Hungarian University of Agriculture
and Life Sciences

OPTIMAL MATERIAL FLOW CHANNELS
FOR CROP DRYERS

Thesis of doctoral (PhD) dissertation

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1. INTRODUCTION, OBJECTIVES

Reducing the moisture content of harvested grains (drying) is an essential step in preparing them for further processing or storage. Ideally, this process could be accomplished using natural drying methods, harnessing solar energy directly. However, for industrialized countries with significant food and raw material demands, natural drying alone is insufficient, necessitating artificial drying methods. Due to the high energy demand and potential environmental impact of artificial drying, it is crucial to perform the process with the highest possible efficiency. This dissertation aims to enhance drying efficiency by modifying the design of gravitational cross-flow dryers.

In agricultural practice, drying accounts for 60-80% of direct energy consumption. Therefore, improving drying efficiency is a fundamental interest for all enterprises engaged in grain drying. Efficiency improvements can be pursued in two main directions: optimizing thermodynamic processes (e.g., reducing the specific consumption of fossil fuels) or leveraging the potential in influencing grain flow dynamics. This research focuses on the latter approach. The advancement of explicit dynamic modeling methods, particularly due to increased computational capacity, has enabled researchers to analyze granular movement in grain dryers in greater detail.

The quality of the final product is significantly influenced by under- or over-drying, which is largely dependent on the residence time of grains within the dryer. The residence time is governed by the velocity of granular flow, which can be effectively analyzed using the Discrete Element Method (DEM).

Previous research attempted to achieve uniform material flow conditions by altering the angular position and spatial distribution of straight lamellae. However, further modifications in this direction did not yield significant improvements in flow uniformity. This dissertation demonstrates that modifying the geometry of lamellae (air inlet channels) can lead to further improvements in material flow uniformity, thereby reducing drying losses.

The objective of this research is to determine the optimal lamella geometry in gravitational cross-flow dryers. To achieve this goal, the following research questions are addressed:

1. What dimensionless characteristic can be used to describe material flow unevenness in the dryer?
2. How do the tribological properties of grain-wall interactions affect material flow unevenness?
3. How do the tribological properties of grain-grain interactions affect material flow unevenness?
4. How does the inclination angle of straight lamellae affect material flow unevenness?
5. Is there a non-straight lamella geometry that can further improve flow uniformity and, consequently, drying efficiency?

This dissertation demonstrates that an optimal geometry can be developed by utilizing an analytical solution to a 17th-century geometric problem combined with numerical methods.

2.1. Experimental investigations

To analyze material flow processes within the drying equipment, experimental investigations were conducted in three main areas: tests on the original drying system, a model dryer, and calibration measurements necessary for the discrete element model (DEM).

Cross-flow dryers typically operate in batch mode. During drying, the grain moves downward in a vertical direction, while guide lamellae ensure that an adequate amount of air flows through the system and that the grains remain in the dryer for the required duration.

The grain motion processes were examined in an industrial-scale HSZ-15 continuous-flow dryer (Figure 2.1.). This system consists of vertically aligned modules with hot and cold air channels on both sides. The grain enters the dryer through a buffer storage tank located at the top. Sensors at the upper and lower levels of the buffer tank regulate the continuous grain feed and control the feeding system.

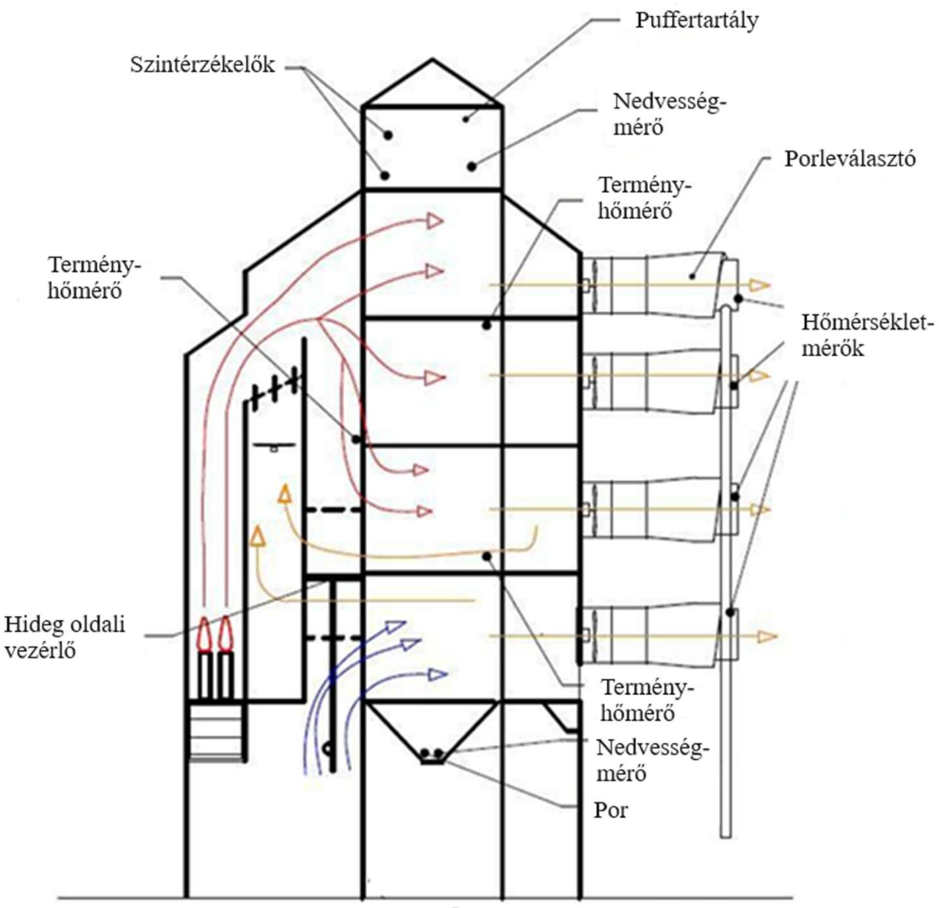


Figure 2.1.: Main components of the industrial dryer

For material flow tests windows were added to the sides of the channels and video recordings were taken of the flow of grain during operation. During the assembly of the drying equipment it was also possible to examine the movement of granular material in individual modules without air injection.

Granular motion investigations were carried out both on the separate drying module and inside the operational industrial dryer. Comparing the flow conditions between the separate module and the industrial dryer, the velocity values showed no significant differences.

Two conclusions can be drawn from the measurements conducted on the industrial dryer:

- The presence of lamellae significantly influences velocity conditions, thereby affecting the unevenness of granular flow.
- The airflow processes occurring in the operational dryer have no substantial impact on the granular movement processes.

Since the measurements conducted on the large-scale dryer indicated that the lamellae significantly influence the unevenness of granular flow, it was necessary to examine the effect of lamella inclination on velocity conditions. To facilitate this investigation, a model dryer was constructed, consisting of two columns from the original drying module. The structure of the model dryer is shown in Figure 2.2.

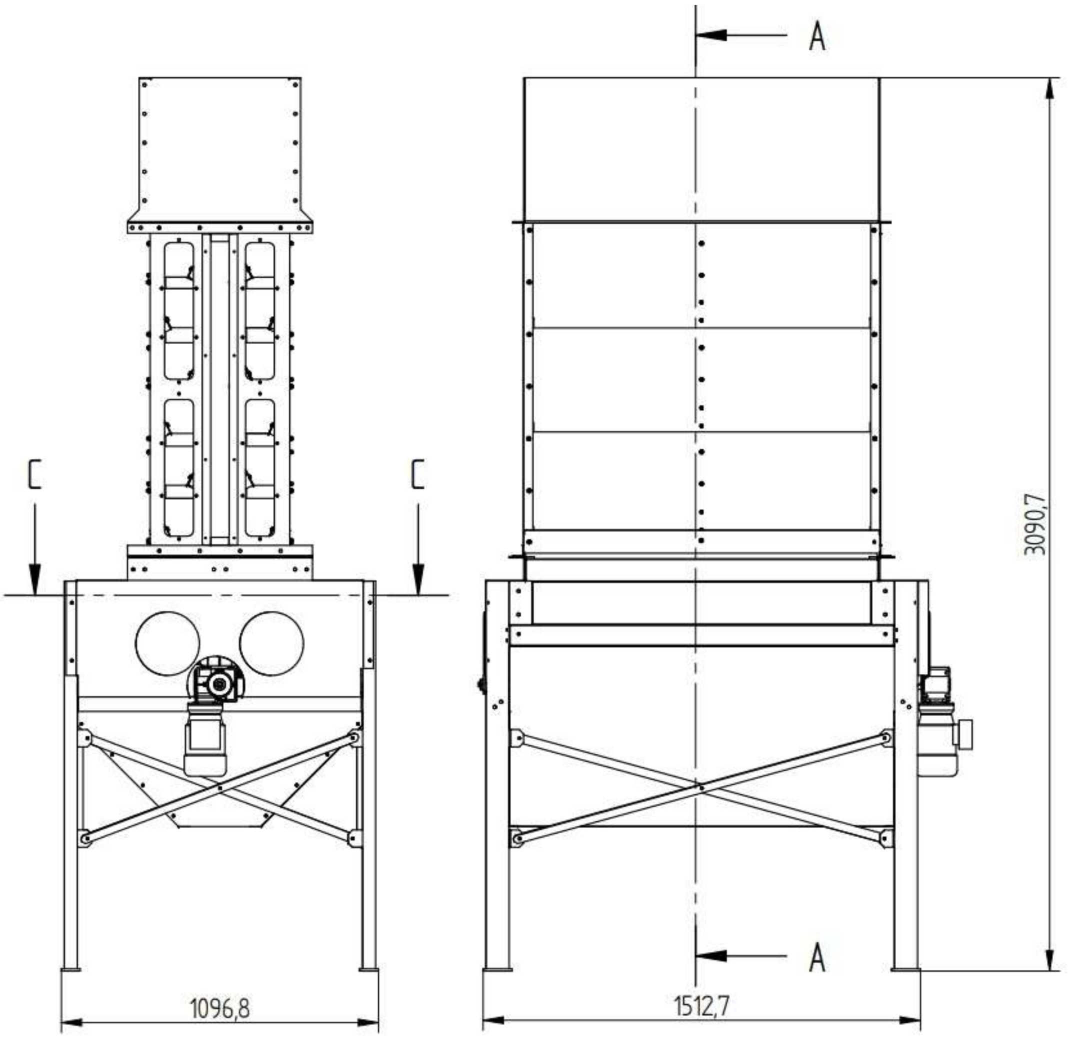


Figure 2.2.: The structure and main dimensions of the model dryer

The measurements conducted on the model dryer had two main objectives. First, to examine how the material flow processes in the model dryer differ from the granular movement conditions observed in the full-scale dryer. Second, to collect measurement data necessary for the validation of future discrete element models.

The examination of material flow conditions was significantly easier in the model dryer compared to the full-scale dryer. Unlike the large dryer, certain layers within the granular mass could be marked with dye, allowing the movement of these marked bands to be tracked, thereby facilitating the determination of velocity conditions.

The material flow velocity is primarily determined by the discharge system's opening time. The rotational speed of the model dryer's rotating discharge unit was adjusted to match the velocity conditions of the industrial dryer as closely as possible. By properly setting the discharge unit's opening time, a strong correlation between the velocity conditions in the model dryer and the industrial dryer can be achieved. Based on these findings, it can be concluded that the model dryer is suitable for simulating the material flow conditions occurring in the full-scale drying system.

2.2. Numerical simulations

To develop the numerical model, it was necessary to determine the shapes of the corn kernels present in the granular mass. Based on my investigations it was appropriate to work with four different particle shapes (Figure 2.3).

Figure 2.3.: The corn kernels in the sample and their classification based on shape

In the discrete element simulation, the different particle shapes were created based on the average dimensions corresponding to each shape, as shown in Figure 2.4.

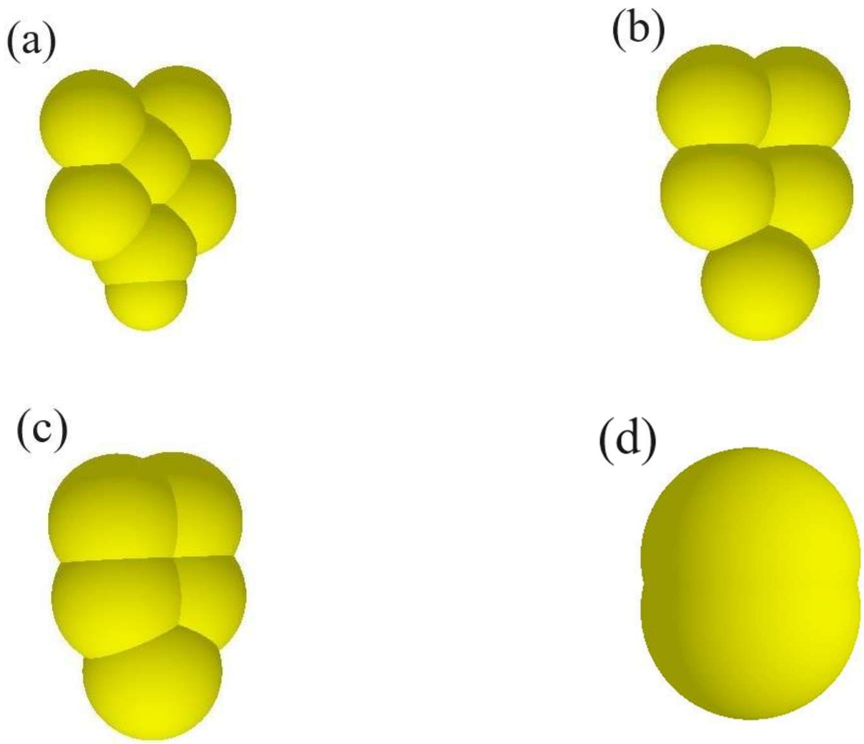


Figure 2.4.: Particle shapes used in the discrete element simulations: (a) flat, (b) elongated, (c) angular, (d) round

Since the experimental investigations were conducted at an operational grain drying facility, it was essential to minimize any disruption to its normal operations [Bablena et al., 2022]. For this reason, the angle of repose measurement was chosen as the calibration method. The measured angle values were: α_1 = 19.2°; α_2 = 18.8°; α_3 = 17.4°.

For analyzing granular movement within the drying equipment, the model dryer geometry shown in Figure 2.2 was used as the basis (Figure 2.5).

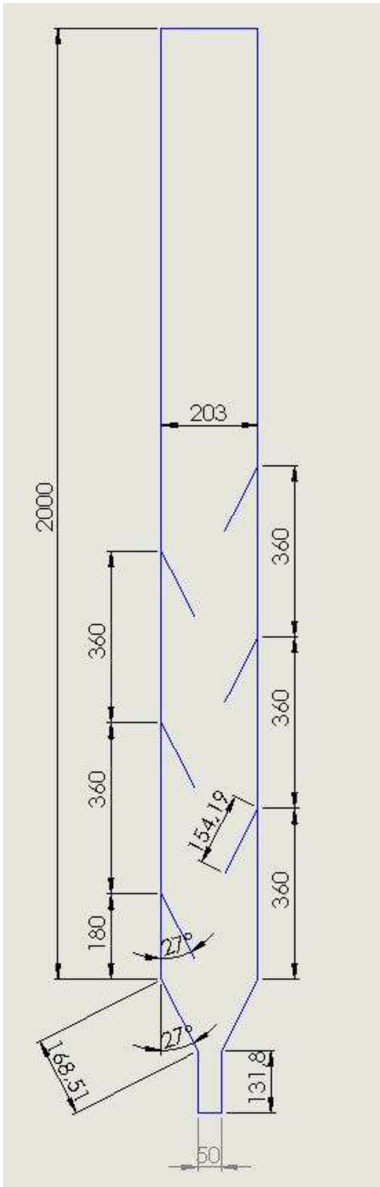


Figure 2.5.: The geometry in the numerical model

During the investigation of the effect of lamella inclination, the α value was varied as follows: α = 22°; α = 24°; α = 27°; α = 30°; α = 32°.

As shown in Figure 2.5, the 27° inclination corresponds to the original angle. The simulations were performed with three repetitions for each case.

In simulations marked bands were used to examine the movement of granular material. In each simulation, the position of the marked bands was considered such that each band extended along a single lamella, ensuring that the marked particles remained on the lamella without falling off (Figure 2.6).

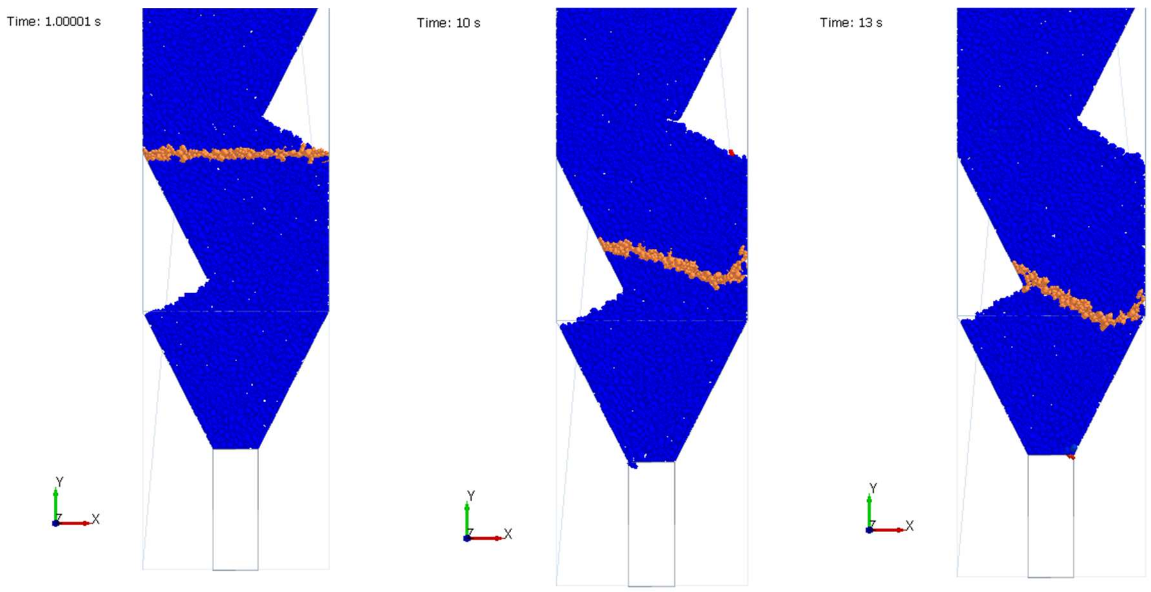


Figure 2.6.: The position of the marked bands at the initial time (1 s), and after 10 s and 13 s for a 27° lamella inclination angle

To describe the unevenness of material flow, I introduced the ξ ratio (unevenness factor) as follows.:

$$\xi = \frac{y_{max} - y_{min}}{y_{max}}, \quad (2.1)$$

where:

- y_{max} is the *y* coordinate of the centroid of the highest-positioned particle,
- y_{min} is the *y* coordinate of the centroid of the lowest-positioned particle.

These y coordinates can be easily retrieved from the software (Figure 2.7.). Additionally, a key advantage of this calculation method is that displacement is not a derived quantity but a directly measurable parameter, making it more accurately determinable. The more uniform the flow, the closer the ξ value approaches 0.

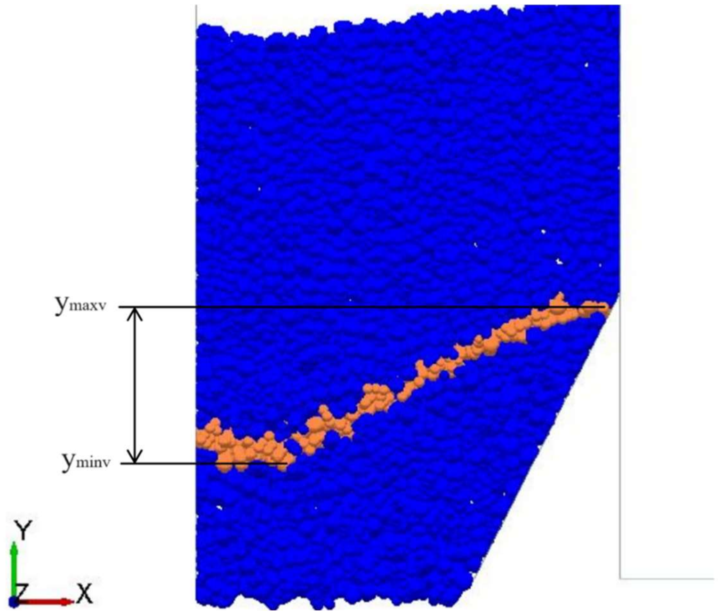


Figure 2.7.: Determination of flow unevenness based on particle displacement

Figure 2.8 shows the ξ ratio calculated from the measured data in the model dryer and the simulation results for different lamella inclination angles.

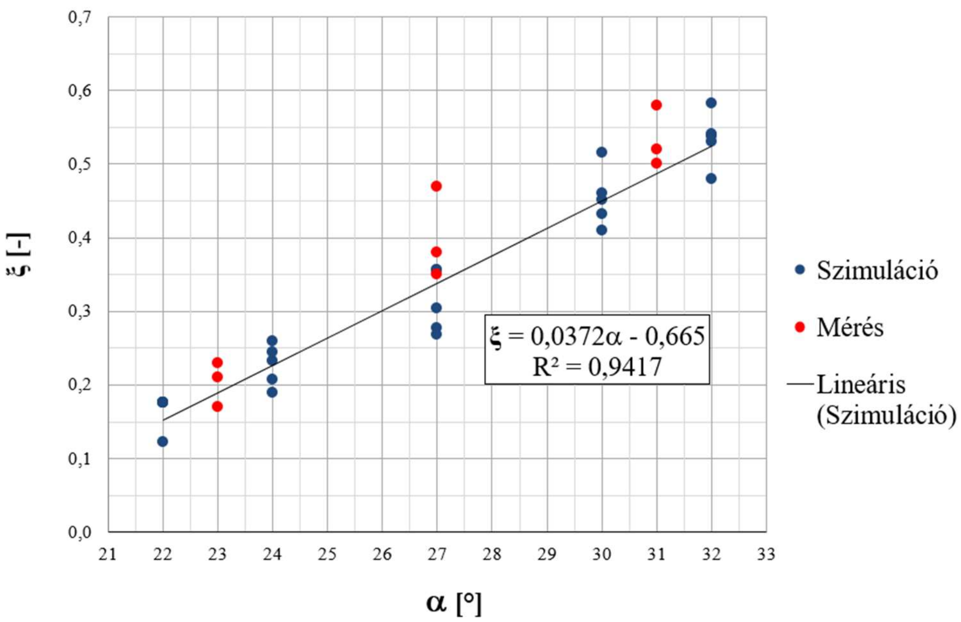


Figure 2.8.: Comparison of the measured and numerically determined unevenness factor values

The equation of the function obtained from the linear fitting of the simulation results is:

$$\xi = 0{,}0372\alpha - 0{,}665, \qquad (2.2)$$

The correlation coefficient is $R^2 = 0.9417$. Considering the characteristics of the examined material, this R^2 value can be considered appropriate.

During the comparison of straight and cycloid lamella geometries, the straight lamella used had an inclination angle of α = 27°, which was also applied in the model dryer.

For constructional reasons, the geometry of the cycloid-shaped lamella was designed so that the tangent at point A (the end of the lamella) coincides with the straight lamella, while at point B, the tangent aligns with the vertical axis (Figure 2.9).

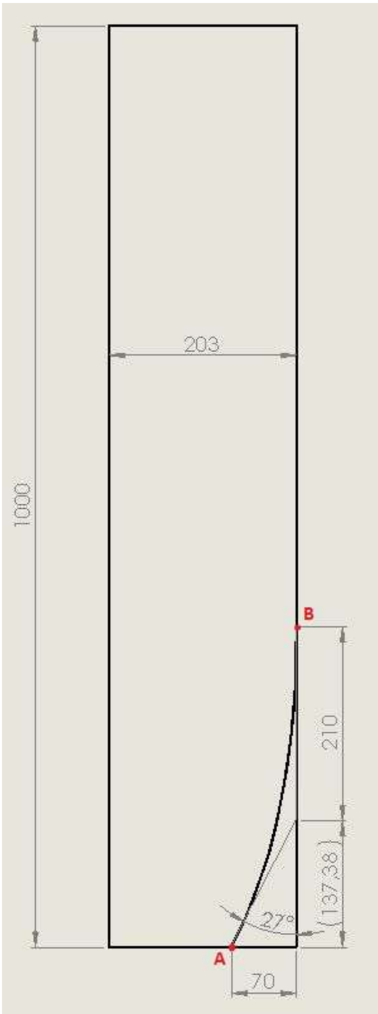
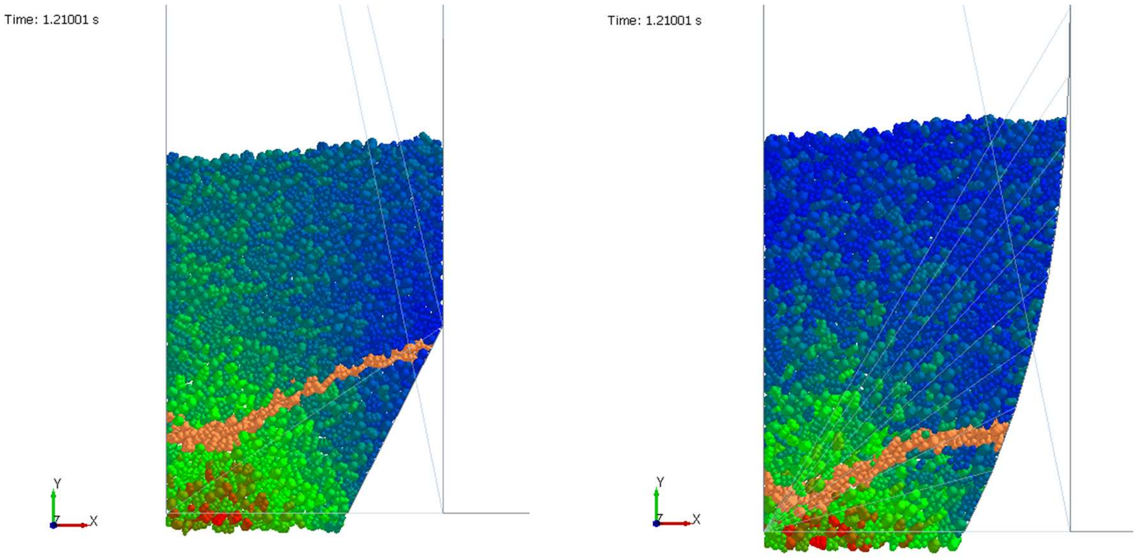


Figure 2.9.: Module geometry for the comparison of straight and cycloid-shaped lamellae

In this case, the unevenness of movement was also determined using the unevenness factor (Figure 2.10).



a) b)

Figure 2.10.: The shape of the centrally positioned marked bands after Δt = 0.21 s for a) straight and b) cycloid-shaped lamella

The effect of the grain-wall and grain-grain friction coefficients on the unevenness of movement were examined for both straight and cycloid lamellae, considering the centrally marked bands in the granular mass, similar to the previous case.

The changes in the ξ unevenness factor values resulting from variations in the friction coefficients are shown in the diagrams in Figures 2.11 and 2.12.

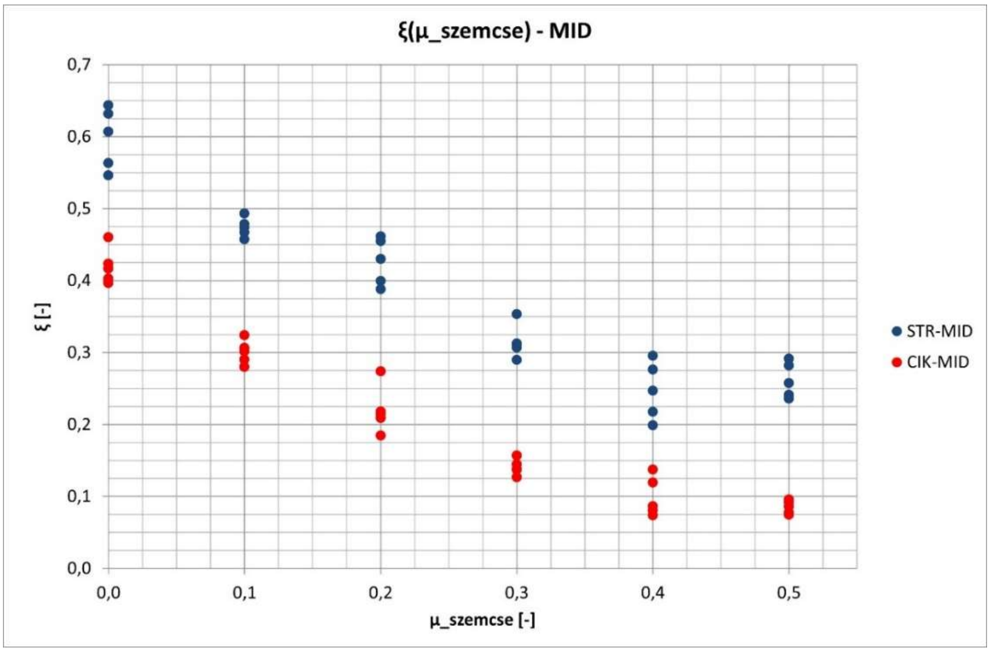


Figure 2.11.: The ξ values determined for the marked bands in the case of straight (STR) and cycloid (CIK) lamellae as a function of the grain-grain friction coefficient

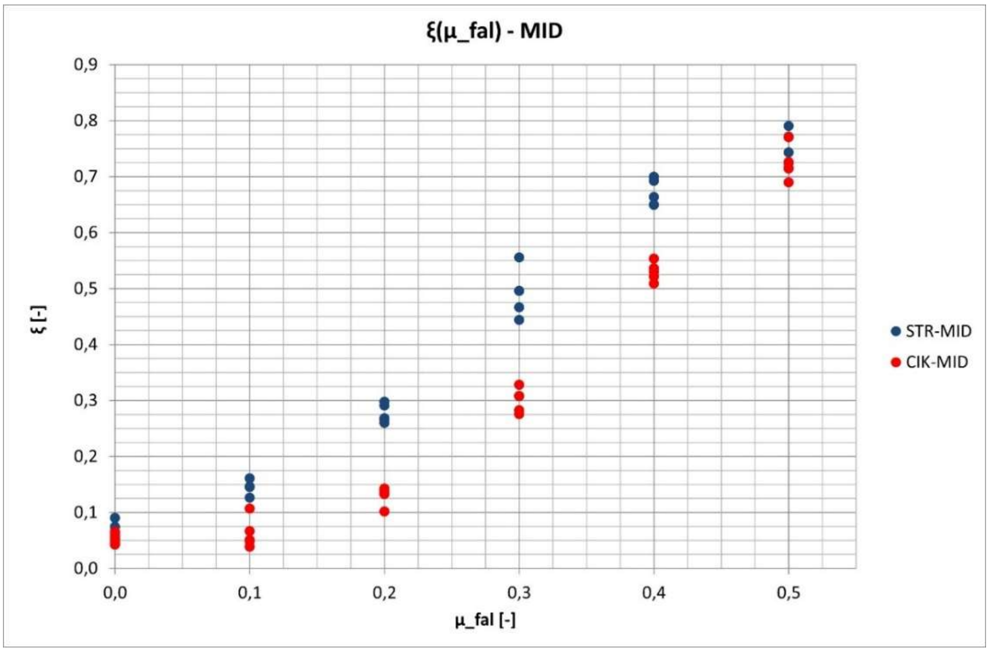


Figure 2.12.: The ξ values determined for the marked bands in the case of straight (STR) and cycloid (CIK) lamellae as a function of the grain-wall friction coefficient

According to literature sources and my own measurement experiences, both under-drying and over-drying in drying equipment cause significant deterioration in product quality, which is primarily due to material flow unevenness within the dryer. The flow paths inside the dryer are regulated by lamellae. In my dissertation the effect of these lamellae on material movement and proposed structural modifications that reduce flow unevenness was examined, thereby improving drying efficiency and the quality of the final product.

3.1. The unevenness factor

First, I sought a dimensionless characteristic that could quantify the unevenness of material flow. While the literature primarily uses the concept of "residence time" to describe this phenomenon, I defined unevenness based on the vertical displacement of particles using the unevenness factor.

3.2. The effect of wall friction

First, I examined how changes in the wall friction coefficient affect material flow unevenness in the model presented in Figure 3.30, assuming a constant lamella inclination angle of 27° and a grain-grain friction coefficient of 0.2. The following diagram (Figure 3.1) presents the results of my investigation for wall friction coefficient values ranging from 0 to 0.5.

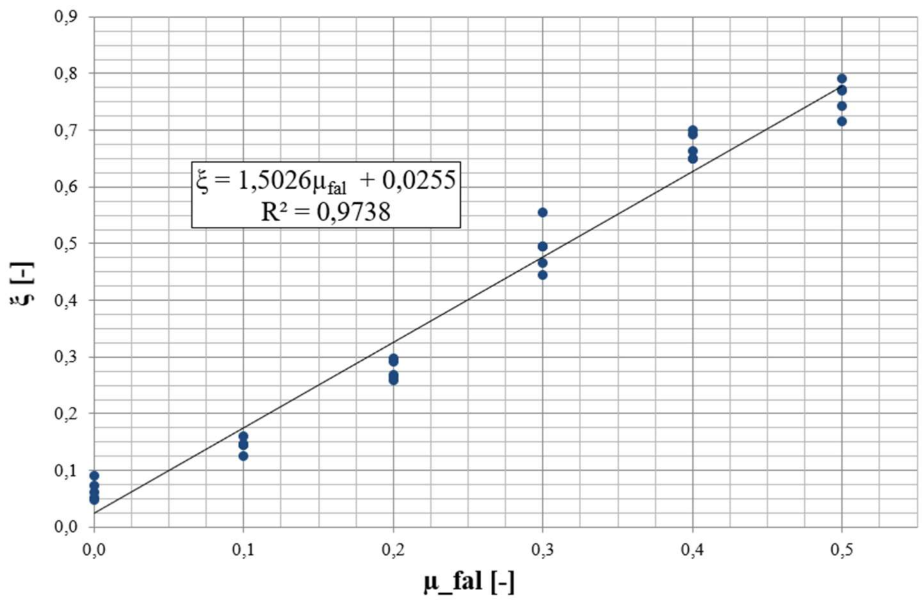


Figure 3.1.: Material flow unevenness as a function of the grain-wall friction coefficient for a 27° lamella inclination angle

The value of the unevenness factor is described by the following approximate equation as a function of the wall friction coefficient:

$$\xi = 1{,}5026 \cdot \mu_{fal} + 0{,}0255. \quad (3.1)$$

The increase in wall friction clearly "worsens" the uniformity of material flow, as a higher friction coefficient causes the wall to hinder particle movement more significantly.

3.3. The effect of internal friction

In the next step, I examined how changes in the grain-grain friction coefficient affect material flow unevenness, using the model presented in Figure 3.30. The analysis was conducted with a 27° lamella inclination angle and a constant wall friction coefficient of 0.25. The following diagram (Figure 3.2) presents the results of my investigation for grain-grain friction coefficient values ranging from 0 to 0.5.

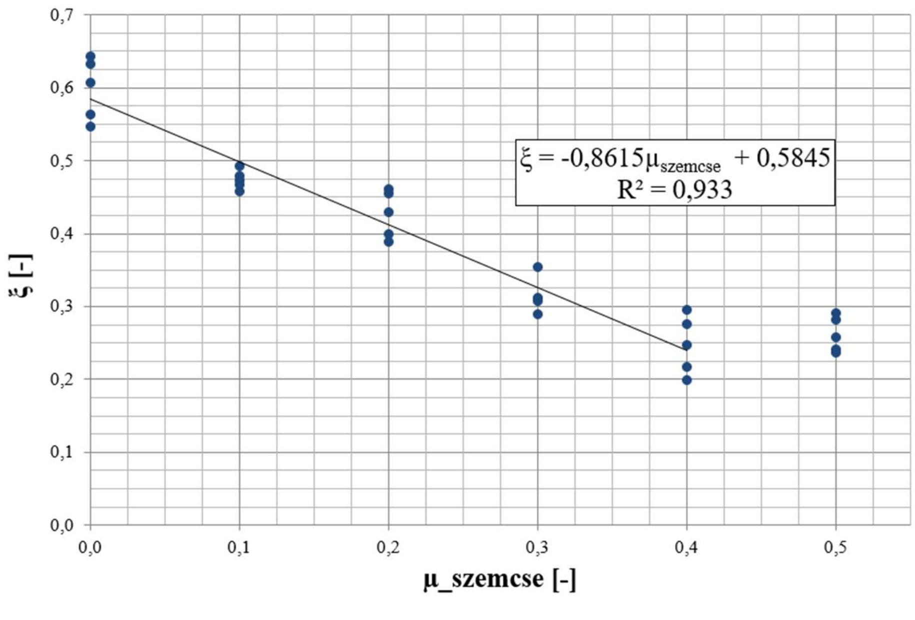


Figure 3.2.: Material flow unevenness as a function of the grain-grain friction coefficient for a 27° lamella inclination angle

In this case, the value of the unevenness factor is described by the following approximate equation as a function of the grain-grain friction coefficient, within the range of 0 to 0.4:

$$\xi = -0{,}8615 \cdot \mu_{szemcse} + 0{,}5845. \quad (3.2)$$

For friction values above 0.4, the function was considered constant. Friction coefficient values greater than 0.5 were not examined, as no materials with such high friction coefficients were encountered during the experiments.

In my opinion, the decrease in unevenness due to increased grain-grain friction can be explained by the fact that at higher friction coefficients, the particles tend to move together more easily, essentially interlocking with each other. As a result, the effect of wall friction becomes less significant.

Sensitivity analyses were also conducted for other micromechanical parameters, including the grain-grain restitution coefficient, elastic modulus, and simulation time step. However, the unevenness factor was not significantly sensitive to these parameters.

3.4. The effect of lamella inclination angle

Using the model shown in Figure 2.9, I examined the effect of the lamella inclination angle on the unevenness of granular flow for a straight lamella. In this case, the friction coefficient values were μ_{fal} = 0.25 and $\mu_{szemcse}$ = 0.2. The investigated lamella inclination angles ranged from 22° to 32° (Figure 3.3).

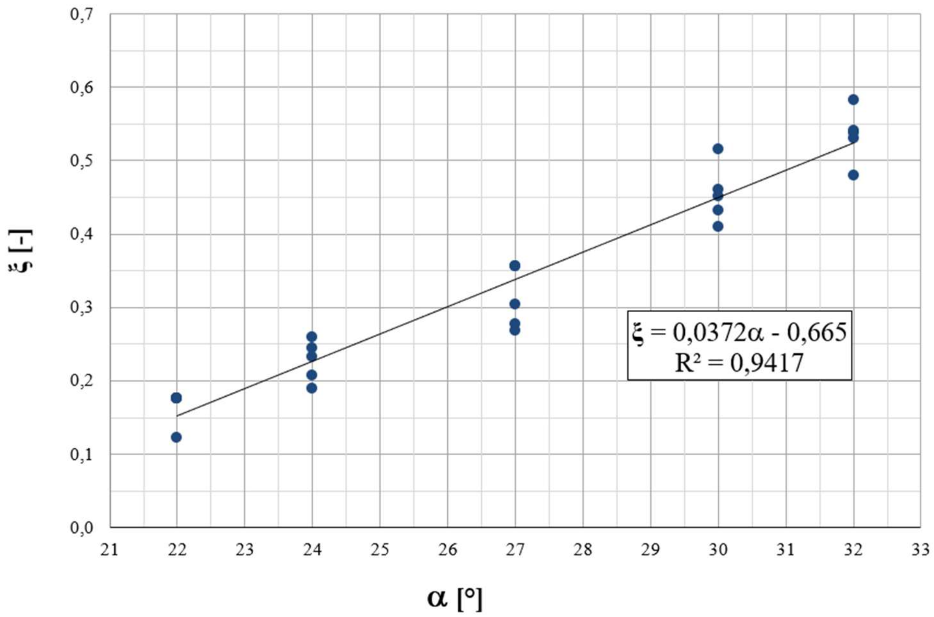


Figure 3.3.: Material flow unevenness as a function of the lamella inclination angle

The equation of the fitted approximation function for the examined interval.:

$$\xi = 0{,}0372 \cdot \alpha - 0{,}665$$

In this case, it can be observed that the fitted approximation function intersects the vertical axis at a negative value, which is not meaningful given the definition domain of the ξ value. Therefore, it is particularly important to note that the approximation function is only valid within the examined range of inclination angles. It is possible that considering smaller α values could alter the nature of the function; however, this was not investigated in this study.

From the perspective of flow uniformity, a 0° lamella inclination angle would obviously be the most optimal, as this would essentially eliminate the presence of lamellae. However, considering the practical aspects of material passage through the drying equipment, both a minimum and a maximum lamella inclination angle must be defined for practical application.

The grains must spend a certain amount of time in the dryer to reach the desired moisture content. Therefore, deflector elements are necessary, as well as inlet openings for air circulation. This residence time can be measured by considering the temperature of the introduced air, along with the initial and target moisture content values, allowing for the determination of the minimum lamella inclination angle.

The maximum inclination angle is defined by the repose angle of the granular mass; if the inclination exceeds this value, arching or bridging of the material can occur. However, these boundary values were not examined in this study..

3.5. Optimal lamella geometry

When selecting the lamella geometry, I used the brachistochrone problem as the starting point. According to this principle, in a conservative force field and neglecting friction, the fastest path between two points (where the x and y coordinates of the points are different) is a cycloid curve. Based on this, I chose a cycloid shape for the lamella geometry.

The selected lamella geometry can be described by the following equation:

$$x = 70 - 70 \cdot \sqrt{1 - \frac{y^2}{4900}} + 150 \cdot \arcsin\left[\frac{y}{70}\right].$$

Using the model presented in Figure 2.5, I also examined the effect of wall friction and grain-grain friction on flow unevenness in the case of a cycloid-shaped lamella. The results of these investigations are shown in Figures 3.4 and 3.5, where the fitted equations for the linear sections are also displayed.

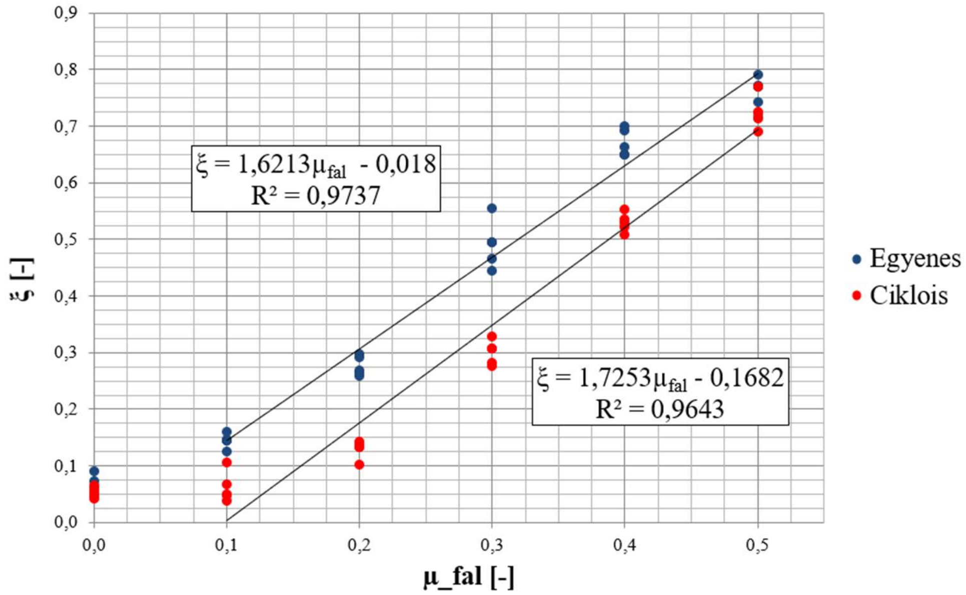


Figure 3.4.: Material flow unevenness as a function of the grain-wall friction coefficient for straight (27°) and cycloid lamellae

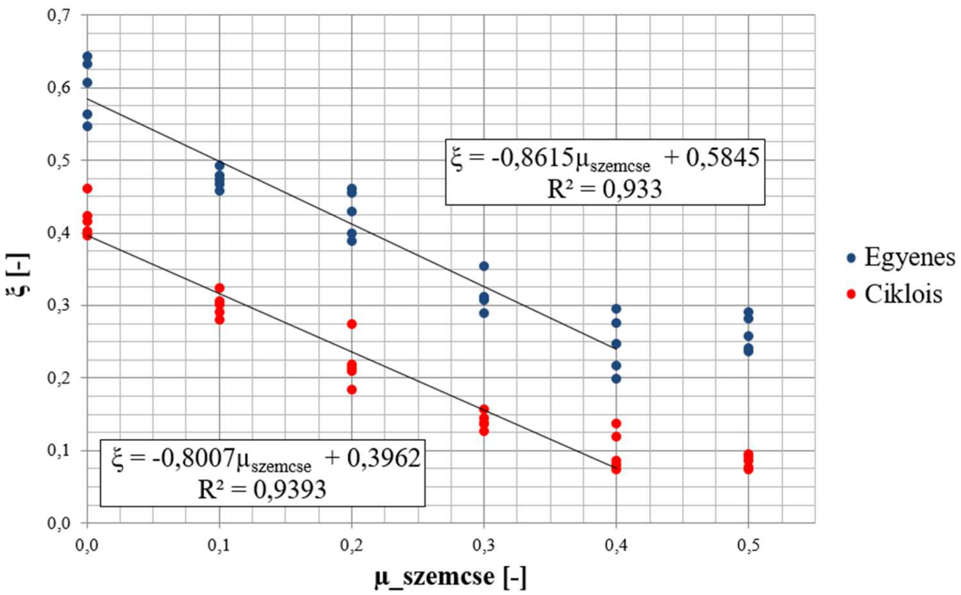


Figure 3.5.: Material flow unevenness as a function of the grain-grain friction coefficient for straight (27°) and cycloid lamellae

The diagrams show that the cycloid-shaped geometry results in a lower ξ flow unevenness value for almost all examined friction coefficient values. The results indicate that applying a cycloid-shaped geometry can significantly improve the uniformity of material flow and, consequently, the quality of the drying process.

4. NEW SCIENTIFIC RESULTS

1. *Unevenness factor:* To characterize the unevenness of material flow (by analyzing the movement of a designated band within the granular mass), I introduced the ξ unevenness factor during modeling: $\xi = \frac{y_{max} - y_{min}}{y_{max}}$. The value of ξ ranges between 0 and 1, where a lower value indicates a more uniform flow. The parameters y_{max} and y_{min} are defined as follows:
   - y_{max} The y coordinate of the centroid of the highest-positioned particle within the designated band at a given time.
   - y_{min} The y coordinate of the centroid of the lowest-positioned particle within the designated band at a given time.

   This dimensionless characteristic is suitable for comparing the unevenness of material flow processes within the dryer.

2. *Effect of wall friction:* Using experimental investigations and numerical simulations, I demonstrated that the value of wall friction has a significant effect on material flow unevenness ξ. The approximate linear function describing this relationship (for corn kernel movement) in the interval [0; 0.5] for μ_{fal}, with a grain-grain friction coefficient of $\mu_{szemcse}$ = 0.2 and a lamella inclination angle of α = 27°, is as follows:

$$\xi = 1.5026 \cdot \mu_{fal} + 0.0255 \qquad R^2 = 0.9738$$

3. *The effect of grain-grain friction:* Using experimental investigations and numerical simulations, I demonstrated that the value of grain-grain friction has a significant effect on material flow unevenness ξ. The approximate linear function describing this relationship (for corn kernel movement) in the interval [0; 0.4] for $\mu_{szemcse}$, with a wall friction coefficient of μ_{fal} = 0.25 and a lamella inclination angle of α = 27°, is as follows:

$$\xi = -0.8615 \cdot \mu_{szemcse} + 0.5845 \qquad R^2 = 0.933$$

4. *The effect of lamella inclination angle:* Using experimental investigations and numerical simulations, I determined the effect of lamella inclination angle α on flow unevenness ξ for straight lamellae. The approximate linear function describing this relationship (for corn kernel movement) in the interval [22°; 32°] for α, with a wall friction coefficient of μ_{fal}= 0.25 and a grain-grain friction coefficient of $\mu_{szemcse}$ = 0.2, is as follows:

$$\xi = 0.0372 \cdot \alpha - 0.665 \qquad R^2 = 0.9417$$

5. *Optimal lamella geometry:* Based on analytical considerations, supported by experimental investigations and numerical simulations, I demonstrated that a cycloid-shaped lamella is the most suitable for drying equipment. In all examined cases, the application of a cycloid-shaped lamella resulted in more uniform granular flow compared to a straight lamella.

5. CONCLUSIONS AND RECOMMENDATIONS

In my dissertation, I focused on optimizing granular motion conditions in cross-flow drying equipment. According to the literature, uneven granular movement leads to under-drying or over-drying, resulting in significant losses. My research demonstrated that modifying the inclination angle of a straight lamella has a substantial effect on drying uniformity and, consequently, on the quality of the final product.

To improve flow uniformity, one potential solution for straight lamellae could be the application of friction-reducing coatings. However, due to wear, this would only provide a temporary solution, and the associated costs would be high.

The requirements related to airflow in the dryer favor larger lamella inclination angles, while those related to flow uniformity require smaller inclination angles. These two opposing effects suggest the existence of an optimal inclination angle, the precise determination of which requires further investigation.

Additionally, it should be considered that the values of the wall friction coefficient and grain-grain friction coefficient are not constant inside the drying equipment. Due to temperature and moisture content variations, different zones develop, each with different friction coefficient values. Therefore, an alternative approach to improving drying efficiency could involve adjusting the lamella inclination angle in different zones of the drying equipment. However, this aspect was not investigated in the present study.

Considering the above findings, it is evident that the application of straight lamellae has inherent limitations, and efficiency cannot be increased beyond a certain point. A potential solution to further improve performance is modifying the geometry of the lamellae, which was the primary focus of this research.

I introduced a dimensionless parameter that is experimentally and numerically applicable to describe flow unevenness. I demonstrated the effects of grain-grain and grain-wall friction, as well as the inclination angle of a straight lamella, on material flow unevenness. Based on analytical considerations, supported by experimental investigations and numerical simulations, I showed that a cycloid-shaped lamella results in a more uniform granular flow compared to a straight lamella.

6. SUMMARY

Drying harvested grain crops prior to storage is a crucial task in the prevailing climatic conditions of Europe. Drying is an extremely energy-intensive process. Its inappropriate application leads to environmental pollution, quality deterioration, and ultimately significant financial losses.

Various methods are available for conducting drying operations, with the mixed flow dryer being one of the most employed approach. The mixed flow dryer utilizes air blower systems to redirect the flow of the granulate. Previous research has indicated that uneven distribution of grain flow around the air blower lamellae can cause drying irregularities. By leveraging insights from a long-established classical mechanical problem (the Brachistochrone problem) and harnessing the explicit dynamical modelling capabilities offered by contemporary computing technology (Discrete element method) an optimized lamella geometry was successfully devised that minimizes the non-uniformity of particle flow.

To quantify the unevenness of material flow within the dryer, the dimensionless displacement ratio ξ was used. This parameter allows for the characterization of the uniformity of material movement within a designated band and provides a suitable tool for comparing the uniformity of material movement processes within the dryer.

Using experimental investigations and numerical simulations it was demonstrated that it is advantageous to employ cycloidal-shaped lamellae in drying devices. It was found that the particle displacement ratio ξ shows linear dependence on the particle-particle and the particle-wall friction coefficients. The cycloidal lamella, under all examined friction coefficient values between particle-wall and particle-particle interactions, can result in up to a 30% improvement in the displacement ratio.

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