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BEZIER CURVE SHAPED LAMELLAE IN CROSS FLOW DRYERS

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Abstract: Recent advancements in dynamic modeling, supported by improved computational technologies, have enabled detailed investigations of particle motion within drying equipment. Under and over drying of harvested crops causes significant financial losses in agriculture. To overcome this issue, we analyzed the particle motion in cross flow dryers using analytical and numerical modeling techniques. In our earlier work we determined the theoretically optimal lamella geometry shape, using the Brachistochrone problem and finding the cycloid curve. The manufacturing problems of creating an approximate cycloidal curve for our experimental investigations showed us that it is not a simple task to solve. To overcome this issue, we investigated the possibility of using other geometries close to the original cycloidal one. This study explores the influence of Bezier curve-shaped lamellae on particle residence time. By examining various geometries and tribological parameters, the research aims to identify an optimal lamella design that minimizes under- or over drying while maintaining ease of manufacturing.

Keywords: agricultural particulate materials, discrete element method, cross flow dryer, flow unevenness, geometry optimization

1. Introduction

Lowering the moisture content of harvested grains is a critical step in preparing them for subsequent processing or storage. While natural drying using direct solar energy is an ideal approach, it is insufficient to handle the large volumes of grain required to meet the food and industrial raw material needs of developed nations. As a result, artificial drying becomes indispensable. To minimize the significant energy consumption and environmental impact associated with artificial drying, it is imperative to optimize the process. This can be achieved through several strategies, including geometric modifications to drying equipment, which enhance airflow and heat transfer, and the use of advanced numerical modeling to simulate and refine drying parameters. These approaches not only reduce energy demands and environmental pollution but also improve the quality of the final product, ensuring it meets the standards of modern industrial and food production systems.

2. The drying efficiency problem

The earliest experimental findings on the unique mechanical behavior of granular materials can be traced back to Janssen's studies in 1895 [1]. Despite numerous researchers highlighting various shortcomings in the theory over the past century, the principles outlined in the European Union's standard collection (EUROCODE 1, Part IV: Actions in silos and tanks) are essentially applications of Janssen’s 1895 results. Unlike ideal fluids, granular material assemblies exhibit a limited ability to withstand shear stresses. Due to wall friction, part of the load of the stored material is borne by the silo walls, resulting in the vertical stress component not increasing linearly with depth. Janssen was the first to experimentally investigate the nature of this variation. He also provided an analytical solution to the problem by examining the equilibrium of a slice of material of thickness Δy within the silo, treating the stored material as a continuous medium.

Accounting for wall friction revealed a deviation of the wall pressure from linearity, with the resulting equation resembling the barometric height formula.

The constrictions in drying equipment channels further complicate the phenomena described above [2]. The effects of such constrictions have been studied experimentally and analytically by several authors, including [3], [4], [5], [6], [7], and [8]. However, the application of analytical models has been significantly limited by the presence of numerous, spatially distributed channel constrictions. Additionally, these models failed to account for discontinuities arising from interruptions in material flow.

Kocsis et al. [9] conducted experimental studies on material flow processes in drying equipment. Their research identified inconsistencies in the material movement velocities between the air channels within the drying equipment.

The experimental investigations conducted by Mellmann using a model dryer [10], [11] revealed that current dryer designs lead to significant variations in residence time, moisture content, and temperature of the dried material. Their findings indicated that the uneven distribution of moisture content is primarily influenced by the arrangement of the air channels. The model dryer used in their experiments consisted of two parallel, vertically arranged drying shafts—one dedicated to particle flow studies and the other to drying experiments. The equipment measured approximately 2 meters in height, 0.6 meters in width, and 0.4 meters in depth, featuring a total of 26 inlet and outlet air channels.

Mellmann's experimental studies and accompanying analytical models demonstrated that material flow irregularities are mainly caused by interactions with inclined walls. Building on Mellmann's hypothesis of equal residence time, we proposed that achieving optimal material flow conditions requires that grains traveling downward along the channel walls and those moving along the channel's centerline must pass through a module of the drying equipment within the same timeframe.

The question of a particle’s downward motion is essentially a classical problem of the calculus of variations: the brachistochrone problem. This problem seeks the shape of a frictionless path along which a point mass, moving under gravity, travels between two points A and B, not aligned vertically, in the shortest possible time. Solving this mathematical problem, we get the equation of a cycloid.

The movement of an entire granular assembly within a drying apparatus is inherently a more complex problem, as it requires accounting for particle-particle interactions, necessitating numerical solutions. The intermittent interruptions in material flow preclude the use of finite element-based numerical methods, making the discrete element method (DEM) a particularly suitable alternative. DEM has proven effective in modeling pressure conditions in silos, analyzing discharge behavior, and assessing the effects of flow-directing elements [12], [13], [14], [15], [16], [17].

Yang and Hsiau [18] examined the influence of baffle geometry on particle movement and wall pressure using a two-dimensional DEM model. They studied velocity distributions near obstacles by observing the "deformation" of colored stripes. Even with a simple two-dimensional model of circular particles, their results showed that material flow slows in the vicinity of inclined walls, a finding with significant implications for motion dynamics in drying equipment.

During the flow of granular assemblies through constricted cross-sections, self-supporting arches can form, which may obstruct material discharge [18], [19]. Oldal et al. [20] demonstrated that the formation and collapse of such arches significantly impact material flow velocity profiles. Kruggel-Emden et al. [21] further showed that discharge time and velocity are strongly influenced by the friction coefficient of the particles. Tao et al. [22] investigated the discharge of particles from a rectangular container with a flat bottom and a rectangular outlet. They found that vertical velocity differences between particles moving through the center and near the walls were much larger for non-spherical particles compared to spherical ones. Colored stripes were used in both experiments and simulations to visualize motion dynamics.

Mellmann et al. [11] reviewed experimental studies on cross-flow dryers and included a simple two-dimensional DEM model to describe granular motion within drying equipment. While their model reasonably simulated the discharge mechanism, the predicted material flow patterns only broadly corresponded to experimental observations. Similar results were achieved by [23] and [24] with their two-dimensional models.

Khatchatourian et al. [25], [26] studied the discharge of soybeans from a cross-flow dryer, using spherical particles in their simulations. In this case, the flow patterns matched experimental observations well. Later work by Weigler and Mellmann [27] introduced elliptical particles approximated by five interconnected circles in their two-dimensional simulations. These simulations, when compared to earlier models with circular particles and experimental data, showed significantly better agreement in velocity profiles. Similar improvements were reported by other authors, such as [28].

The efficiency of the drying process has been improved by addressing several critical questions, as detailed in our publications [29] and [30]. Which dimensionless characteristic best captures the uniformity of material flow within the dryer? How do the tribological interactions between particles and the dryer wall influence material flow uniformity? How do tribological interactions among particles affect the uniformity of material flow? Can alternative lamella geometries, deviating from straight designs, further enhance material flow uniformity and improve drying efficiency? These questions were thoroughly examined using a combination of theoretical analyses, experimental studies, and numerical simulations, leading to a deeper understanding and optimization of the drying process. These questions lead us to the application of the Brachistochrone problem [29] and deriving the theoretical shape of the optimal lamella geometry. Later manufacturing difficulties rise another question: is there a lamella geometry in which the flow unevenness is acceptable, but it is easier to manufacture? To answer this, we analyzed the applicability of Bézier curves to replace cycloidal ones.

3. Bezier curves shaped lamellae

Based on the analytical solution of the brachistochrone problem and numerical simulations, it can be concluded that the use of cycloidal-shaped lamellae would be the most effective approach to reducing drying irregularities in crossflow dryers. However, manufacturing considerations suggest that the cycloidal shape should ideally be replaced with a simpler geometry. As we can see on (Figure 1.), it is quite a complicated task to create the approximate shape of the required cycloidal lamella and it needs quite a lot of line segments, which is finally a costly solution.

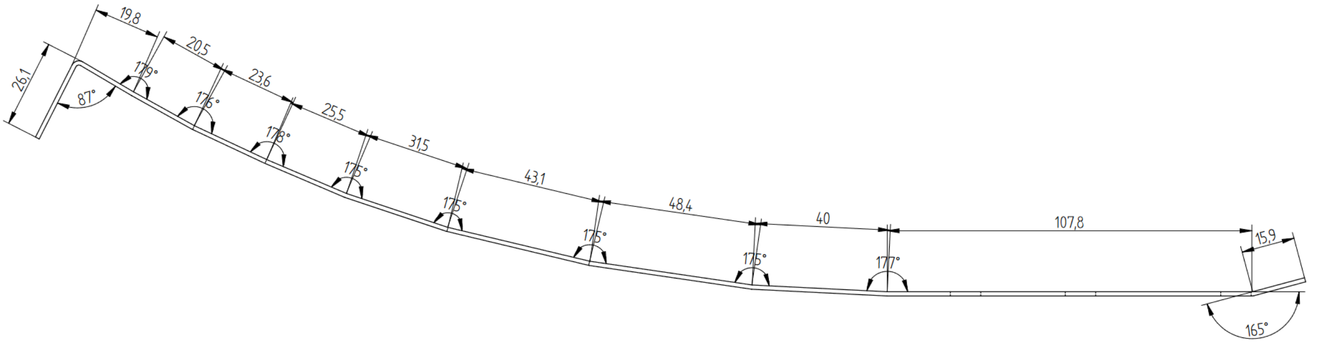


Figure 1. Approximation of cycloidal lamella geometry by using multiple line segments

Manufacturing considerations led us to conclude that baffles with Bézier curve shapes are easier to produce. Consequently, numerical simulations were also conducted for this design. For the modeling, third-degree Bézier curves were used, defined by four points (P_0, P_1, P_2 and P_3) (see Figure 2.).

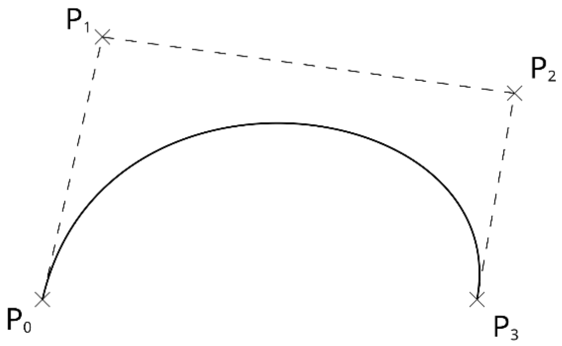


Figure 2. Points defining third degree Bézier curves

These points can be easily adapted to fit the existing dryer design. The equation for a third-degree Bézier curve is as follows:

$$\mathbf{B}(t) = (1-t)^3\mathbf{P}_0 + 3(1-t)^2 t\mathbf{P}_1 + 2(1-t)t^2\mathbf{P}_2 + t^3\mathbf{P}_3 \quad t \in [0,1].$$

The Bézier curve points we selected were chosen in such a way that the starting and ending points align with the cycloidal lamella of the drying apparatus described in [29] and [30]. As a result, we had to choose the following coordinates: P_0 and P_1 consistently had coordinates x = 133 mm, y = 0, z = 0. The y-coordinate of point P_2 varied depending on the specific design, while the x and z coordinates remained constant at P_2x = 203 mm, P_2z = 0. The coordinates of P_3 also remained unchanged, with x = 203 mm, y = 347 mm, z = 0. By adjusting the coordinates in this manner, I was able to ensure that the Bézier curve closely matched the starting and ending points of the cycloid, while the variation in P_2y caused the curve to deviate more significantly from the original shape (Table 1).

Table 1. Modification of Bézier curves for simulations

	1	2	3	4	5	6	7	8	9
P_{2y}	0	25	50	75	100	125	150	175	200

The effect of changing the P_2y value on the shape of the curve is illustrated in a figure showing three different coordinate cases (Figure 3).

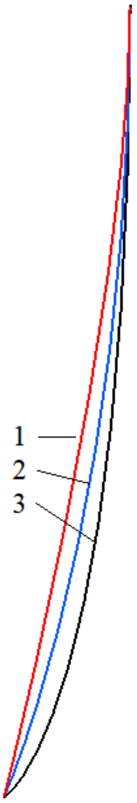


Figure 3. Effect of changing P_{2y} to the shape of the curve. 1: $P_{2y} = 200\text{mm}$, 2: $P_{2y} = 100\text{mm}$, 3: $P_{2y} = 0$

Figure 4. shows the difference between the cycloidal and the one of the Bézier curve shaped lamella geometries. Here P_2y = 25 mm version is used to see the difference between the two curves.

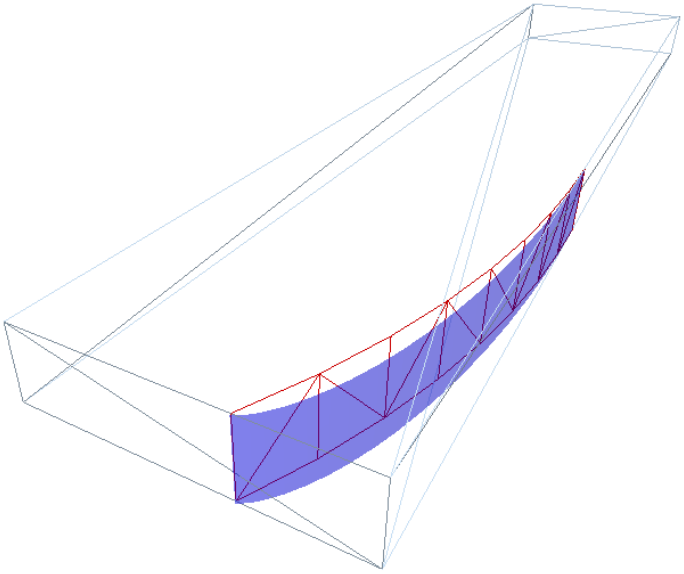


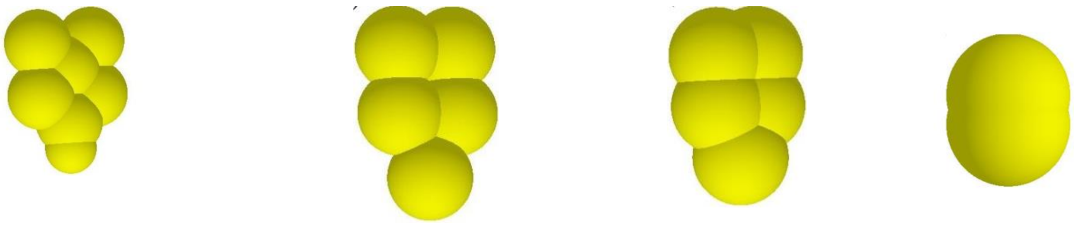
Figure 4. Comparison of the cycloidal (red) and one of the Bézier curve shaped lamellae (blue)

4. The discrete element model

Four different particle shapes were applied for the discrete element method (DEM) analysis (see Table 2. and Figure 5.)

Table 2. Shape of particles used in the DEM model

	average length [mm]	average width [mm]	average thickness [mm]	percentage [%]
Flat	12,1	9,1	4,7	36
Elongated	11,8	8,0	4,7	20
Angular	12,0	8,5	5,8	32
Spherical	9,4	9,0	7,6	12



Flat Elongated Angular Spherical

Figure 5. Particle shapes used in DEM model

Table 3. Micromechanical- and contact parameters

Micromechanical parameters		*Contact parameters*	
Poisson-coefficient [-]	0,31	Coeff. of restitution [-]	0,1
Density [kg/m^3]	1180	Coefficient of friction [-]	0,2
Shear modulus [Pa]	$3 \cdot 10^7$	Rolling friction [m]	0,01

Instead of a mathematical analysis of the velocity vector field (Figure 6.), a much simpler (and easily measurable) parameter was used to quantify the flow irregularities (Table 3.).

The flow unevenness factor:

$$\xi = \frac{y_{max} - y_{min}}{y_{max}},$$

where meaning of the above values can be seen on (Figure 7.)
An example particle velocity field can be seen on Figure 6., after the opening of the bottom of the geometry.

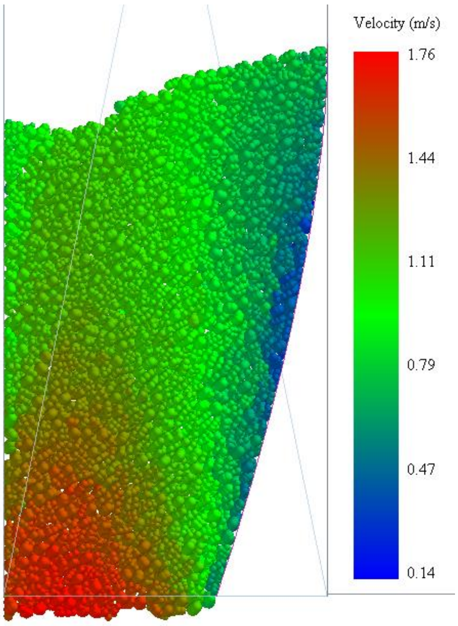


Figure 6. Particle velocity field

The flow unevenness can be seen on (Figure 6). The particle-wall friction slows down the flow, causing residence time difference in the drying apparatus. Analyzing this by mathematical means is much more complicated, than using the simple scalar quantity ξ introduced above. The measurement of the velocity field is also more complicated than simply observe experimentally the "deformation" of the originally straight colored stripe (Figure 7).

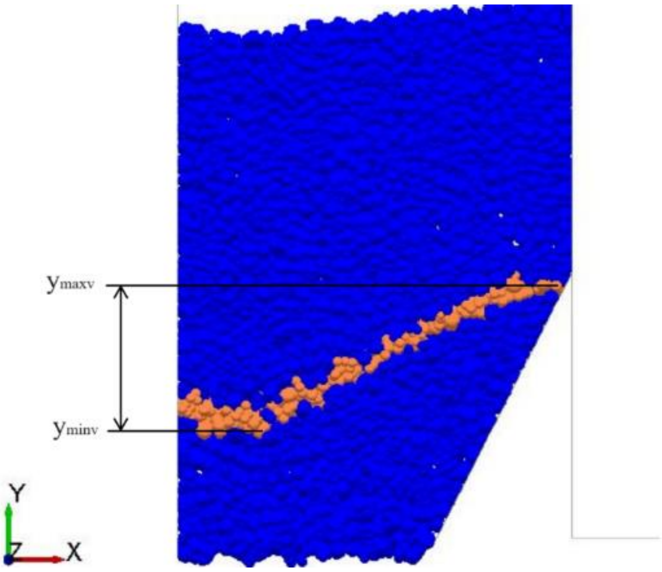


Figure 7. Flow unevenness factor

The more uniform the flow, the closer the value of ξ approaches 0. To analyze the applicability of Bézier curves first we compared the different geometries regarding their flow unevenness, then by choosing the best shape, we made sensitivity analysis on particle – particle and particle – wall friction.

5. Results

Firstly, we examined how the flow irregularity factor is affected when using different Bézier curve shapes, as presented in Table 1. See Figure 8.

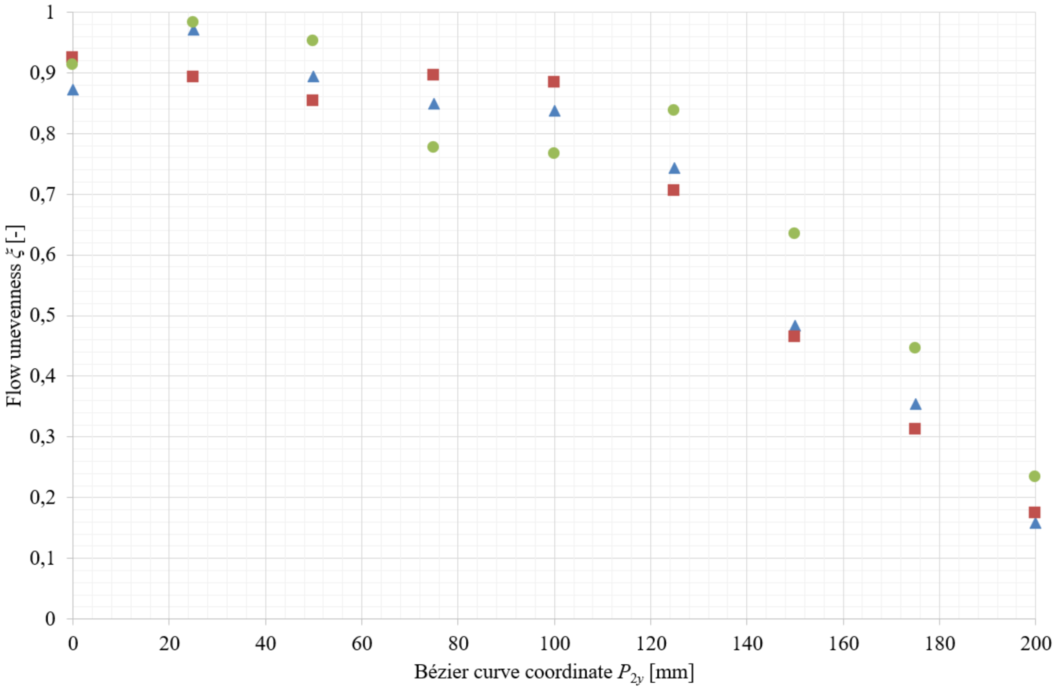


Figure 8. The effect of Bézier curve shape on flow unevenness

By selecting the value of P_2y that provided the best irregularity factor (the Bézier curve aligned more closely with the original cycloidal lamella as the P_2y value increased, so P_2y = 200 mm was used), we investigated how the new lamella geometry affected flow irregularities in relation to the particle-particle (Figure 9.) and particle-wall (Figure 10.) friction coefficient values.

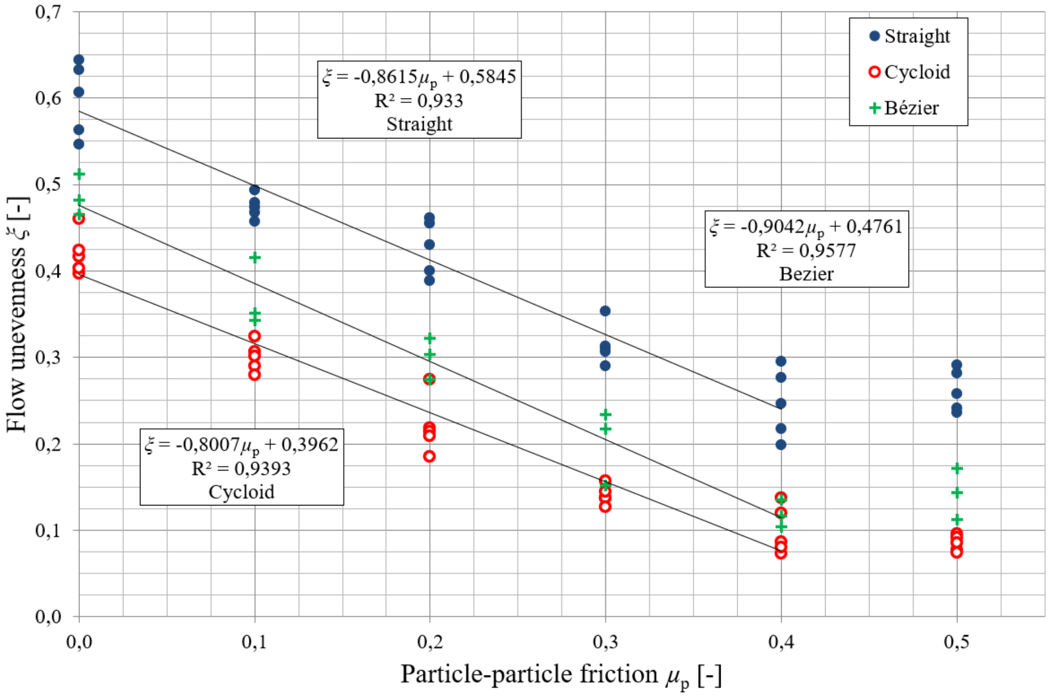


Figure 9. The effect of particle- particle friction on the flow unevenness in cases using straight, cycloidal and Bézier curve shaped lamellae

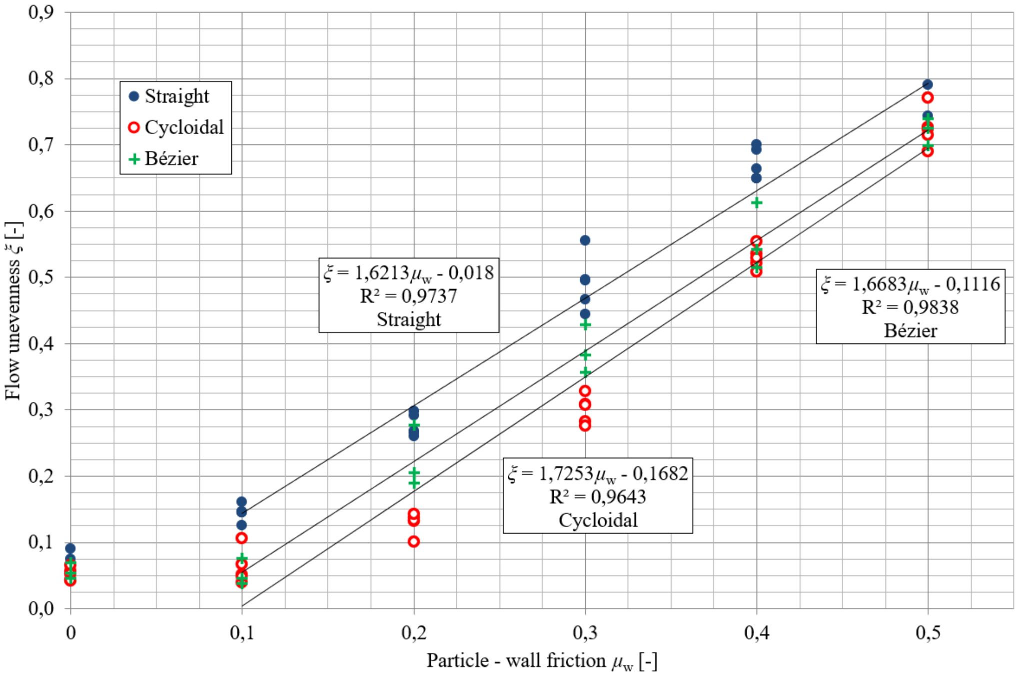


Figure 10. The effect of particle- wall friction on the flow unevenness in cases using straight, cycloidal and Bézier curve shaped lamellae

6. Conclusions

Reducing the moisture content (drying) of harvested grains is an essential step in preparing them for further processing or storage. Due to the high energy demand and potential environmental impact of artificial drying, it is crucial to perform this task as efficiently as possible. This article presents a method for improving efficiency by modeling the material flow processes in a gravity-based cross-flow drying system and modifying the design of the drying equipment. It identifies the mechanical phenomena responsible for quality degradation and material loss caused by under-drying or over-drying of grains and demonstrates how specific design modifications can minimize these issues. Based on theoretical considerations, the study proposes a lamella geometry that is easy to manufacture and significantly reduces the unevenness of grain movement within the dryer, thereby improving the quality of the final product.

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