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Study on the Effect of Drag Force on the Particle Motion of Coir Pith in Rotary Drying

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Abstract. This study investigates the effect of drag force on the free-fall motion of coir pith particles under varying moisture contents and particle sizes. Particle-air interactions play a vital role in drying efficiency. Understanding these dynamics is critical for optimizing rotary drying operations. The main objective was to analyze how moisture content affects the drag coefficient and velocity profiles of coir pith particles. A simple experimental setup was used, where particles of three average diameters and five different moisture contents were dropped from varying heights, and their fall times were recorded. Drag coefficients were estimated numerically using measured fall times and calculated velocities. The velocity-time profiles were analyzed to assess whether particles approached terminal velocity during the available fall distances. Results obtained indicate that increased moisture content leads to higher drag coefficients, which delays the attainment of terminal velocity. Additionally, drag coefficients increased with particle diameter. These results provide deep insights into particle-fluid interactions relevant to rotary drying.

Keywords: drag force, drag coefficient, coir pith, rotary drying, free fall

1 Introduction

Coconut is the third most important crop in Sri Lanka, making the country the fourth-largest global producer of coconut. Sri Lanka is also a significant coir fiber exporter, second only to India [1]. Coir pith is an organic waste byproduct of coir fiber extracted from the husks of coconuts, which is biodegradable and eco-friendly [1]. It is a light, spongy, lignocellulose fibrous material with natural chemical constituents [1], [2], [3], [4]. In modern research, coir pith has become an agricultural resource as a growth medium due to its high-water retention capacity, porosity, and fertility, because of the micro and macronutrient composition [2]. It is utilized as an adsorbent in water treatment [5], and soil conditioning, growing bags in the agriculture sector, due to their physical and chemical properties [6].

In rotary dryers, the moisture content of the coir pith decreases as it moves through the drying process. Coir pith particle motions in the rotary dryer depend mostly on the drag force and terminal velocity. Aerodynamic drag is one of the key forces affecting particle trajectories during drying. Understanding the changes in the moisture content of particles helps improve the accuracy of the drying process, as the air drag force on a particle is a major factor in the movement of particles [7]. Drag force is influenced by the relative velocities of the air and the particles, as well as the particles' shape, density, and moisture content. The drag force that the particles experience might vary significantly depending on the moisture level of the coir pith. Understanding effective forces is crucial for accurate prediction, including gravity, buoyancy, particle contact, electrostatic, and air drag forces. The variation between drag force and moisture content highlights the interdependence of these factors and the need for precise control and modeling in practical drying applications [8][9].

Additionally, substantial studies have examined the drying kinetics of coir pith, focusing on moisture content reduction through various drying technologies. Due to the complexity of measuring particle motion in real story dryers, simplified experimental approaches are often used.

Similar research on low-density objects has been conducted by Günther and Hoang [10], who investigated the feasibility of determining drag coefficients through free-fall experiments. Average drag coefficients for falling spheres were theoretically estimated and experimentally validated. This work supports the validity of using a simplified experimental setup to evaluate aerodynamic properties of low-density materials.

Bagheri and Bonadonna (2016) [11] proposed a drag coefficient model for freely falling non-spherical particles based on Reynolds number and simple shape descriptors like flatness and elongation. Their findings highlight those irregular particles in air exhibit random orientations, which are relevant to materials like coir pith, where drag force plays a key role in determining free-fall and drying trajectories.

Gorial and O'Callaghan (1990) [12] investigated the separation of grain from straw in a vertical air stream, focusing on how particle characteristics, air velocity, and injection direction affect separation efficiency. This research provides foundational insights into pneumatic particle separation techniques, which are highly relevant for materials such as coir pith, where aerodynamic behavior plays an important role.

Coir pith, a heterogeneous agricultural residue with particles of varying shapes, sizes, and densities, undergoes significant property changes during drying as moisture loss alters density and inter-particle interactions. However, the combined effects of particle size and moisture content on drag force remain poorly understood. This study addresses this gap by examining how these factors influence particle behavior, providing novel insights essential for improving simulation accuracy of particle motion in drying processes such as rotary drying.

The present study utilizes a free-fall experiment to isolate and analyze the effect of drag force on coir pith particles. The objectives of this research are to investigate the impact of moisture content on the drag force of coir pith particles during drying and to quantify the effect of drag force on falling coir pith particles by measuring the deviation from ideal free fall and extrapolating the findings to rotary drying conditions. This approach provides a foundational understanding of particle-air interactions and offers data that can be extended to computational simulations or empirical dryer optimizations

2 Materials and Methods

a. Materials

Fresh coir pith particles were obtained from the mill and oven-dried at 150 °C for 2 hours to facilitate sieving. The dried material was then separated by particle size using a sieve shaker. Specific amounts of water were added to adjust the moisture content of the particles to the desired levels. This study utilized coir pith particles with average particle diameters of 1.2 mm, 0.855 mm, and 0.355 mm, which were determined using sieve analysis. The particles were characterized by known bulk density, moisture content of 20%, 30%, 40%, 50%, and 60%. To simplify the aerodynamic modelling, particles were assumed to be spherical. Each practical involved a 5g sample, ensuring that individual particle behavior dominates over bulk effects.

b. Experimental setup

Experiments were conducted by releasing coir pith particles from 0.5 m, 1 m, 1.5 m, 2 m, and 2.5 m. A 5g sample was dropped for each experiment, and the fall time was recorded using a stopwatch. Three repetitive experiments were conducted for each height to ensure consistency and reduce human error. Average times used for the data analysis [10], [11], [13].

c. Data analysis

In this study, the motion of coir pith particles during free fall was analyzed. The drag coefficient was estimated for various particle sizes and moisture contents. Excel Solver was used to numerically determine the drag-related constant by minimizing the error between measured fall time and model-predicted distance, based on the analytical drag equation.

Drag coefficients were calculated using that estimated constant. This process was repeated for each particle size and moisture content condition. The particle velocities and their rate of change, dv/dt, are calculated using the constant value obtained. The effect of moisture content on the calculated drag coefficient was analyzed for each particle size.

A series of graphs were plotted with moisture content (%) on the x-axis and drag coefficient on the y-axis. Each graph represented one particle size and included multiple series corresponding to different fall heights. This allowed clear visualization of how the drag coefficient varies with moisture under free fall, as influenced by both particle dimension and fall distance.

d. Theoretical framework

In rotary drying systems, particles undergo complex motion involving cascading, rolling, and free-fall phases. Particles are subject to gravity and aerodynamic drag forces during free-fall phases. It is important to understand the drag force acting on a particle since it directly affects the particle's residence time and drying efficiency.

However, due to the dynamic and opaque nature of the rotary dryer, directly measuring drag under real conditions is challenging. A vertical free-fall experiment is conducted to simplify the analysis and isolate the effect of drag. Modelling the free fall of a particle under quadratic drag with a constant drag coefficient is used as the theoretical framework.

The following equation describes the motion of falling particles with mass m and no initial velocity [10], [14].

$$\frac{dv}{dt} = g - \Psi v^2$$

where g is gravitational acceleration and ψ is a lumped parameter defined as,

$$\Psi = \frac{\rho_{air} C_d A}{2m}$$

Here, ρ_{air} is the density of air, A is the projected area, and C_d is the drag coefficient. This equation can be analytically solved by assuming a constant drag coefficient C_d over the fall duration. The velocity as a function of time is then given below.

$$v(t) = \sqrt{\frac{g}{\Psi}}\tanh(\sqrt{g\Psi}t$$

Integrating v(t) yields the displacement equation as follows,

$$s(t) = \frac{1}{\Psi}\ln(\cosh(\sqrt{\Psi g}t))$$

Vertical descent of a particle falling under gravity and quadratic drag is modelled by these expressions. In the experiment, the known fall distances and measured fall times are used to numerically estimate ψ using Excel Solver. Once ψ is known, the drag coefficient C_d is calculated as follows,

$$C_d = \frac{2m\Psi}{\rho_{air}A}$$

This method, which is adapted from Günther and Hoang [10] allows estimation of an average drag coefficient over the fall period for low-density, spherical particles.

The main advantage of this approach is its simplicity and its ability to isolate drag effects in the absence of other interfering forces common in rotary dryers. Furthermore, the particle velocities and their rate of change, dv/dt, are calculated to determine whether terminal velocity was achieved during the fall.

Rotary dryers feature a repeated particle-free-fall phase because of their internal lifter flights [15]. The drag behavior observed in vertical drop experiments can be used as an analogue for drag-dominated motion segments in actual drying systems. Specifically, for varying particle sizes and moisture contents, the estimated drag coefficients help predict how particles of different properties respond to airflow during drying.

3 Results and Discussion

a. Effects of moisture content on velocity profiles

The velocity-time profiles of coir pith particles with different diameters under varying moisture contents have revealed distinct patterns in their free fall behavior. Across all particle sizes and moisture contents, the velocity increased over time but did not attain a constant velocity within the highest experimental drop height of 2.5m, indicating that terminal velocity was not attained. This is validated by the non-zero values of acceleration(dv/dt) at the final time points of all conditions as indicated in table 1 shown below. In a previous research study, the same pattern of graphs was identified as in Fig. 1, Fig. 2, and Fig.3 [16][13].

Notably, the acceleration values have increased with moisture content across all particle sizes. In the case of D=1.2mm particles, dv/dt has increased from 0.0036 m/s2 at 20% moisture to 0.0077 m/s^2 at 60% moisture. Similar trends were observed for D=0.85mm and D=0.35mm particles. This increment implies that higher moisture content delays the approach to terminal velocity, due to increased particle mass and inertia, which require greater air resistance before equilibrium is achieved.

Table 1. Acceleration of particles

dv/dt when H=2.5m			
MC%	**D=1.2mm**	**D=0.85mm**	**D=0.35mm**
20	0.0036	0.0025	0.0005
30	0.0037	0.0031	0.0019
40	0.0039	0.0034	0.0021
50	0.0070	0.0037	0.0033
60	0.0077	0.0038	0.0037

As moisture content is increased, particle mass increases significantly, while surface area remains relatively unchanged. Since the gravitational force(F_g=mg) becomes greater relative to the resistive drag force($F_d \alpha v^2 A$), a higher velocity is required for the drag to counterbalance gravity and obtain the terminal velocity. Thus, particles with higher moisture content experience a longer period to obtain the terminal velocity, and up to that point continue accelerating.

Importantly, these data show that the terminal velocity condition has not been met within the available fall distance where dv/dt=0. Future experiments should engage greater drop heights to allow particles to approach steady-state velocity.

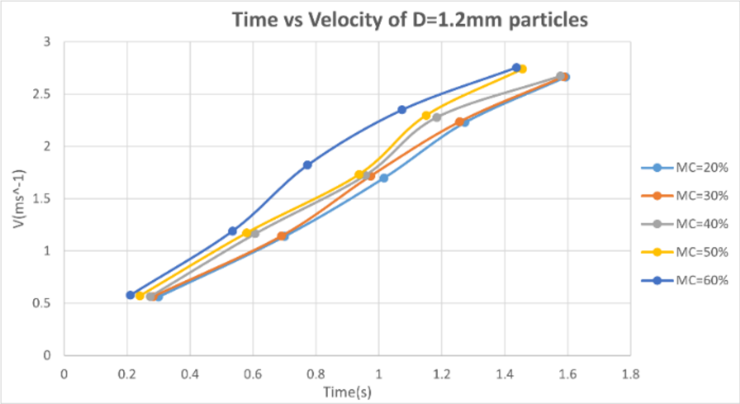

Fig. 1. Time vs Velocity graph for 1.2mm particle size

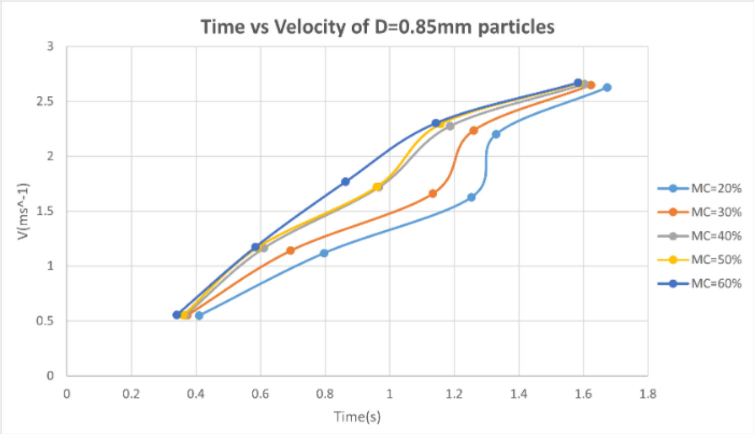

Fig. 2. Time vs Velocity graph for 0.85 mm particle size

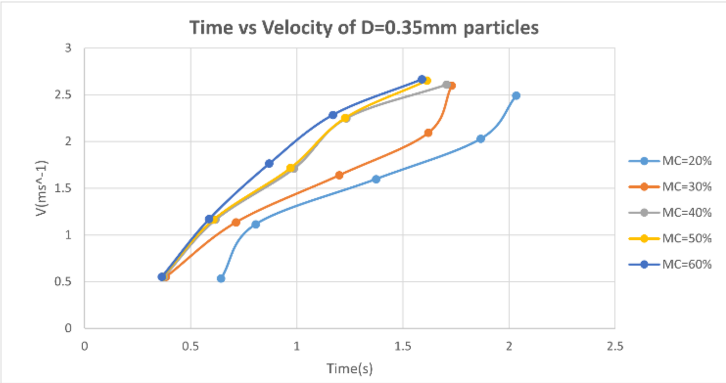

Fig. 3. Time vs Velocity graph for 0.35 mm particle size

b. Influence of moisture content on drag coefficients

The drag coefficient (C_d) of each particle size was analyzed as a function of fall distances and moisture contents. Across all distances, a consistent pattern has been developed. For a given height, the drag coefficient increases with moisture content as we can see in Fig 4, Fig 5, Fig6. These trends offer insights into the dynamics of particle-fluid interaction during free fall in still air.

The positive correlation between moisture content and drag coefficient at all drop heights is primarily due to increased particle mass without a proportional increase in projected surface area. Higher moisture particles generate greater gravitational force, which, for a given velocity, results in a higher calculated C_d. In addition, structural changes such as particle swelling, surface roughening, and aggregation may adjust the flow regime around the particles, increasing from drag. Overall, these results highlight that moisture not only affects mass and acceleration but also influences drag behavior and settling dynamics.

At lower drop heights (particularly 0.5 m), deviations from the overall drag trend were observed. These are primarily due to the limited time available for particles to accelerate and reach near-terminal velocity. In such cases, the particle's motion is still in the early transient stage, where velocity is low and the assumption of a stable flow regime does not hold. This can cause the model-fitting procedure to overestimate the drag coefficient to match the observed displacement. Furthermore, the short time intervals involved increase the sensitivity to timing errors, making the resulting C_d values less reliable at these heights.

Therefore, drag coefficients estimated from lower heights should be interpreted cautiously and are not as representative as those obtained from longer fall distances.

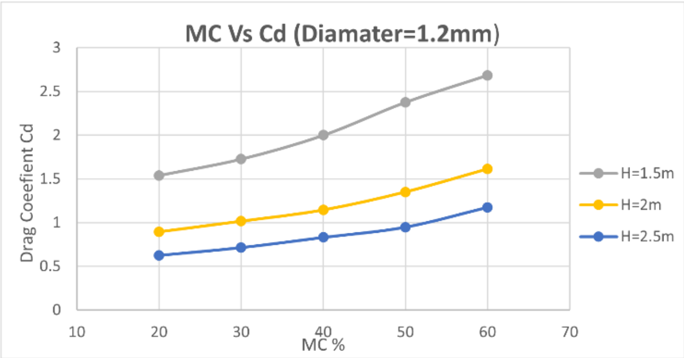

Fig. 4. Moisture content vs C_d graph for 1.2mm

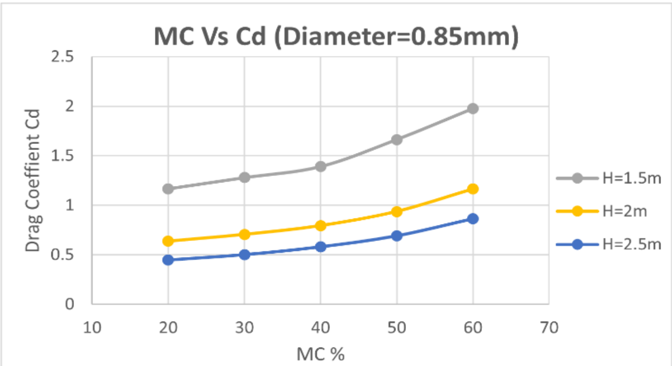

Fig. 5. Moisture content vs C_d graph for 0.85mm

c. Variation of drag coefficients with particle size

The C_d vs. diameter plots in Fig. 7 and Fig. 8 exhibit a general trend of increasing drag coefficient with particle diameter. Across all moisture content levels, larger particles consistently show higher C_d values compared to smaller ones. This can be attributed to elevated Reynolds numbers at larger sizes, as well as greater surface moisture retention, which may cause shape irregularities and increase the effective projected area.

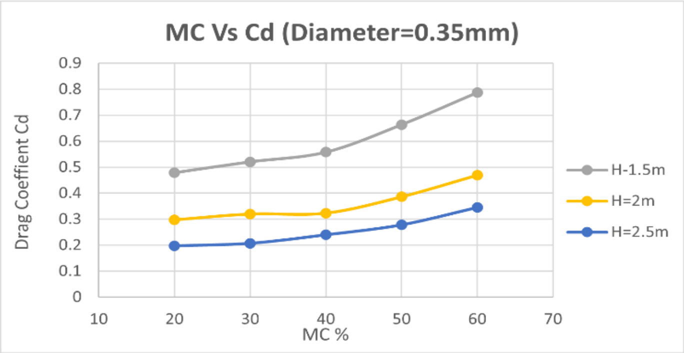

Fig. 6. Moisture content vs C_d graph for 0.35mm

Notably, this trend becomes more prominent at higher moisture contents, where moisture amplifies drag-inducing effects. Moreover, C_d values vary slightly between drop heights; for example, C_d is marginally higher at S = 1.0 m compared to S = 1.5 m for the same particle size and moisture level. This could be due to shorter fall distances allowing less time for particles to reach stable velocity, resulting in higher transient drag effects. These height-dependent variations highlight the importance of considering falling distance when evaluating drag behavior, particularly under variable moisture conditions.

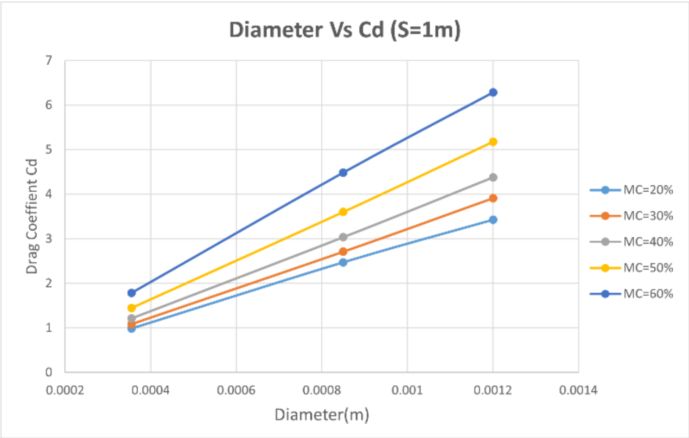

Fig. 7. Diameter vs C_d graph for 1m height

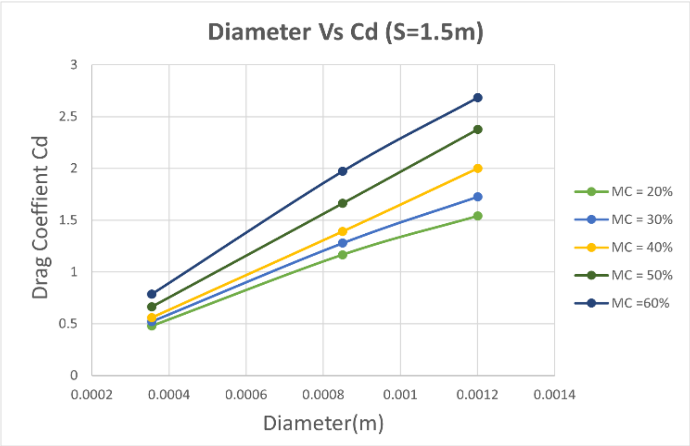

Fig. 8. Diameter vs C_d graph for 1.5 m height

d. Implications for rotary drying conditions

The trends observed for particle velocity and drag coefficient under varying moisture content and particle sizes have a direct impact on rotary dryer design and operation. High moisture content significantly slows down particle motion, requiring longer drying times and reducing thermal efficiency. Moist particles are likely to clump and slower settling. Smaller particles are more affected by moisture-induced cohesion, which increases their aerodynamic resistance and decreases drying uniformity.

Altering drum diameter or lifter design to increase fall height within the dryer can reduce drag, which helps to improve particle dispersion, enhancing heat and mass transfer. Drying systems must consider the combined effects of size, moisture, and dynamic behavior because of the increase in C_d with particle size under moist conditions.

Particle size and moisture content should be balanced for effective rotary drying operations to optimize flow behavior, residence time, and energy consumption. These findings support customized drying strategies based on material properties and process geometry [8].

4 Conclusions

This study quantitatively demonstrates the effect of particle size and moisture content on the aerodynamic drag of coir pith particles in free fall, providing insights directly relevant to rotary drying. Experimental results show that increasing moisture content from 20% to 60% raised drag coefficients (C_d) by 65–95% depending on particle size and fall height. On average, C_d increased by ~83% for 1.2 mm particles, ~70% for 0.85 mm particles, and ~73% for 0.35 mm particles.

Moisture also had a pronounced impact on acceleration. At 2.5 m drop height, the acceleration of 1.2 mm particles more than doubled (0.0036 → 0.0077 m/s²), while for 0.35 mm particles it increased nearly sevenfold (0.0005 → 0.0037 m/s²). This confirms that higher moisture content not only increases drag but also delays the approach to terminal velocity by amplifying particle inertia and aerodynamic resistance.

Larger particles consistently exhibited higher drag coefficients under moist conditions, highlighting a strong size moisture interaction. For rotary dryers, these findings imply that high-moisture particles resist airflow more strongly and settle more slowly, extending residence times and reducing drying efficiency. The observed ~5–7% increase in C_d per 10% additional moisture underscores the importance of accounting for moisture variability in dryer design and control.

Future work should extend drop heights to capture terminal velocity and apply computational fluid dynamics (CFD) to generalize these quantified findings to rotary dryer geometries.

References

1. J. A. K. M. Fernando and A. D. U. S. Amarasinghe, Drying kinetics and mathematical modeling of hot air drying of coconut coir pith, *Springerplus*, 5(1), Dec. 2016, doi: 10.1186/s40064-016-2387-y.
2. J. A. K. M. Fernando and A. D. U. S. Amarasinghe, Effects of retting and drying on quality of coir pith and coco discs, J Natl Sci Found, 45(1), pp. 3–12, 2017, doi: 10.4038/jnsfsr.v45i1.8032.
3. R. Rasheed, R. Raffik, B. Sabitha, and S. R. Karthickeyan, Induction Based Coir Pith Drying Machine, 2021. [Online]. Available: www.tjprc.org
4. P. Agarwal, S. Saha, and P. Hariprasad, Agro-industrial-residues as potting media: physicochemical and biological characters and their influence on plant growth, Jul. 01, 2023, Springer Science and Business Media Deutschland GmbH. doi: 10.1007/s13399-021-01998-6.
5. V. Jakka, A. Goswami, A. K. Nallajarla, U. Roy, K. Srikanth, and S. Sengupta, Coconut coir–derived nanocellulose as an efficient adsorbent for removal of cationic dye safranin-O: a detailed

mechanistic adsorption study, Environmental Science and Pollution Research, pp. 1–22, Aug. 2023, doi: 10.1007/S11356-023-29075-7/METRICS.

6. S. Alagendran, V. Prakash, J. Kavitha, R. Kamaleshwaran, P. Prabharan, and S. Alagendran, Effect of coir pith compost in agriculture, Journal of Medicinal Plants Studies, 9(4), pp. 106–110, 2021, Accessed: Aug. 30, 2024. [Online]. Available: www.plantsjournal.com
7. B. Matthew Waters, T. Yan, S. Celik, and J. Darabi, The Analysis and Optimization of an Industrial Countercurrent Flow Rotary Dryer, 2023.
8. M. H. Lisboa, D. S. Vitorino, W. B. Delaiba, J. R. D. Finzer, and M. A. S. Barrozo, A study of particle motion in rotary dryer, Brazilian Journal of Chemical Engineering, 24(3), pp. 365–374, 2007, doi: 10.1590/S0104-66322007000300006.
9. M. A. Karali, E. Specht, J. Mellmann, H. A. Refaey, M. R. Salem, and A. Y. Elbanhawy, Granular transport through flighted rotary drums operated at optimum-loading: Mathematical model, Drying Technology, 2019, doi: 10.1080/07373937.2019.1582062.
10. T. H. Günther and K. A. Hoang, Drag Coefficient Estimation of Low Density Objects by Free Fall Experiments, Annals of West University of Timisoara - Physics, 65(1), pp. 51–66, Dec. 2023, doi: 10.2478/awutp-2023-0005.
11. G. Bagheri and C. Bonadonna, On the drag of freely falling non-spherical particles, Powder Technol, 301, pp. 526–544, Nov. 2016, doi: 10.1016/j.powtec.2016.06.015.
12. B. Y. Gorial and J R O'callaghan, Separation of Grain from Straw in a Vertical Air Stream, 1991.
13. P. Gluck, Air Resistance on Falling Balls and Balloons, Phys Teach, 41(3), pp. 178–180, Mar. 2003, doi: 10.1119/1.1557510.
14. P. Timmerman and J. P. Van Der Weele, On the rise and fall of a ball with linear or quadratic drag, 1999.
15. K. R. Sunkara, F. Herz, E. Specht, J. Mellmann, and R. Erpelding, Modeling the discharge characteristics of rectangular flights in a flighted rotary drum, Powder Technol, 234, pp. 107–116, Jan. 2013, doi: 10.1016/J.POWTEC.2012.09.007.
16. R. Cross and C. Lindsey, Measuring the Drag Force on a Falling Ball, Phys Teach, 52(3), pp. 169–170, Mar. 2014, doi: 10.1119/1.4865522.