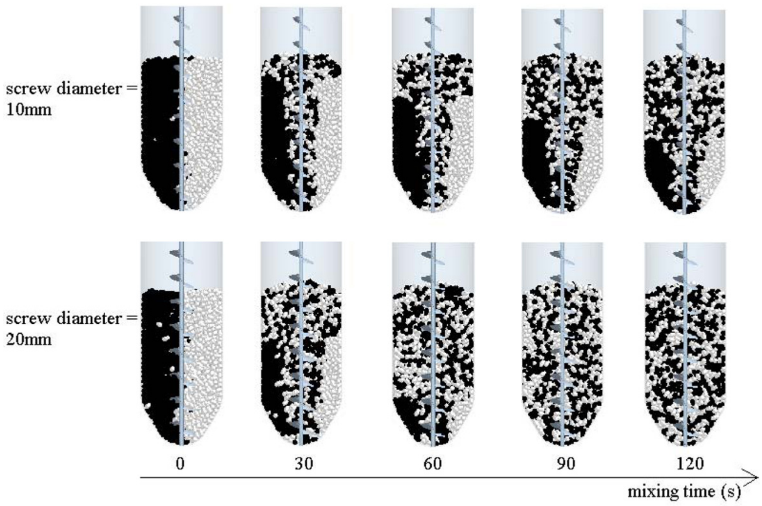


Fig. 8. Series of internal structures of the mixtures along mixing time when using different screw diameter dimensions

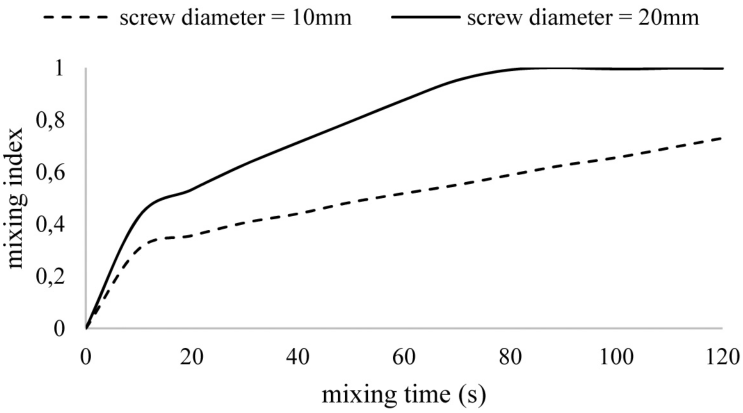


Fig. 9. Mixing index curves in term of mixing diameter

5.4. *Effect of screw rotational speed*

Undoutedly, the velocity of the screw has an important impact on the mixture. Intuitively, a low rotational speed of the screw would lead to a less uniformity among the mixed particles. In addition, according to results stated in [23], a high screw rpm could damage the quality of grains, thus an 80 rpm screw velocity was set as an upper limit. The aforecited intuitive approach has been confirmed by calculating the mixing indices for various screw rotational velocities (Fig. 10). Furthermore, the curves depicts the optimal mixing time that should be pre-set, for instance mixing of the material above 80 s at 60 rpm is unnecessary as over-mixing is time consuming and costly.

6. Conclusions

This study tackled homogeneity examination of a binary mixture of wheat particles. The loaded material was mechanically mixed in a hopper-bottom screw mixer under various dimensions of the screw pitch and screw diameter, also various screw rotational velocities. The discrete element simulations allowed to have an insight into the internal structure of the different mixture configurations, in addition the so-called nearest neighbour's method was used for quantitative assessments. This index is accurate as it is based on the coordinates of each particles rather than the conventional methods that require a grid which still convoluted to get accurate results.

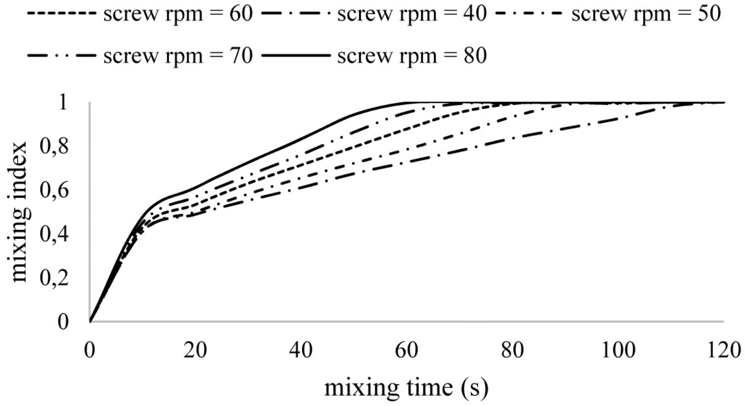


Fig. 10. Mixing index curves in term of screw rotational speed

Findings could be drawn as follows:

- Filling one type of particles inside the mixer, then the other type of particles (top-bottom configuration) is unsuccessful in achieving a good mixture state.
- Changing the screw direction of rotation has almost no impact on the mixture.
- Using a 30 mm screw pitch length improved the mixture by 36.93% compared to a 10 mm screw pitch during 120 s mixing time, however using a 40 mm and 50 mm screw pitches have worsen the mixture by around 1% and 6%, respectively compared to a 30 mm screw pitch.
- Maintaining the screw pitch at 30 mm and increasing the screw diameter from 10 mm to the double has drastically improved the mixing quality, where the mixture has improved by 35.9% as average during 120 s mixing time.
- Results showed that the mixture of the binary system improves when setting a higher screw rotational speed. Data revealed that the mixture homogeneity increased by 16.25% when using 80 rpm screw speed instead of 40 rpm as average in 120 s mixing time. Moreover, mixing above 60 s at 80 rpm screw velocity is unnecessary since homogeneity reached the peak.

As for recommendations, further study could be conducted considering cohesive particles by adding moisture and other designs of the mixer could be examined.

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