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Particle motion in mixed flow dryers: The effect of the wall inclination angle and friction

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Abstract: In Europe, the weather patterns require harvested grain crops to be dried before storage to prevent significant quality loss. The uneven movement of grains inside the drying equipment is a key issue affecting the drying process, causing under- or over drying the harvested crops and thus leading to quality degradation and ultimately to financial losses. To characterise the unevenness of material flow, we introduced a dimensionless displacement ratio. This dimensionless parameter was suitable for comparing the uniformity of the material movement processes within the dryer. Using experimental investigations and numerical simulations, we determined the effect of the lamella inclination angle, the friction between the grain-wall and grain-grain on the uniformity of the flow. The linear functions approximating the quantitative relationships were determined in all the cases. Our findings indicate a significant variation in the displacement ratio ξ corresponding to different lamella inclination angles and friction values demonstrating that the discrete element modelling approach provides further opportunities for determining the optimal operating parameters of mixed flow dryers.

Keywords: agricultural particulate materials; drying; DEM; particle motion; optimisation

To maintain appropriate moisture levels for harvested grain crops in European climates, drying before storage is essential. Poor drying conditions can lead to significant losses and to the deterioration in the grain quality. A popular method for drying corn in Europe is the mixed flow dryer, which allows the simultaneous movement of air and grain in various directions within the drying equipment.

The arrangement of the internal structural elements that control the material flow significantly influences how seeds move within the dryer (Klinger 1977; Mellman and Teodorov 2011). Non-uniform particle velocities, mainly caused by differences in the residence times, create difficulties in achieving consistent drying and avoiding under-drying or over-drying when assuming uniform airflow.

Extensive scientific investigations, both experimental and numerical, have clearly shown how the mass flow affects grain drying. Mellmann et al. (2011) found that poor design choices in mixed-flow grain dryers can cause uneven residence time distributions. Weigler and Mellmann (2014) showed how the flow pattern of grains significantly influences the drying process. Moreover, Khatchatourian et al. (2014) created a model representing soybean seeds as individual entities and successfully matched their simulations

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with real-world experiments. Their simulations highlighted significant variations in the particle velocity and residence time during continuous flow.

The discrete element method has greatly advanced the modelling of grain movement phenomena. Many researchers have focused on understanding how particulate matter flows in silos. Oldal et al. (2012) showed that arch formation and collapse in bins help maintain a steady discharge rate. Golshan et al. (2020) studied a wedge-shaped silo and found that particles near the outlet had the shortest residence times, while those on the inclined wall outside the outlet zone had the longest residence times.

Together, these discoveries suggest that the angle at which the lamellas, responsible for directing the drying air into the dryer, are inclined can greatly affect how evenly materials flow. Therefore, our experimental and numerical investigations aimed to establish a clear relationship between the angle of inclination of the lamellas and the unevenness seen in the material flow.

MATERIAL AND METHODS

Experimental investigations (industrial dryer). To study particle flow, experimental analyses can be divided into two main parts: measurements in a real industrial dryer and measurements in a model dryer. First, we examined the particle flow conditions in an industrial dryer through various experiments.

To study the material flow, viewing windows were installed along the sides of the grain channels in the dryer, enabling a visual observation of the particle movement during operation. The dryer is 16 metres tall and can hold up to 50 m^3 of material. Video recordings were made to document the flow behaviour. Additionally, during assembly, the particle motion within the modules was investigated. Figure 1 shows the positions of the inspection windows and slots for the endoscope camera probe on the industrial drying module.

Video recordings helped describe the particle motion in the duct by analysing the displacement profiles. To determine the vertical displacement values, we selected 8 corn kernels in a row on the recording (blue colour in Figure 2) and then searched for the same corn kernels again at a later time of the same recording (red dots). By knowing the two locations and the dimensions of the window, we were able to determine the value of the vertical displacement of the individual corn kernels.

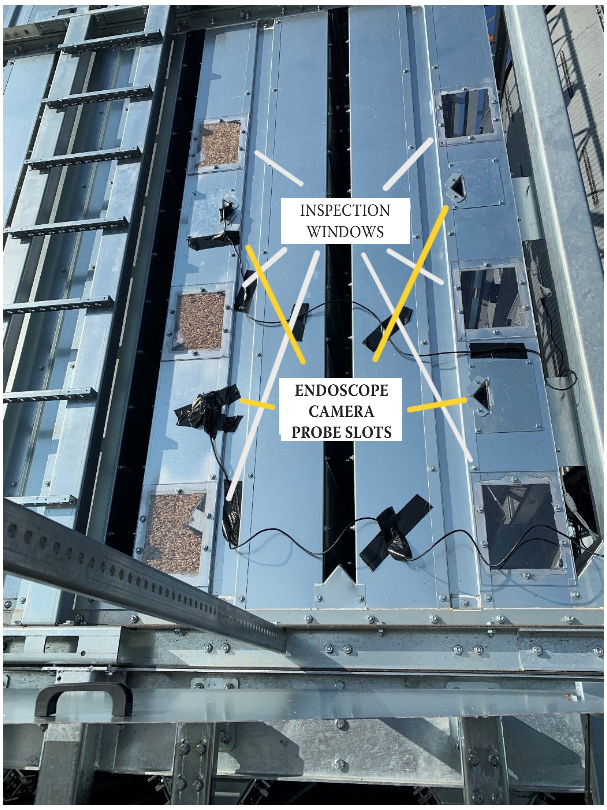

Figure 1. Inspection windows and endoscope camera probe slots on the drying module

To understand the particle dynamics during the drying module emptying, video footage was taken at three times, producing three vertical displacement profiles with slight magnitude differences.

Particle displacement experiments were carried out on both an individual dryer module and within a working industrial dryer. A comparative analysis showed no significant differences in the veloc-

Figure 2. Vertical displacement value measurement method using video recordings

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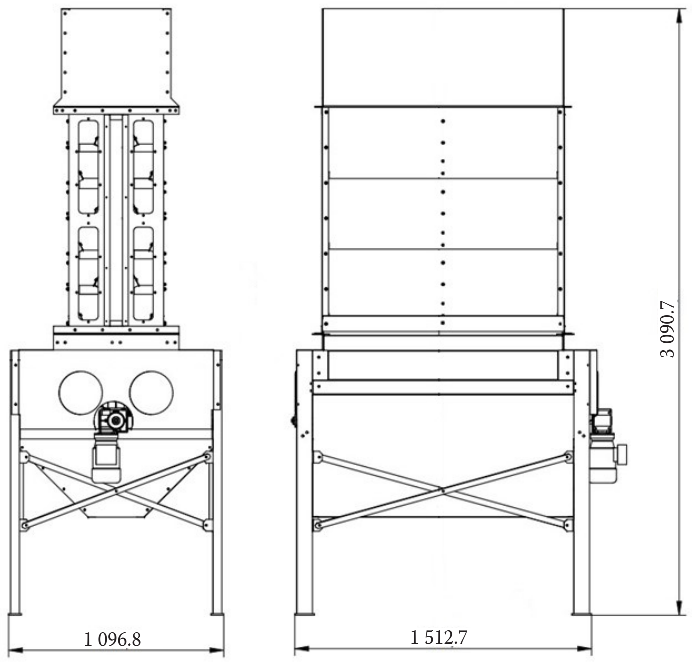

Figure 3. Main dimensions of the model dryer

ity and vertical displacement values between the two set-ups. The particle movement conditions remained consistent, suggesting that the operational industrial dryer did not notably alter the observed particle dynamics compared to the stand-alone module. Based on the measurements conducted, two conclusions can be drawn:

(1) The presence of lamellae has a strong effect on the consistency of the grain flow. Patterns of particle displacement and changes in velocity suggest that the lamellae strongly affect the overall flow dynamics, potentially causing uneven grain movement.

(2) The airflow within the operational dryer does not notably affect the grain movement. Similar velocity and displacement values in both the stand-alone dryer module and the operating industrial dryer indicate that airflow in the operational dryer does not cause significant changes in the observed grain movement behaviour.

These findings emphasise the significance of the lamellae presence in achieving uniform grain flow. Additionally, they suggest that the airflow in the operational dryer may not play a significant role in influencing the grain movement.

Experimental investigations (model dryer). To overcome the difficulties of measuring within an operational industrial dryer and ensure efficient plant operations, we decided to construct a model dryer. This model provides a more convenient platform for studying the effects of design changes compared to the original large-scale dryer. However, to ensure that the material flows in the model dryer accurately represent particle movements in the industrial dryer, we needed to conduct comparative measurements. Figure 3 illustrates the structure of the model dryer, which was specifically designed for this purpose.

Using a model dryer allowed us to investigate how different angular positions of the lamella affect the grain movement behaviour. There were two main goals with the measurements with the model dryer: firstly, to compare the material flow in the model dryer with the grain movement in a full-scale dryer, and secondly, to collect essential measurement data for validating the discrete element models we used in our research.

During the measurements on the model dryer, we used a technique to study material flow relationships. By applying paint stripes to the particle assembly, we could track their movement more effectively. This method helped us determine the velocity relationships more easily. Refer to Figure 4 for the visual representations of this methodology.

To evaluate how closely the particle vertical displacement distribution near the inclined air ducts of the industrial dryer matches that of the model dryer, we conducted a comparison.

After a thorough analysis and comparisons, we concluded that the model dryer is suitable for accurately modelling the material flow conditions observed in real dryers. The successful matching of the particle displacement distributions, comparable velocity relationships, and grain movement behaviour between the model dryer and the industrial dryer confirms

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Figure 4. Distortion of the painted stripes due to the uneven particle flow

the reliability as a representation of the real-scale system. These findings boost the confidence in using the model dryer for future investigations and simulations concerning material flow dynamics in dryers.

Numerical model calibration. The influence of the tribological characteristics of the grain-grain and grain-wall interactions was analysed by creating a numerical model. The numerical model had to be able to take the discontinuities created in the granular assembly into account, therefore using the finite element method was out of the question. We also had to take the effect of the non-spherical shape of the particles into account, which precluded the use of the smoothed particle hydrodynamics method. In order to be able to analyse the interactions taking place inside the granular assembly at the level of individual grains, the use of the discrete element method seemed most appropriate.

To simulate particle motion within the dryer, we used the academic version of the EDEM 2.7 discrete element software. The model we employed is based on the discrete element model initially proposed by Cundall and Strack (1979). In this model, contact forces arising between the particles are calculated using the "Hertz-Mindlin no slip" contact model. The material properties and contact parameters are crucial in determining the normal and tangential forces. The interaction forces and moments arising between the particles can be calculated using the equations given in (Keppler and Bablena 2024).

As previously noted, grain interactions are affected by different material parameters. Some of these parameters can be directly measured in experiments, while others require comparing experimental data from a simple mechanical process with a corresponding numerical model. The process of finding the material parameters used in the discrete element method is called model calibration.

While we will not delve extensively into calibration here, for those interested in further exploration, we recommend investigating the significant contributions of Coetzee (2017) and González-Montellano et al. (2011) regarding discrete element method (DEM) parameter calibration. Coetzee and Nel (2014) assessed the micromechanical properties of packed rock beds through various tests, while Derakhshani et al. (2015) utilised the angle of repose, a conical pile, and sandglass tests. Simons et al. (2015) employed a ring shear tester, and Keppler et al. (2016) utilised standard a shear testing technique to calibrate and evaluate the model's sensitivity to different material parameters.

In some cases, it is necessary to gather the calibration measurements at the experimental site. Methodologies like those demonstrated by Keppler et al. (2022) can aid in this process. However, due to the resource constraints and time limitations in our case, we had to rely primarily on the angle of repose test for the calibration. We also conducted a compression test on material samples to determine Young's modulus, recognising that the angle of repose test alone may not suffice in determining all the material parameters.

The shape of grains significantly affects their sliding and rolling behaviour during interaction. According to our experience, the grain shape has a significant effect on the values of the micromechanical parameters controlling the interaction processes. In the case of agricultural seeds, the first step of calibration is to create a geometry that sufficiently follows the real grain shape. Therefore, our first aim was to determine the appropriate grain geometry. We analysed a random sample assembly and carefully examined the shapes and distribution of grains within it (Figure 5). Based on our findings, we concluded that

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Table 1. Corn particle average size

	Length	Width	Thickness	Incidence rate (%)
		(mm)		
Flat (1)	12.1	9.1	4.7	36
Elongated (2)	11.8	8.0	4.7	20
Square (3)	12.0	8.5	5.8	32
Round (4)	9.4	9.0	7.6	12

Figure 5. Corn particle shape categories

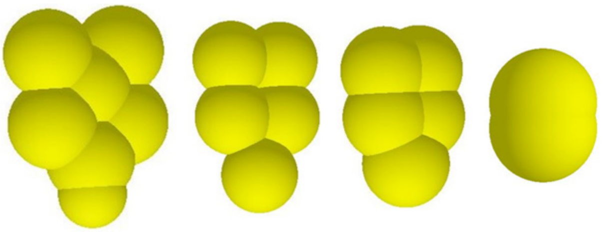

Figure 6. Corn particle DEM models

employing four distinct grain shapes in the discrete element model would be suitable, given the observed characteristics and distribution patterns.

The average sizes of the four types of grain shape are shown in Table 1. Type 2 and 3 seem to be the same in the image, but their size ratios were different.

Figure 6 depicts a discrete element model representing the grain types that align with the size and shape characteristics outlined in Table 1.

To determine the material properties, we conducted a series of angle of repose tests and compression tests.

For the angle of repose measurement of the corn particle assembly, a steel cylinder with a diameter of D = 200 mm and height of h = 250 mm was employed. The cylinder, positioned on a concrete floor, was filled to capacity with corn, after which it was gradually raised to allow the corn to form a conical pile. Three measurements of the cone angle were recorded as follows: $\alpha 1$ = 19.2°; $\alpha 2$ = 18.8°; $\alpha 3$ = 17.4°. The estimation of certain material parameters utilised in the discrete element model was derived from relevant literature sources.

The shear modulus value was not chosen based on the real-world conditions, but rather optimised for simulation. This choice had a negligible impact on the angle of repose, as confirmed by using a shear modulus value close to those for steel and concrete with a single adjustment. However, this specific configuration was only used once due to significantly increased simulation time. Also, to measure the angle of repose on a concrete floor, it was crucial to determine the contact properties of the concrete.

We calibrated the coefficient of static friction between the grain seeds using the angle of repose test. To calibrate the discrete element model, we used the same geometry as the measurement cylinder (Figure 7). However, it is essential to note that the depicted cylinder is about three times taller than the one used in the actual measurement. We made this choice to ensure that the measurement space could be filled with seeds, allowing them to settle under gravity. Using this increased height ensures that the settled pile's height matches that of the measurement set-up.

Table 2 presents the grain-grain friction coefficients employed in the calibration simulations, along with the corresponding angle of repose values determined from the simulation outcomes depicted in Figure 7. Table 3 contains the interaction parameters determined by our test which were in good correlation with the results of (Pooja and Iaerapetritou 2020).

Following the simulation results listed in Table 4, we chose a value of 0.2 for the grain-to-grain friction coefficient. This relatively low coefficient was

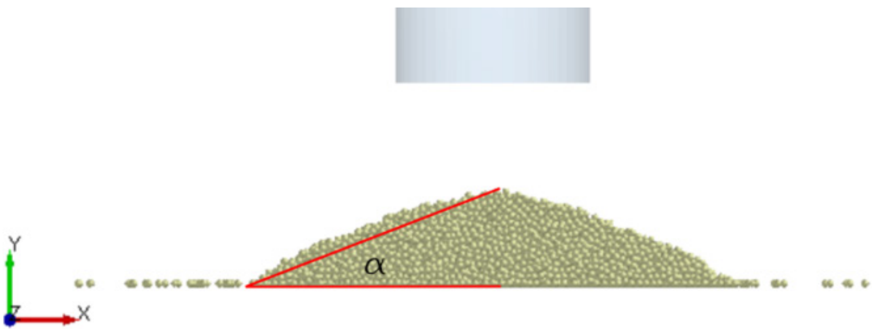

Figure 7. Determining the angle of repose of the particle assembly in the numerical model

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Table 2. Material properties (Moya et al. 2013)

	Steel	Concrete
Poisson's ratio (–)	0.3	0.2
Density (kg·m^{-3})	7 500	2 400
Shear modulus (Pa)	10^6	10^6

Table 3. Interaction parameters (Moya et al. 2013)

	Corn –steel	Corn – concrete
Coeff. of restitution *k* (–)	0.1	0.1
Coeff. of static friction μ (–)	0.25	0.53
Coeff. of rolling friction *f* (–)	0.01	0.01

Table 4. Angle (α) of repose values (μ)

μ (–)	α (°)
0.15	17.07
0.2	20.05
0.25	21.86
0.3	23.21

selected due to the surface unevenness observed in the cluster of spheres. In this set-up, grains tend to interlock more easily within the model compared to real-world conditions.

Compression tests. To determine the shear modulus value, a compression test was conducted on the corn kernels. Young's modulus was determined using an Instron 5965 testing machine (Instron GmbH, UK) specifically designed for testing agricultural materials. The tensile testing machine was equipped with a load cell capable of accommodating a max. load of 5 kN.

Through an analysis of the linear section of the experimental test curves and employing simplifications for the stress state, we were able to approximate the average value of Young's modulus as E = 78 MPa. A study conducted by Moya et al. (2013) reported a value of 35 MPa for corn seeds with a moisture content of 14%. Considering that our corn seeds had an average moisture content of 10%, the approximate value obtained appears to be suitable for simulation purposes. Using a Poisson's ratio of 0.31, we obtained a shear modulus of G = 29.77 MPa. Table 5 shows the values of the interaction parameters used in the simulations.

Discrete element model of the particle motion inside the drying apparatus. The geometry of the constructed model dryer, as depicted in Figure 8, served as the foundation for studying the particle motion within the dryer.

In the numerical model, the height of the dryer was set to 2 000 mm to account for particle gravitational settling. To ensure a reasonable simulation runtime, only a 50 mm thick slice of the dryer was tested. Initially, simulations were performed on a 200 mm thick model, which took several days to complete. However, comparing the particle velocity field obtained from the 200 mm thick model to that of the 50 mm thick model revealed no significant differences. Finally, the rotary discharge mechanism of the original dryer was simplified in the discrete element model. In the numerical model, the emp-

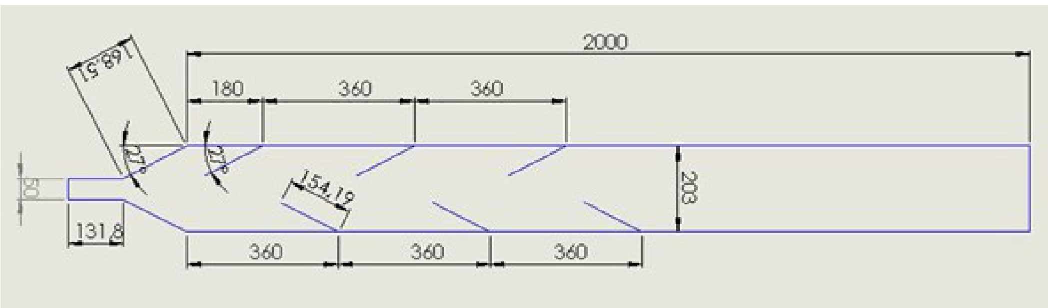

Figure 8. Geometry of the numerical dryer model

Table 5. Material and interaction parameters of corn seeds

Micromechanical parameters	Corn	Interaction parameters	Corn – corn	Corn – wall
Poisson's ratio (–)	0.31	coefficient of restitution (–)	0.1	0.1
Density (kg·m^{-3})	1 180	coefficient of static friction (–)	0.2	0.25
Shear modulus (Pa)	3×10^7	coefficient of rolling friction (m)	0.01	0.01

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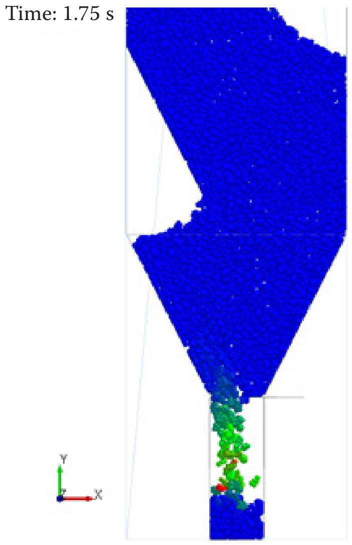

Figure 9. Simplified discharge mechanism model

tying process begins by displacing the sheet covering the discharge unit. The flap moves horizontally at a constant speed of v = 0.05 m·s^{-1} for 1 second. During this period, the discharge unit fully opens, allowing seeds to flow out from the dryer (Figure 9).

After 0.5 seconds, the closing unit starts closing for 1 second at speed v, moving in the opposite direction. Once the top flap closes, the bottom of the exclusion unit opens in 0.01 seconds at a constant speed v = 5 m·s^{-1}. This allows seeds within the exclusion unit to exit the simulation space, making them irrelevant for further considerations by the discrete element method software. Then, the bottom flap closes back in 0.01 seconds, maintaining the speed v = 5 m·s^{-1}. Then this cycle restarts. To determine displacement ratio values in the discrete element model, we used painted layers similar to those in the model dryer experiments. Each simulation lasted 13 seconds, covering four open-close cycles. At the end of these cycles, noticeable changes in the shape of the painted layers occurred (Figure 10).

RESULTS AND DISCUSSION

Experiments. Our particle flow related experimental analyses can be divided into two main parts: measurements in a real industrial dryer and measurements in a model dryer. First, we examined the particle flow conditions in an industrial dryer through experiments. Then, we compared the measurements conducted on the model dryer with the results of the industrial one. The measurement results are shown in Figure 11.

Figure 11 illustrates how the lamella (positioned at 0 cm) affects both the velocity of the particle flow and the subsequent vertical displacements, indicating a significant impact. Figure 11 also shows the results of the model dryer measurements, revealing a high level of agreement between the displacement values observed in the model dryer and those recorded in the industrial dryer. The close match between the two datasets indicates that the model dryer effectively replicates the particle behaviour seen in the industrial-scale counterpart.

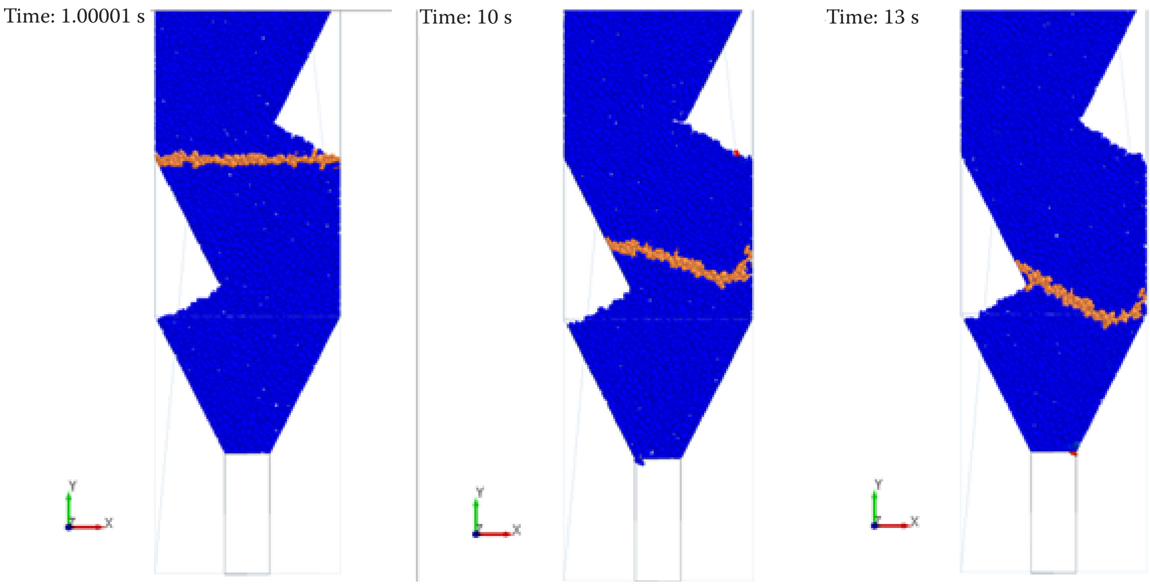

Figure 10. Changes in the shape of the painted layers during four emptying cycles

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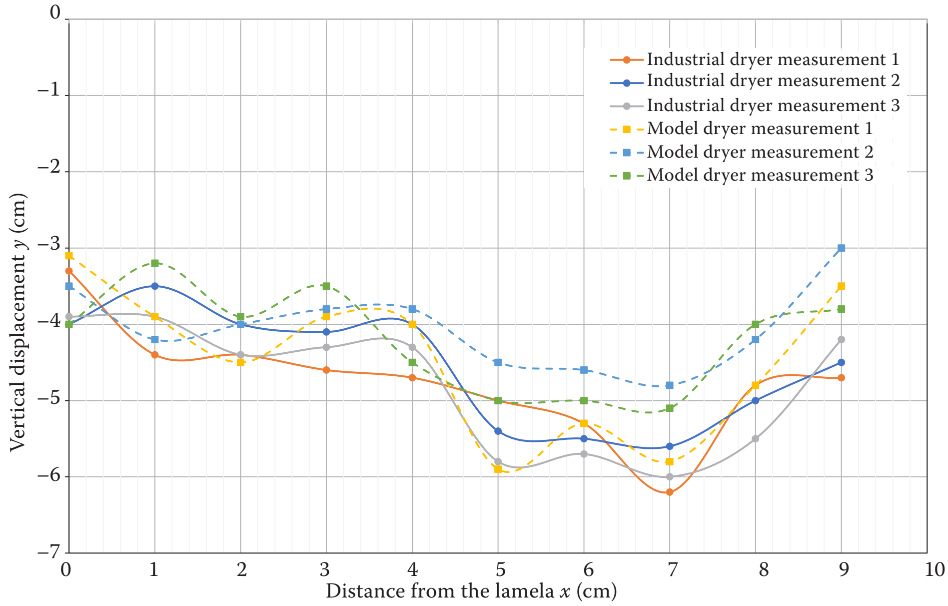

Figure 11. Vertical displacement values measured in a dryer channel

To determine the displacement ratio ξ in the simulations, the vertical *y* coordinates of the grains' centre of gravity within the painted band were utilised (Figure 10). Given that the considered time interval was consistent across all the cases, the displacement ratio ξ was derived using the following equation: $\xi = (y_{max} - y_{min})/y_{max}$. The displacement ratio ξ measures the particle flow stability. When ξ is 0, the flow is steady and uniform. As ξ approaches 1, the flow becomes more erratic, with larger variations in the particle displacements. It is crucial to use the same time intervals for all the cases when calculating ξ to ensure accurate comparisons and analyses.

Numerical simulations. The objective of our investigation was to examine the effect of the lamella inclination angle on the displacement ratio of the dryer apparatus. For the simulations, we considered the following inclination angle values α = 22°; α = 24°; α = 27°; α = 30°; α = 32°. Each simulation was repeated five times. The original lamella inclination angle of the model dryer was α = 27°. The influence of the lamella inclination angle on the displacement ratio can be observed in Figure 12. The linear function describing the mathematical relationship between the displacement ratio and the lamella inclination angle (Figure 12) is $\xi = 0.0372\alpha - 0.665$, $22 < \alpha < 32$.

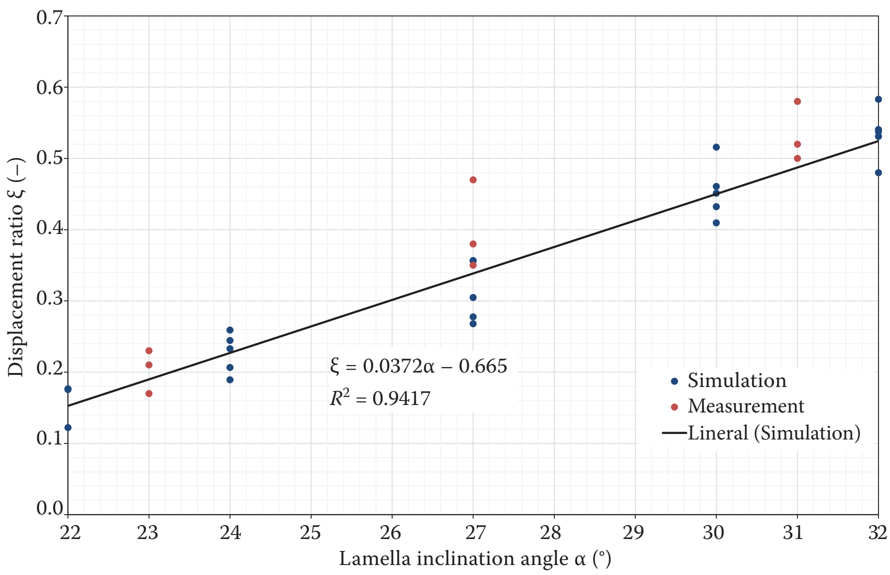

Figure 12. Relationship between the displacement ratio and the lamella inclination angle

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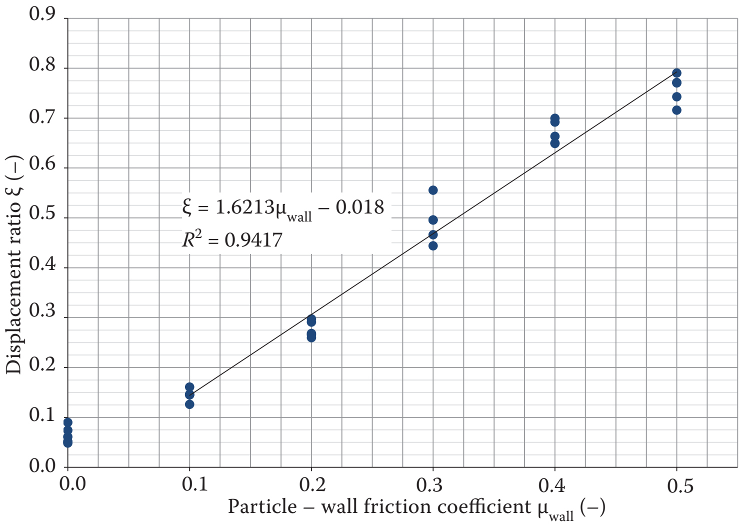

Figure 13. The effect of particle-particle friction on the displacement ratio

To validate the accuracy of our findings, we additionally constructed lamellae with inclination angles of 23 and 31 degrees for the experimental dryer. The displacement ratio measurements obtained after installing the modified lamellae, depicted in red in Figure 12, demonstrate a notable agreement between the simulation and experimental results.

Since the tribological properties of the grains to be dried can be significantly different, we also examined the impact of changes in the interparticle friction (Figure 13) and the particle wall friction (Figure 13) on the uniformity of the flow by systematically changing the coefficients of friction while keeping all the other micromechanical parameters the same.

The approximate linear function describing the effect of the particle-particle friction on the displacement ratio in the interval $0 < \mu_{particle} < 0.4$, with a particle-particle friction coefficient of $\mu_{wall} = 0.25$ and a lamella inclination angle of $\alpha = 27°$, is as follows: $\xi = -0.8615\ \mu_{particle} + 0.5845$.

The approximate linear function describing the effect of the particle-wall friction on the displacement ratio in the interval $0.1 < \mu_{wall} < 0.5$, with a particle-particle friction coefficient of $\mu_{particle} = 0.2$ and a lamella inclination angle of $\alpha = 27°$, is as follows: $\xi = 1.6213\ \mu_{wall} - 0.018$

CONCLUSION

Using experimental investigations and numerical simulations, we determined the effect of the lamella inclination on the flow non-uniformity in the case of straight lamellae. The linear function describing the relationship, within the interval $22° < \alpha < 32°$, for friction coefficient values of $\mu_{wall} = 0.25$ and $\mu_{particle} = 0.2$, is as follows: $\xi = 0.0372\alpha - 0.665$. We also examined the effect of changing the friction between the grain-wall and grain-grain on the uniformity of the flow. We found that the linear function describing the effect of particle-particle friction on the displacement ratio in the interval $0 < \mu_{particle} < 0.4$ with a particle-particle friction coefficient of $\mu_{wall} = 0.25$ and a lamella inclination angle of $\alpha = 27°$ is as follows: $\xi = -0.8615\ \mu_{particle} + 0.5845$. We also demonstrated that the linear function describing the effect of particle-wall friction on the displacement ratio in the interval $0.1 < \mu_{wall} < 0.5$ with a particle-particle friction coefficient of $\mu_{particle} = 0.2$ and a lamella inclination angle of $\alpha = 27°$ is as follows: $\xi = 1.6213\mu_{wall} - 0.018$. Our findings indicate a significant variation in the displacement ratio ξ corresponding to different lamella inclination angles and friction values. Specifically, smaller angles result in smaller ξ values. Consequently, the displacement ratios are expected to be minimal when the lamellae have an inclination angle of 0°, effectively minimising the presence of lamellae in the dryer. However, practical considerations must also be taken into account. A sufficient residence time of the seeds in the drying system is necessary to ensure an adequate drying rate, making the presence of lamellae essential. Additionally, the drying air must be introduced into the drying apparatus through ducts located beneath the lamellae openings. A larger inclination angle requires a greater volume of drying air to flow into the system. These conflicting requirements present an opportunity to identify an optimum solution, although determining this opti-

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mum is not the objective of our current research. The increase in the particle-to-particle friction coefficient causes the improvement of the flow uniformity because the high friction coefficient allows the seeds to move together with better adhesion and the effect of the increase in the wall friction, which impairs flow uniformity, occurs due to the braking effect of the walls.

In conclusion, it can be stated that the discrete element modelling approach provides further opportunities for determining the optimal operating parameters of mixed flow dryers. A further increase in efficiency can be achieved by modifying the lamella geometry, although it could mean a significant increase in the development costs related to the design of such new lamellae. In the longer term, it may also be possible to consider heat and air flow processes, as long as the available computing capacities allow this.

REFERENCES

Coetzee C.J., Nel R.G. (2014): Calibration of discrete element properties and the modeling of packed rock beds. Powder Technology, 264: 332–342.

Coetzee C.J. (2017): Review: Calibration of the discrete element method. Powder Technology, 310: 104–142.

Cundall P.A., Strack O.D.L. (1979): A discrete numerical model for granular assemblies. Geotechnique, 29: 47–65.

Derakhshani S.M., Schott D.L., Lodewijks G. (2015): Micro-macro properties of quartz sand: experimental investigation and DEM simulation. Powder Technology, 269: 127–138.

Golshan S., Esgandari B., Zarghami R., Blais B., Saleh K. (2020): Experimental and DEM studies of velocity profiles and residence time distribution of non-spherical particles in silos. Powder Technology, 373: 510–521.

González-Montellano C., Ramírez Á., Gallego E., Ayuga F. (2011): Validation and experimental calibration of 3D discrete element models for the simulation of the discharge flow in silos. Chemical Engineering Science, 66: 5116–5126.

Keppler I., Safranyik F., Oldal I. (2016): Shear test as calibration experiment for DEM simulations: a sensitivity study. Engineering Computations, 33: 742–758.

Keppler I., Bablena A., Salman N.D., Kiss P. (2022): Discrete element model calibration based on *in situ* measurements. Engineering Computations, 39: 1947–1961.

Keppler I., Bablena A. (2024): Optimal lamella geometry for mixed flow dryers. Archive of Applied Mechanics, 94: 961–972.

Khatchatourian O.A., Binelo M.O., Lima R.F. (2014): Simulation of soya bean flow in mixed-flow dryers using DEM. Biosystems Engineering, 123: 68–76.

Klinger J. (1977): Einige thermodynamische und strömungstechnische Untersuchungen zur Modellierung der Vorgänge in Dächerschachttrocknern für Getreidekörner. [PhD Thesis]. Dresden, Technische Universität Dresden.

Mellmann J., Iroba K.L., Metzger T., Tsotsas E., Mészáros C., Farkas I. (2011): Moisture content and residence time distributions in mixed-flow grain dryers. Biosystems Engineering, 109: 297–307.

Mellmann J., Teodorov T. (2011): Solids transport in mixed-flow dryers. Powder Technology, 205: 117–125.

Moya M., Aguado P.J., Ayuga F. (2013): Mechanical properties of some granular agricultural materials used in silo design. International Agrophysics, 27: 181–193.

Oldal I., Keppler I., Csizmadia B., Fenyvesi L. (2012): Outflow properties of silos: The effect of arching. Advanced Powder Technology, 23: 290–297.

Simons T.A.H., Weiler R., Strege S., Bensmann S., Schilling M., Kwade, A. (2015): A ring shear tester as calibration experiment for DEM simulations in agitated mixers – a sensitivity study. Procedia Engineering, 102: 741–748.

Weigler F., Mellmann J. (2014): Investigation of grain mass flow in a mixed flow dryer. Particuology, 12: 33–39.

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