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ELEMENTS METHOD'S VALIDATION IN ORDER TO DETERMINATE SOYBEANS' FINAL VELOCITY

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Abstract. *The knowledge of grains' physical properties such as final velocity and dragging coefficient is important in the creation and development of tools used in post-harvesting. Experimental studies and numerical simulations are powerful assets in understanding and better predicting their behavior. This paper has four goals: a) To perform experiments in order to determinate the final fall velocity of soybeans. b) To determinate the dragging coefficient of soybeans. c) To incorporate the effects of grains' air resistance within DEM model. d) To validate DEM model for determination of soybeans' final fall velocity. In order to obtain data about final velocity, an experimental set was used to perform four different experiments using grains in different levels of humidity. The grain projection area was obtained through an image recognition algorithm and dragging coefficient was calculated through parameters measured in a laboratory. DEM was used and validated for simulations of soybeans final velocity determination. The outcomes obtained in the experiments and in the simulation show excellent compliance, even though considering soybeans in the simulations as spheres.*

Keywords: *Final Velocity, Dragging Coefficient, Discrete Element Method.*

1. INTRODUCTION

Improvements in conception and performance of machines and structures used in post-harvest operations require knowledge about physical properties and the dynamic behavior of the particulate materials. Experimental studies and numerical simulations are powerful assets in understanding and better predicting their behavior. Considering its discontinuous nature, the study of the transportation of particulate materials is supposed to need a discontinuous numerical method. The Discrete Element Method (DEM) is currently a method used to engage these problems (Fard (2000)).

Many processes to separate particles of different size and shape depend on variations of particles behavior when submitted to the action of a moving fluid. Knowledge about the aerodynamics properties of agriculture products, such as final velocity and dragging force, is significative in designing and operating equipment and structures used in operations like pneumatic and hydraulic transportation of a product and materials separation and classification (Polyak and Csizmazia (2010)).

In literature, there are diverse works where final velocity and dragging coefficient were studied in different types of grains, such as soybeans, corn, oats, wheat, lentil, sorghum seeds and even foods as potatoes and apples.

Gursoy and Guzel (2010) made a work which studied some physical and aerodynamics properties of wheat, barley, chickpeas, and lentil grains. The authors performed experimental sessions and theoric calculations in order to determinate final velocity and dragging coefficient of each grain and then confronted the respective data obtained. To determinate the theoric final velocity of these grains, were used equations corrected with a coefficient that considered the shape of each grain. As a result, the authors concluded that for all the types of grains the theoric final velocitys were inferior to the experimental values. To obtain dragging coefficient, calculations were made where the grains' orientation was varied. Consequently, its area of projection varied as well. The dragging coefficient was also calculated considering the grains as equivalent spheres. As expected, the authors verified that the dragging coefficient is strongly influenced by grain's orientation.

Rajabipour *et al.* (2006) studied the final velocity of three different wheat grains variations. In order to determinate final velocity, the authors performed fluidized bed experiments with wheat samples of different degrees of humidity, around 8%, 12%, 14%, 18%, 22%. As a result, the authors concluded that as the humidity degree is raised the final velocity of all wheat grain varieties raised as well. From data experimentally obtained, the authors also suggested a different equation for each type of grain variety where final velocity was written in function of humidity degree.

Ghamari *et al.* (2011) worked on a study that experimented with a fluidized bed in order to determinate the final velocity of chickpeas, rice, and lentil seeds. It used samples with different degrees of humidity. The results achieved by the authors show that the degree of humidity has significative effects on the final velocity of each one of the three tilth. The final velocity of the chickpeas grains, rice and lentil varied among 11.13 - 15.08, 4.25 - 5.01 e 5.08 - 6.41 m/s, respectively. It still suggested mathematical models to predict final velocity, which the shape of chickpeas, rice, and lentil, respectively were considered spherical, cylindrical and flat.

In some of the mentioned works and many others in the literature, mathematical models are developed to predict the final velocity of grains. It's usual for the authors of those works to make simplifications, for instance, to consider any type of grain a sphere through its geometrical diameter. However, it's known that in fact most of the agricultural products are bodies of irregular shape. Therefore, predicting the final velocity and dragging coefficient using traditional mathematical models is very difficult and probably will lead to results not reliable. According to **?** the final velocity of irregularly shaped grains cannot be theoretically calculated with enough precision so, it's best determined experimentally.

In the literature, there are basically two methods to find final velocity experimentally: the free fall method and the fluidized bed. The fluidized bed technique is the most known among researchers, which consists in submitting the grain material to an upward air flow until it begins to float. The air velocity needed for the grains to begin floating is considered the final velocity.

In free fall technique, the particle is let to fall only under the action of gravity. After this, height and fall timing are measured. The data obtained are used to final velocity calculation through the equation that follows (1):

$$y = \frac{v_\infty^2}{g} ln \left(cosh \left(\frac{gt}{v_\infty} \right) \right) \tag{1}$$

Where (y) is height (v) is final velocity, (g) is gravity and (t) is falling time. The objectives of this work are the following:

- To perform experiments to define the final velocity of soybeans grains;
- To define the dragging coefficient of soybeans grains;
- To incorporate within DEM the effects of air resistance on grains;
- To validate DEM model for defining final velocity of soybeans grains.

2. AERODYNAMIC FORCES

One of the objectives of this work is to incorporate within DEM the effect of air resistance on different types of grains. Originally, DEM considers only gravity as an active force. Thus, if the simulation of the fall of two particles of the same size and different densities (for instance, a steel sphere and a styrofoam sphere) would be performed, both would reach the ground at the same time instant, which in fact is different.

Dragging force is, by definition, an aerodynamical force which opposes the movement of a body through a fluid (air or water, for instance). Dragging is a force originated by the interaction and contact between a solid body and a fluid, which is generated by the difference between the solid body's velocity and the fluid's velocity, what demands movement between both. In case there is no movement, there is no dragging. Dragging is considered a friction force because it acts in the opposite way of the body in movement's velocity and therefore decreases its velocity (Williams (2016)). The aerodynamical dragging of an object depends on a few factors, including its shape, velocity relative to the fluid and dragging coefficient. The equation that allows knowing the dragging force acting upon a submerged body is defined by (2).

$$F_d = \frac{1}{2} C_d \rho_f A v^2 \tag{2}$$

Where F_d is dragging force, C_d is dragging coefficient, ρ_f is fluid's density, A is the are of projection and v is the velocity relative between the object and the fluid.

Besides dragging, another important aerodynamical property is final velocity. The knowledge of the final velocity is an essential information to the correct use of tools which use air flow to separate grains apart from impurities. According to Mohsenin (1986), final velocity can be described as a simple phenomenon. A body that falls freely inside a fluid, under the action of a constant force (gravity) undergoes the effect of acceleration during a short period of time. After this period, the acceleration stabilizes and the body's velocity becomes constant, reaching its maximum velocity, which is named final velocity.

As long as a particle falls, the dragging force increases and when the body reaches final velocity, the dragging force is going to be identical to the body's weight, thus: (3)

$$F_d = mg \tag{3}$$

where m is the particle's mass. Replacing (3) in (2), we have (4)

$$mg = \frac{1}{2} C_d \rho_f A v^2 \tag{4}$$

Performing the rightness mathematical manipulations, it comes to (5), which is the equation that defines the velocity of a body.

$$v_\infty = \sqrt{\frac{2mg}{\rho_f C_d A}} \tag{5}$$

And if equation (5) was rewritten in function of final velocity, it comes to equation (6)

$$C_d = \frac{2mg}{\rho_f A v_\infty^2} \tag{6}$$

This work aims to find in the more precise way possible the dragging coefficient of soybeans grains, in order to, after that, to include it and to validate it within DEM model for simulations of free fall. Thus, experiments were performed to define the final velocity of soybeans grains and after this, to find its correlative dragging coefficient.

3. MATERIALS AND METHODS

3.1 Final Velocity

To obtain data relative to soybeans grains' velocity, it was used the technique of fluidized bed described previously. An experimental aparatus was made that can be seen in figure 3.1

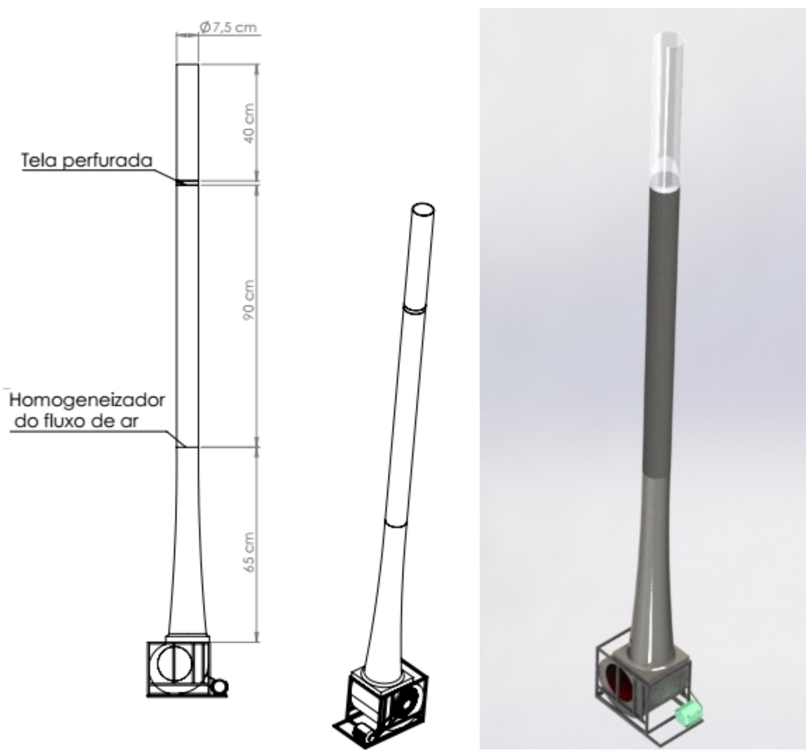

Figure 1. Schematic drawing of the equipment used to determine the final velocity.

The set is composed of a centrifugal fan connected to a PVC tube. On the top of the PVC tube was coupled a transparent acrylic tube, in order to make the grains visible once they undergo air action and float. On the bottom part of the transparent tube was linked a perforated net, where the grains were placed and on the top part of the acrylic tube was made the measurement of the air's velocity using an anemometer. The collection of data was made at the Laboratory for Physical Measures for Mathematical Modeling of the Regional University of the Northwest of Rio Grande do Sul (Unijuí).

3.2 Projection Area

Another important parameter that must be introduced in the equation (6) is projection area (A). This parameter is associated with the shape of particles. Grain, in general, have an irregular shape, what turns into a hard task to find this parameter with precision. Many researchers adopt the strategy of finding the equivalent diameter and to consider the grains as spheres. This is calculated using the three main axes of the grain, what can be seen in image 2.

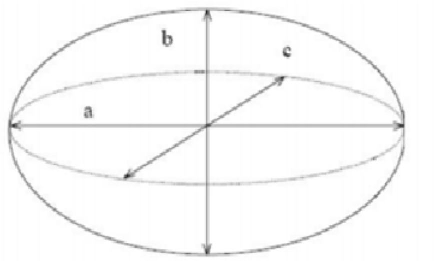

Figure 2. Characteristic dimensions of soy. Source:Weber (2005)

Considering a, b e c are the axes of the ellipsoid.

In this kind of simplification, the equivalent diameter (D_m) of each grain is calculated using the value of each axis measured using equation (7), as it follows:

$$D_m = \sqrt[3]{abc} \tag{7}$$

And the projection area is calculated using equation (8)

$$A = \frac{\pi}{4} (D_m)^2 \tag{8}$$

But some care in needed when using this kind of simplification, it can lead to considerable errors, for instance, in the case of grains that have low spherical shape, such as corn, oats or wheat.

In this work, the projection area of the samples was obtained by an image processing algorithm using the software Matlab. The process was performed as follows: first of all, the sample was placed on a flat surface. Then, it was photographed with a high-resolution camera. The image of the sample is introduced in the algorithm to the stage of pre-processing.

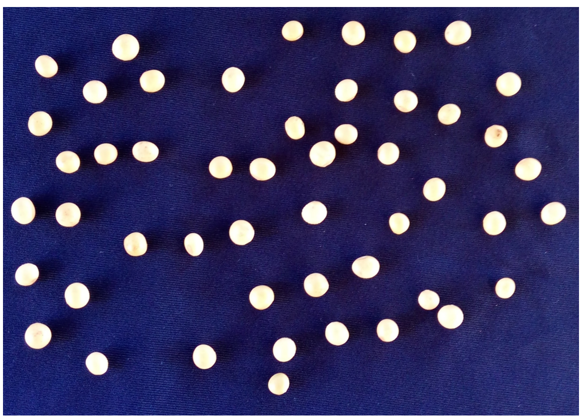

Figure 3. Sample of soybean grains.

The original image undergoes a process of segmentation. In this stage, the algorithm performs different tasks, such as: first, it smooths the gray tones, what is done to enhance the quality of the image. Then, it detects the borders, from which are extracted the geometrical characters of the grains. After this, it performs the stage of dilation of the outlines, which is used to enlarge shapes inside the image and to repair possible flaws, like discontinuities and weak outlines. Then, the algorithm performs the filling of the enlarged continued outlines and removes borders and discontinues outlines. The last segmentation stage is the removal of objects smaller than 700 pixels detected in the image. These objects could be identified but they could not be necessarily grains but some kind of intruders in the image. In figure 4 the original image is shown with the grains properly identified and numbered, finishing the grains recognition stage.

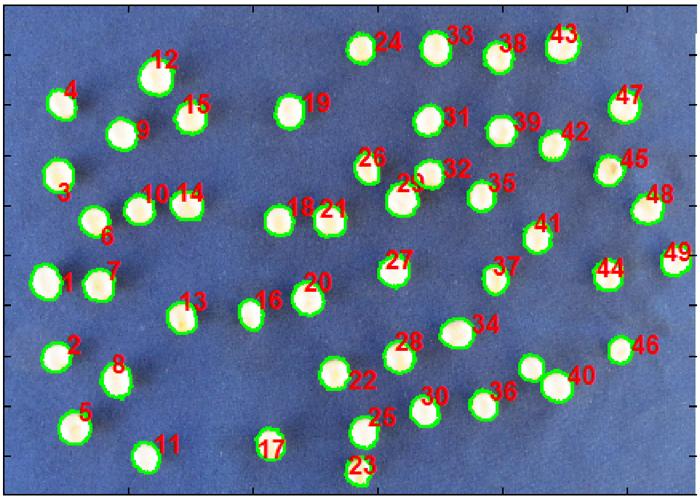

Figure 4. Soya beans identified

After the stage of image processing and grain recognition, the algorithm performs the calculation of the area of the identified grains. The areas' calculation is made as follows: from the outlines of the grain, the algorithm performs an adjustment of the curves using the method of minimal squares, adjusting the outlines to the shape of an ellipse, according to image 5.

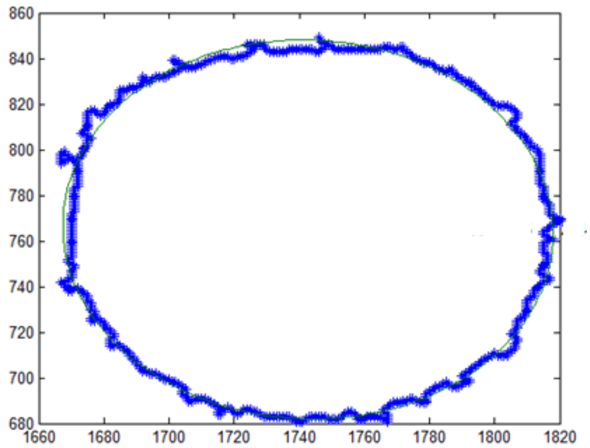

Figure 5. Projection area with curve fitting

On image 5 it is possible to distinguish the grain outlines (in blue) and the ellipse (in green) adjusted with the method of minimal squares. From the grains ellipses, it was calculated the average projection area of the samples.

3.3 Discrete Element Method

The Discrete Elements Method created by Cundall and Strack (1979) is a method of numerical simulation of the movement of a big number of particles. DEM is based on a numerical explicit scheme where the particles interaction is monitored individually. Each particle, designated as an element, is shaped by a body that is similar to its geometry. The most used geometry is the sphere, however, it is possible to shape an element through a combination of geometries, for instance, a set of spheres.

DEM is an interactive method. It considers a finite number of discrete particles interacting by means of contact forces and each piece of time is so small that, during a single period, the contacts cannot propagate from any particle until its immediate neighbors, which can be other particles or outlines elements. DEM's calculation is divided into two stages:

first, it is performed the calculation of the forces of contact and after this, the calculation of the movement of the particles is done using the Second Newton Law.

For every piece of time, DEM performs the following operations: a) determining collisions among elements; b) integration of forces for time (Second Newton Law); c) update of elements' positions.

The modeling of the particles' movements consists of the resolution of the Second Newton Law equation of movement through numerical integration. According to Luding (2008), the equations that govern translational and rotational movement of a particle are the following:

$$m_i \frac{d^2}{dt^2} r_i = f_i + m_i g \quad (9)$$

$$I_i \frac{d}{dt} \omega_i = t_i \quad (10)$$

Where m_i is the mass of particle i in kg; r_i is the position vector of the particle i in m; f_i is the resultant of all forces acting over the particle i in N, so that $f_i = \Sigma f_i^c$; g is the acceleration of gravity in ms^{-2}; ω_i is angular velocity in rad/s and t_i is the total torque in Nm.

To the execution of the computational simulations in this work, it was used the Yarde software (Yet Another Dynamic Engine) which has as foundation the discrete elements method, originally suggested by Cundall and Strack (1979). Yade software created by Kozicki and Donze (2008) is a project that uses the free software approach, licensed under GPL, and thus it has the possibility of expanding at a large pace as does the scientific community.

4. RESULTS AND DISCUSSION

To find the final velocity of soybeans grains, it was searched for the balance point of the sample in the acrylic column subjected to the action of air. The definition was visual and on the moment of balance the air's velocity was measured with an anemometer. Ten repetitions were executed to four different levels of humidity. In the following tables are presented the parameters values obtained in laboratory (projection area, final velocity and mass) and their respective dragging coefficient properly calculated with the equation mentioned from the data obtained. The samples were used with sixty grains each, in the following levels of humidity: 15, 18, 23 e 30%. Although the density parameter shown on the tables is not used in the equation (C_d) it must be used in free fall grains DEM simulations

To validate DEM in this work, grain free fall simulations were created to verify the grain final velocity. The experimental data and the simulated data were confronted. The entry parameters used in DEM simulations were the average values found in each experiment. For the DEM simulation the soybeans grain was shaped as a sphere and its radius was calculated from the average projection area.

In the first experiment executed, the soybeans grains samples had humidity of 15%. On table 1 it's shown their respective data after measurements.

Table 1. Soya bean experiment with 15% moisture

Repetition	$A\ (m^2) \times 10^{-5}$	$v_\infty\ (m/s)$	$m\ (kg) \times 10^{-4}$	C_d	Density (kg/m^3)
1	4.3534	12.4	1.9533	0.4494	870
2	3.976	13.3	1.9458	0.4427	1030
3	3.8219	13.1	1.8490	0.4511	1040
4	3.96	12,8	1.8067	0.4455	964
5	3.8947	13	1.8183	0.442	994
6	3.9530	12.7	1.7900	0.4492	957
7	3.9098	13.1	1.8761	0.4474	1020
8	3.9094	12.8	1.7955	0.4485	976
9	4.0619	12.7	1.8085	0.4417	983
10	4.1548	12.6	1.8226	0,4421	904
Average	3.9996	12.85	1.8466	0.44596	973,8
Standard Deviation	0.1549	0.271825	0.05994	0.003603	53.95
CV(%)	3.87490	2.11537	3.24608	0.80795	5.54038

In this image, it's shown the graphics of final velocity as function of time respective to the simulation with the average values of the first experiment.

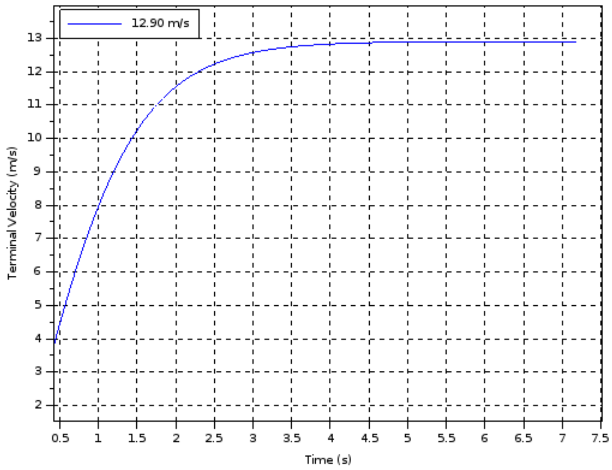

Figure 6. Final grain velocity with 15% humidity.

According to DEM simulation, the final velocity of soybeans grain with the average values from table 1 was 12.9 m/s, which was very similar to the experiments average value of 12.85 m/s.

The second experiment was conducted with soybeans samples with humidity of 18%. On table 2 their data are shown.

Table 2. Soya bean experiment with 18% moisture.

Repetition	$A\ (m^2) \times 10^{-5}$	$v_\infty\ (m/s)$	$m\ (kg) \times 10^{-4}$	C_d	Density (kg/m^3)
1	4.3556	13.3	2.1993	0.4567	1017
2	4.0546	13	1.9680	0.4595	1013
3	4.0368	13.2	2.0369	0.4634	1057
4	4.0292	13.1	2.0077	0.4646	1043
5	3.9274	13.2	1.9445	0.4546	1050
6	3.7720	13.3	1.8803	0.4509	1079
7	3.9842	13	1.8750	0.4455	1225
8	3.8705	13	1.8595	0.4584	1026
9	4.2610	12.8	1.9576	0.4487	935
10	4.1131	12.9	1.9167	0.448	965
Average	4.0404	13.08	1.9646	0.46	1041
Standard Deviation	0.173357	0,168655	0.100614	0.006611	77.63
CV(%)	4.290538673	1.28941	5.121478539	1.452822	7.457269684

The graphics on the computational simulation relative to the data on table 2 is presented as follows.

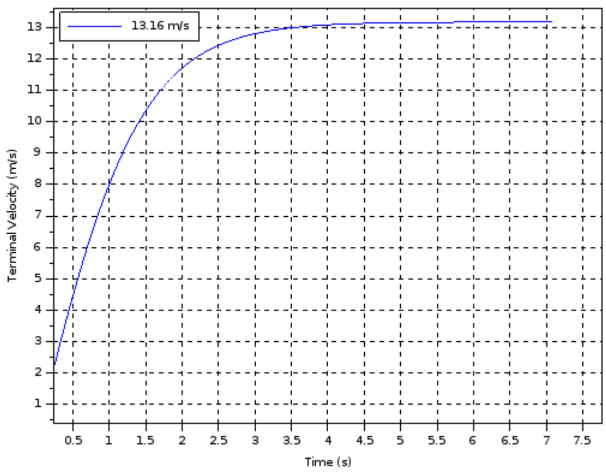

Figure 7. Final grain velocity with 18% humidity.

According to this image it is possible to observe that the final velocity achieved by the grain was 13.16 m/s. Once again the DEM simulation has shown good agreement in the experiments executed.

In the third experiment the soybeans grains samples had a level of humidity of 23%. The data referring to the ten repetitions are shown on table 3.

Table 3. Soya bean experiment with 23% moisture.

Repetition	$A\ (m^2) \times 10^{-5}$	$v_\infty\ (m/s)$	$m\ (kg) \times 10^{-4}$	C_d	Density (kg/m^3)
1	4.5082	13	2.1500	0.4515	944
2	4.6152	12.7	2.1250	0.4568	900
3	4.2782	12.9	2.0210	0.4542	960
4	4.1157	13	1.9783	0.4551	996
5	4.3848	12.8	2.0050	0.4465	917
6	4.1649	12.9	1.9783	0.4567	978
7	4.1067	12.8	1.8843	0.4481	951
8	4.7753	12.2	1.9667	0.4427	792
9	4.1123	13.1	2.0033	0.4542	1008
10	4.0079	12.8	1.8777	0.4575	983
Average	4.3069	12.82	1.9990	0.45233	942,9
Standard Deviation	0.25515	0.248551358	0.08755	0.005009	62.83921281
CV(%)	5.9243	1.938778147	4.3798	1.107304	6.664

In this simulation, where the grain had 23% of humidity, the value of experimental final velocity presented the smallest discrepancy, once the maximum velocity on DEM was 12.83 m/s and the average experimental was 12.82 m/s.

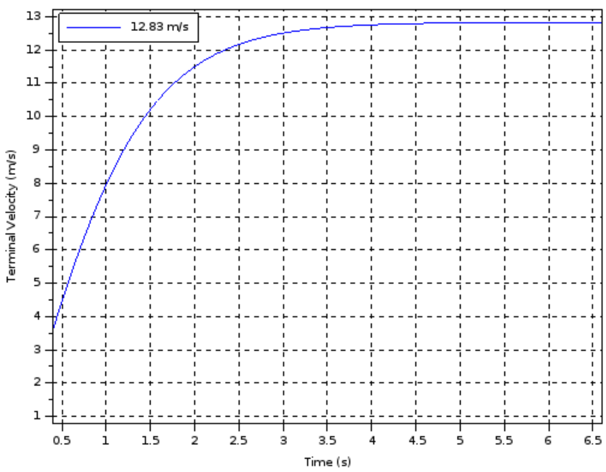

Figure 8. Final grain velocity with 23% moisture.

In the fourth and last experiment, the samples had the level of humidity of 30%. In the next table it is possible to verify its data.

Table 4. Soya bean experiment with 30% moisture.

Repetition	$A\ (m^2) \times 10^{-5}$	$v_\infty\ (m/s)$	$m\ (kg) \times 10^{-4}$	C_d	Density (kg/m^3)
1	4.6541	12.9	2.1970	0.4539	919
2	4.5866	12.9	2.2142	0.4642	947
3	4.7125E	12.8	2.2388	0.4639	919
4	4.6070	12.9	2.2124	0.4617	940
5	4.7661	13	2.2475	0.4464	908
6	4.4671	13.1	2.2300	0.4654	992
7	4.8623	13	2.3770	0.4628	932
8	4.9561	13.1	2.3816	0.448	907
9	4.6536	12.9	2.2323	0.4612	934
10	4.5024	12.8	2.1195	0.4597	932
Average	4.6768	12.94	2.24503	0.45872	933
Standard Deviation	0.15279	0.107497	0.0792886	0.006864207	24.54474372
CV(%)	3.27	0.830732	3.531740314	1.496382691	2.630733518

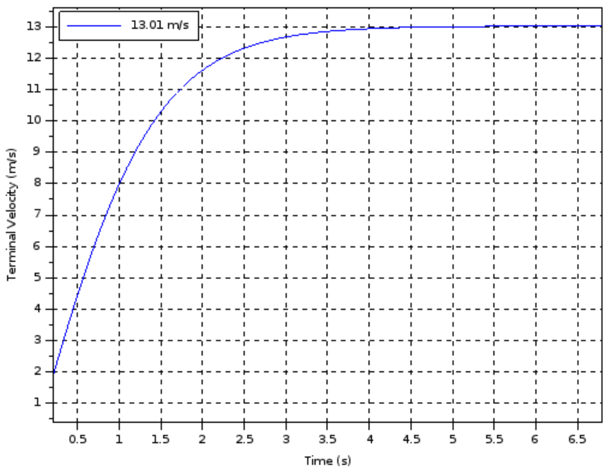

Figure 9. Final grain velocity with 30% humidity.

In the last DEM simulation, the final velocity of soybeans grains with humidity of 30% was 13.01 m/s. This value also is similar to the average value obtained in its respective experiment which was 12.94 m/s.

According to the graphics presented, it was possible to observe that the grain has upward velocity up to 4 seconds of free fall. From so on, the velocity increases slowly until it reaches the final velocity. The four comparative analyses among experiments and simulations show excellent agreement. Thus, it is possible to state that DEM is a very useful tool in defining final velocity of soybeans grains, though considering them as a spherical particle.

5. CONCLUSIONS

In this paper was developed an experimental study and computational validation of obtaining final velocity and dragging coefficient of soybeans grains using the Discrete Elements Method. The ability of this model to predict final velocity of this kind of grain was tested through a procedure of validation, confronting the results obtained experimentally with the data simulated. An experimental set was put together where four experiments with different levels of humidity were executed. In each experiment 10 repetitions were made using samples of 60 grains. The experiments had the goal to define final velocity and then to define the dragging coefficient of the samples.

After confronting the data from the experiments with the data from the simulations it is possible to conclude that DEM can be used to estimate the final velocity of soybean grains, and, besides, other conclusions can be mentioned:

- Yade software simulates correctly the final velocity of soybeans grains in different levels of humidity;
- The soybeans grain can be modeled as spheres achieving good results;
- As expected, as the level of humidity in the experiments was increased so the average projection area and masses also increased;

- The soybeans samples have different final velocities, varying between 12.2 m/s and 13.3 m/s, considering that a fact observed in this difference is the grain density;
- The dragging coefficient of soybeans calculated with the experimental final velocity and with the other parameters measured in the laboratory was about 0.4417 and 0.4654.

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