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Experimental Study of Aerodynamic Behavior of Coffee Fruits (Coffea Canephora) During Drying

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Abstract: *Knowledge of aerodynamic properties in agricultural products is of vital importance. In order to design efficient equipment for the harvesting and post-harvesting of coffee, it is necessary to know its aerodynamic behavior. For this reason, a subsonic wind tunnel was used to determine its behavior during the drying phase of different coffee clones. For the study, samples of conilon coffee (Coffea canephora) were used in different stages of maturation clones 83 and 74 of the clonal variety EMCAPA 8141 and clone 31 of the clonal variety EMCAPA 8131. The samples were placed like cluster in the test section of the tunnel to obtain the drag coefficient. The terminal velocity of each of the samples in vertical wind tunnel was also determined. With this study, the terminal velocity and the drag coefficient of each of the clones were determined at different moisture values. The results found were more accurate than the models reported in the literature. With this information, it was possible to find a common model of the aerodynamic behavior of the coffee beans for when it is necessary to process them together.*
Keywords: *Aerodynamic properties, Coffea canephora, drag coefficient.*

I. Introduction

The aerodynamic principles have been used by various researchers in applications such as separation of foreign materials seeds and grains; pneumatic conveyors and handling of grain, cut forage, silage and small and large fruit; and hydraulic handling apples, cherries and potatoes [1]. In aeration and drying of agricultural products, such as grain, the static pressure that the fan has to overcome depends on the airflow rate, grain layer thickness, type, shape, size and orientation. The previous variables affect the drag coefficient of the material and its resistance to flow [1]. Knowledge of the aerodynamic properties of agricultural products, the terminal velocity and drag coefficient are of fundamental importance in the design and sizing of equipment and structures, especially in harvesting operations and post-harvest of these products. Much of this equipment uses air or water to carry or separate the desirable product and quality of impurities or inferior materials, especially in harvesting operations, selection, cleaning, drying, storage, processing and classification of the product. This information can be also widely used in the improvement of operations related to the handling and the various stages of pre-processing the material. The separation of seeds may carried out by pneumatic separators, fabric cleaners or using gravity tables [1].

Many commercial cleaners incorporate more than one of these cleaning methods [2]. Pneumatic separation and transport systems are used in the agricultural machinery and equipment to process food for many years.When an airflow is used to separate a product such as wheat associated with undesirable materials, knowledge of aerodynamic characteristics of all the particles involved is necessary. This helps to define the range of air speeds for effective separation of undesirable material grain. Therefore, the terminal velocity (TV) was used as an important aerodynamic characteristic of materials in applications such as pneumatic conveying and separation of unwanted materials [2]. When beans are harvested, seeds, fruits and vegetables mechanically undesirable materials such as lighter grains, weed seeds, plant leaves and stems may be removed with air. Moreover, materials are transported agricultural and food products using commonly air and water. For operations, such as the interaction between solid particles and fluids in motion determine the forces applied to the particles. This interaction is affected by the density, viscosity and velocity of the fluid.The determination of terminal velocity of bodies, based on expressions that relate the drag coefficient (C_D) and the Reynolds number (Re), has been extensively investigated by several researchers [3]–[10]. The determination of terminal velocity through any of these equations proposed for "C_D versus Re" requires a trial and error procedure, since the speed is present in both variable and the relationship between "C_D and Re" is highly nonlinear. Shape, size, orientation, middle viscosity and the density of the particle and the fluid, influences the terminal velocity and drag coefficient of a particle. The semi-empirical models developed to predict drag forces on bodies immersed in a fluid, largely considers the particles having a spherical shape, although the particles involved in engineering processes have not, in most cases, this form. Currently, it is possible to estimate the drag forces or terminal velocity of a spherical particle under most conditions of practical interest in an incompressible Newtonian medium. However, when it comes to non-spherical particles, the lack of standards for measuring the shape, size and orientation while floating, according to Chhabra et al. [8], it has been a major obstacle to achieving suitable models for predicting drag forces and developing universally applicable correlations. Chhabra et al. [8] investigated the effectiveness of correlation most commonly used to estimate the coefficient of drag of non-spherical particles in viscous incompressible fluid. The authors found that the influence of particle shape on the drag coefficient increases with Reynolds number and that the best estimates of this magnitude could be obtained only if parameters relating to particle shape were added to correlations.

Afonso Júnior et al. [11], studying the aerodynamic properties of Arabica and Conilon coffee. They determined the terminal velocity experimentally by Mohsenin method [1] and obtained errors ranging from 27.75% to 52.58% for Arabica coffee. Regarding Conilon coffee, the error was obtained in the range of 33.55% to 47.31%. Zanini et al. [12] experimentally studied the aerodynamic behavior of maize and beans, determining the terminal velocity according to Pettyjohn and Christiansen [13] and Mohsenin [1]. The authors determined the errors cited by the methods and obtained the error around 30.83% to 73.23% for corn, and 31.26% to 40.34% for beans. Simplicio and Braga [14] used various methods for determining aerodynamic parameters of peanuts, which compared with values of terminal velocity differ significantly. In this context, the errors obtained by Mohsenin method [1] was 72.88%, while the method of Pettyjohn and Christiansen [13] was 37.85%. In relation to assume the drag coefficient of a sphere, the difference was 24.05%. Several researchers conducted aerodynamic tests with different agricultural products and reported to be the terminal velocity function of moisture content, namely sorghum and millet [15], wheat [16], pistachios [17], wheat, barley and lentils [18], linseed [19], grape [20], among others. Because of this problem, it is important to study the aerodynamic behavior of Conilon coffee fruit clones experimentally in order to find the model that best represents the physical phenomenon.

II. Material and Methods

This work was performed in the Laboratory of Physical Properties and Quality Evaluation of Agricultural Products of National Storage Training Center (CENTREINAR), located in the Federal University of Viçosa campus, Viçosa, MG, Brazil.It was used the coffee fruits (Coffea canephora) clones 83 and 74 the clonal variety EMCAPA 8141 and clone 31 of the clonal variety EMCAPA 8131, from the experimental farm of Agricultural Research of Minas Gerais (EPAMIG), located in the Leopoldina city , Minas Gerais. The fruits were harvested manually and only selected the two stages, cherry and green of each clone. During the process of harvesting immature fruits, deteriorated or damaged were eliminated, in order to obtain a homogeneous and better quality material, moreover, coffee fruits with the above size 9 mm sieve holes are used.Subsequently the different batches of coffee were drying in an oven with forced ventilation with air temperature of approximately 60 ± 3 ° C until different levels of water content. The monitoring of the reduction of water content in the course of drying time, was carried out by gravimetric (loss of weight), knowing the initial moisture content of the product. For this monitoring was used an analytical balance accurate to 0.01g. Moisture content of the product were determining by the oven method, 105 ± 3 °C to constant weight in three repetitions [21].During drying, obtained for each water content, samples were homogenized and submitted for determining the aerodynamic properties, in triplicate.

2.1 Determination of Terminal Velocity

In the experimental stage, we used a vertical column to obtain the terminal velocity of coffee fruits, using a device consisting of a centrifugal fan coupled to a transparent acrylic pipe (Figure 1). The sample of coffee fruits were arranging in a screened compartment, being subsequently subjecting to an airflow controlled by a frequency inverter until the moment that the grain stay afloat.Three replicates were made, and the measurements of speed are two (0° and 90°) for each. The speed was measuring with hot wire anemometer before the fluid passing through the screen where the beans were.

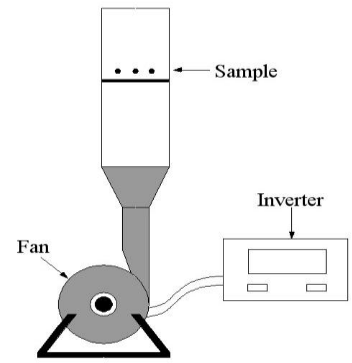

Figure 1 - Schematic device used for determining the terminal velocity.

2.2 Determination of Drag Coefficient

It was used a horizontal wind tunnel, subsonic, at speeds in the range 0 to 14 m/s, located at the Department of Production and Mechanical Engineering (DEP), for studying the aerodynamic behavior of coffee fruits (Figure 2). The tunnel has a transparent test section of 20x20x20 cm that allows locating the object under study, besides allowing observing the aerodynamic behavior. In this tunnel can be determine the drag force on each grain or a cluster of grains in various configurations for different speed values. Knowing the drag force and other properties of the grain can determine the drag coefficient.

Figure 2 - Wind tunnel used for determining the drag coefficient.

Due to restrictions related to the sensitivity of the tunnel, it is not possible to determine the drag force on a grain. In order to solve the unexpected, there was the experiment with a group (cluster) of coffee fruits, as shown in Figure 3. The coffee fruits were glued arrangement 4x5x3 (width x height x depth), with the intention of them get as close as possible in relation to the form showing in Figure 3. To fix the cluster coffee fruits to tunnel test area had to paste these to a thin aluminum plate with a screw in the center, allowing screw it to the tunnel of the power scale (Figure 4).

Figure 3 - Cluster of coffee fruits (4x5x3 fruits).

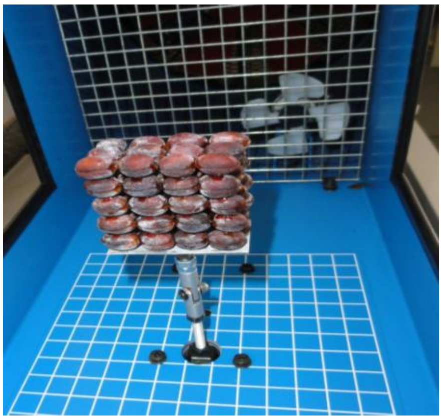

Figure 4 - Coffee fruit cluster in wind tunnel test section.

The drag coefficient was determining by the equation 1, applied to porous media.

$$C_d = \frac{2\,F}{\rho\,A\,v^2}\,\frac{V}{L\,A_c\,(1-\varepsilon)} \tag{1}$$

where:
Cd: Drag coefficient (dimensionless);
F: Drag force (N);
ρ: Air density (kg m^{-3});
A: Cross-grain area (m^2);
v: Air velocity (m s^{-1});
V: Grain volume (m^3);
L: Cluster depth (m);
Ac: Cross area group (m^2); and
ε: Porosity (dimensionless).
The experiment was carried out by mounting three groups (cluster) of coffee fruits for each moisture point studied. The drag force was obtaining with Aerotek program that accompanies the wind tunnel (Figure 5).

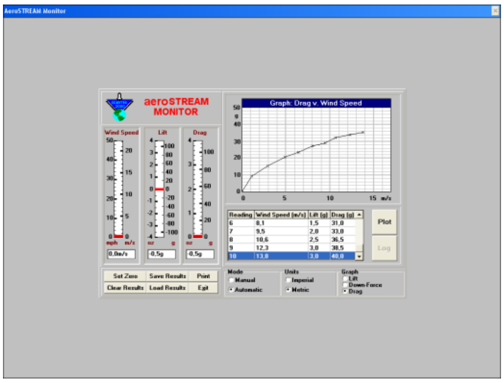

Figure 5 - Wind tunnel Aerotek program screen.

Wind tunnel walls limit the flow of an object, so it is necessary to correct the obtained data. The correction is required because of the flow acceleration near the object to satisfy continuity requirements (solid block). For the few aerodynamic flow over the solid block bodies effects on measured data can be very remarkable. The problem becomes even more serious when it is necessary templates for reasons of similarity or the dimension accuracy [22].
To correct the solid block was applied to Maskell´s correction [23] (equations 2 and 3).

$$\frac{q_c}{q} = \left[1 + \frac{5}{2} C_{Dexp}\left(\frac{A_c}{A_T}\right)\right] \tag{2}$$

$$C_D = \frac{C_{Dexp}}{\left({}^{q_c}/_{q}\right)} \tag{3}$$

where:
qc: Corrected dynamic pressure, Pa;
q: Dynamic pressure without correcting, Pa;
C_D: Drag coefficient;
C_{Dexp}: Experimental drag coefficient;
A_T: Cross area of the tunnel test section, m^2; and
A_c: Body Area, m2.

2.3 Statistical Analysis

The experimental data of variation of the water content, the terminal velocity and the drag coefficient were subjecting to regression analysis (equations 4 and 5). Furthermore, it was making the selection of the appropriate model to express the relationship between variables.

Linear regression model:

$$Y_i = f(X_i, \beta) + \varepsilon_i \tag{4}$$

where:
X_i: The vector of observations of the predictor variables for the i^{th} case;
β: The vector of parameters;
$f(X_i, \beta)$: Represents the expected value $E(Y_i)$; and
ε_i: Errors.

Non-linear regression model:

$$Y_i = f(X_i, \gamma) + \varepsilon_i \tag{5}$$

where:
γ: The vector of model parameters; and
$f(X_i, \gamma)$: A nonlinear function, is the expected value $E(Y_i)$.

The models were selecting considering the magnitude of the coefficient of determination (R^2), the magnitude of the mean relative error (P) and standard estimate (SE) error. The average relative error and the standard deviation of the estimate for each of the models were calculating according to equations 6 and 7:

$$P = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{|Y - \hat{Y}|}{Y}\right) \tag{6}$$

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(Y - \hat{Y})^2}{GLR}} \tag{7}$$

where:
Y: Value observed experimentally;
Y: Value estimated by the model;
n: Number of experimental observations; and
GLR: Degrees of freedom model (number of observations minus the number of model parameters).

There was the identity test of models described by Regazzi [24] in order to evaluate the possibility of a single equation represent the behavior of the variables studied. For each variable were tested all combinations representing various grouping possibilities among the studied clones, as well as the maturation stage (Table 2). The identification of equality or difference between the clones and maturation, in relation to modeled variables was performing through comparison between the square sum of the residuals for each variable in each stage, or clone (full model). The sum square of the difference to the adjusted model with a single database containing all the information clone or clones (reduced model). Whenever the calculated value of F is greater than or equal to the tabulated value of F means that the test was significant at a probability level ($\alpha = 1\%$) preset. In this case, it rejects H_0, i.e., the total sum of squared residuals for each variable in each stage, or clone (full model) differs statistically from the sum of the difference squared to the adjusted model for the whole total data for each variable (reduced model). Otherwise, if accepts H_0, or can use a single model to estimate the variable studied for clone or group of clones.

Table 1 - Combinations representing the various clustering possibilities among the clones studied.

Clonal Variety	Clones	Stages	Combination
EMCAPA 8141	83	Green vs Cherry	1
EMCAPA 8131	31	Green vs Cherry	2
EMCAPA 8141	74	Green vs Cherry	3
All	All	Mixed	4

III. Results and Discussions

The terminal velocities were indicating for each coffee clone in each of the maturation stage. Figure 9 show the behavior of the terminal velocity of green and cherry coffee fruit for clone 83, decreasing non-linearly with drying.

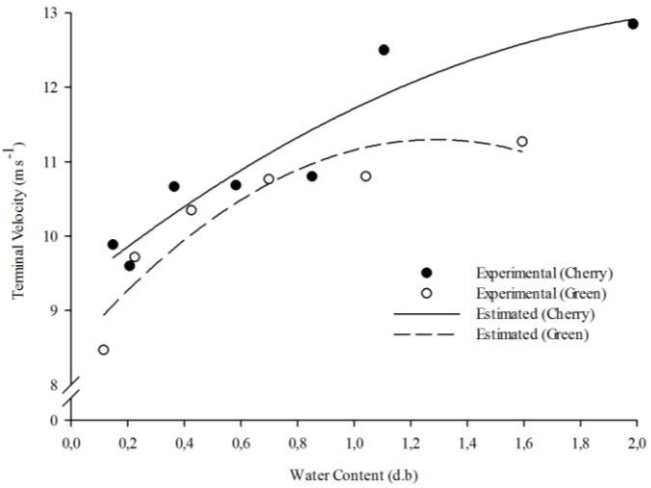

Figure 9 -Terminal velocity behavior during the drying clone 83 (green and cherry).

Figures 10 and 11 illustrates the behavior of the terminal velocity of clones 31 and 74. Such behavior is similar to clone 83, decreasing non-linearly with decreasing water content. This performance is directly related to the behavior of the density, as it advances the drying has increased in the first instants of drying; therefore, there is an increase in speed to ensure the floating of the coffee fruit in the airflow. The lower terminal velocity was found to be 8.47 m s^{-1} for green clone 83 and the highest was 12.87 m s^{-1} for cherry clone 74.

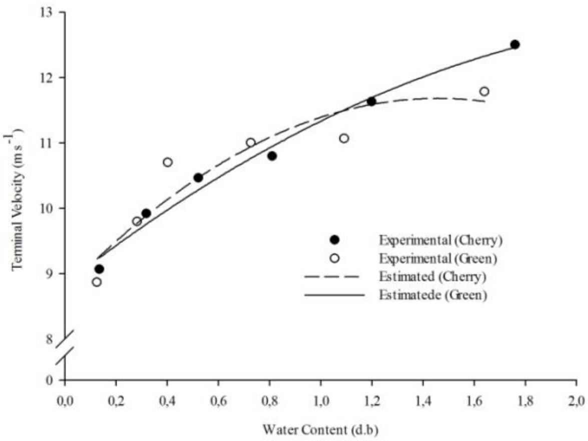

Figure 10 - Behavior of terminal velocity during drying of clone 31 (green and cherry).

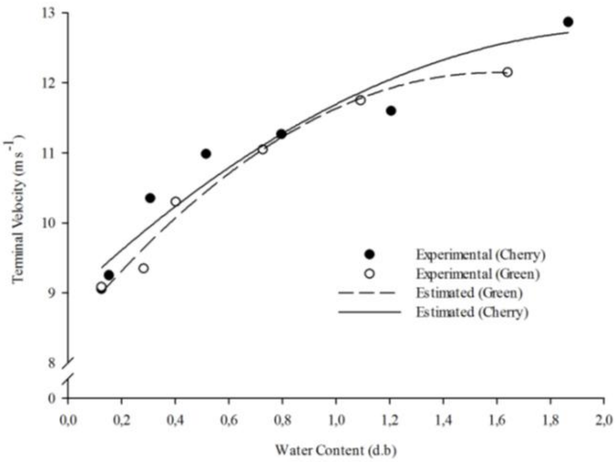

Figure 11 - Behavior of terminal velocity during the drying clone 74 (green and cherry).

Table 2 registers the summary of the nonlinear regression models best fit for each green and coffee cherry conilon clone. In this case, the two-degree polynomial model presented the best fit in all cases the experimental data. The lower coefficient of determination was to clone 83. This value can be explained by the degree of ripeness of this clone to be less uniform in all clones studied. There is, in the previous figures, increasing trend of the dependent variable values terminal velocity with increasing water content, for both the products analyzed, and this behavior the same found in other agricultural products [1], [15]–[18], [20], [17]. Possibly this increase is due to changes in the physical characteristics of the product, especially in weight range, area and volume, with the loss of water. This confirms the expectation that the increased presence of water in the formula contributes decisively to the direct change in the relationship between the mass and volume of the fruit, in order to increase the values of terminal velocity.

Table 2. Nonlinear regression models for each green and cherry Conilon coffee clone.

Clone	Phys. Prop.	β_o	β_1	β_2	R^2
83 cherry	V_T	9.2667	3.0697	-0.6207	0.8880
83 green	V_T	8.4521	4.4239	-1.7186	0.8756
31 cherry	V_T	8.8372	3.0681	-0.5734	0.9844
31 green	V_T	8.7393	4.0403	-1.3864	0.8794
74 cherry	V_T	8.9150	3.6351	-0.8562	0.9354
74 green	V_T	8.4343	4.6647	-1.4657	0.9823
All (Common)	V_T	8.9036	3.3066	-0.7774	0.8654

Table 3 is a summary of the identity test performed on models previously recorded in Table 2, which was determined to be possible to use a common model representing the behavior of the terminal velocity during drying. The study was conducting for a 1% significance level, where if the value of F (calculated) is greater than F (tabular), the test is significant, ie, reject H_0. Thus, the sum of squares of the residuals from each clone was statistically different from the sum of squares of the residuals made for the entire set of data. When the test occur otherwise is not significant, and then accept H_0. In all cases, the calculated value of F is less than the tabulated for alpha equal to 1%, which means it is possible to use common pattern recorded in Table 3.

Table 3 - Results of the identity test for terminal velocity in all combinations studied.

Comb.	Phys. Prop.	Parameters of the model			F_{calc}	F_{tab}	Test
		β_0	β_1	β_2			
1	V_T	9.0725	2.8781	-0.6027	3.04	8.451	NS
2	V_T	8.8414	3.3330	-0.8339	0.83	9.779	NS
3	V_T	8.7624	3.8489	-0.9808	0.68	8.451	NS
4	V_T	8.9036	3.3066	-0.7774	0.33	3.499	NS
NS = Non-significant F-test at 99%.							

In Figure 12, we observe the given common format by the identity test. Similar behavior can be observed to those reported by Couto et al. [25] and Afonso Junior et al. [11] for different varieties of Arabica coffee.

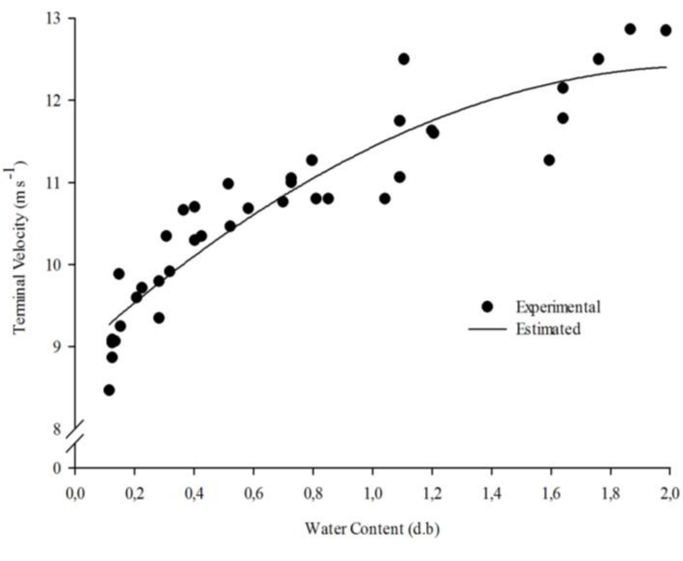

Figure 12 - Behavior of the terminal velocity for all clones adjusted to the common model.

Other agricultural products can have a linear behavior, as observed for sorghum and millet [15], wheat [16], pistachio nuts [17], wheat, barley and lentils [18], linseed [19], grape [20], among others.
The experimental drag coefficient was determined on the horizontal wind tunnel for fruit clusters in each clone green and cherry. There was the identity test between all the clones and maturation stages, finding the common model of best fit. Table 4 shows the models found for each clone and its corresponding stage of maturation, and the results of the test conducted identity.

Table 4 - Result of the identity test for the drag coefficient in all combinations studied

Clone	**Phys. Prop.**	**Parameters of the model**			**F_{calc}**	**F_{tab}**	**Test**
		β_0	**β_1**	**β_2**			
83 cherry	C_D	1.4323	-1.88E-04	9.98E-09	0.20	2.157	NS
83 green	C_D	1.4939	-2.58E-04	1.86E-08	1.94	2.297	NS
31 cherry	C_D	1.455	-2.16E-04	1.30E-08	0.43	2.297	NS
31 green	C_D	1.4677	-2.26E-04	1.37E-08	0.93	2.297	NS
74 cherry	C_D	1.4857	-2.22E-04	1.35E-08	1.17	2.157	NS
74 green	C_D	1.4617	-2.08E-04	1.22E-08	0.55	2.297	NS
All	C_D	1.3468	-1.78E-04	1.01E-08	0.71	1.967	NS
NS = Non-significant F-test at 99%.							

By applying the identity test can use a common template for each clone in each stage of maturation, moreover, was also found a common model for all the clones analyzed. This model allowed us to determine the drag coefficient for any clone in different maturation stages. This result is extremely important for the coffee industry because the conilon varieties are composed of several clones that often make it impossible to obtain a standard model to determine the different physical properties required at the post-harvest. Figure 13 shows the drag coefficient of behavior with respect to the Reynolds number that is directly related to the size (b) characteristic of the coffee fruit and speed study.

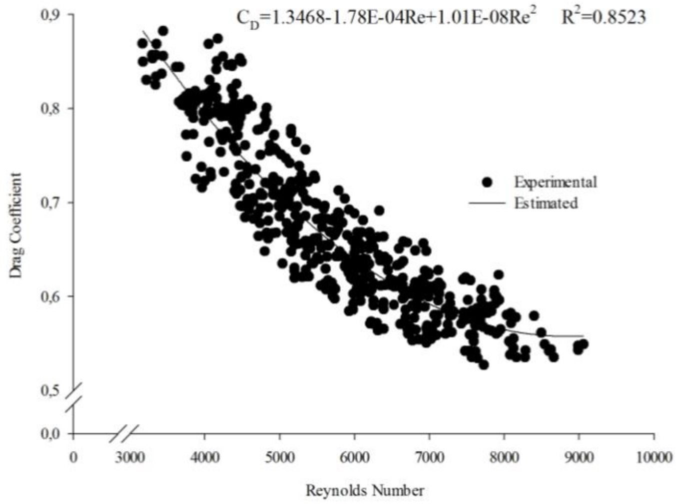

Figure 13 - Drag coefficient behavior for all clones adjusted to the common model.

The results shown in Figure 13 are in full agreement when compared with other reported by Rosendahl [26], which studied the coefficient of drag behavior for different geometric shapes including ellipsoids. The model thus meets the needs of the area skilled in the use of aerodynamic properties in machine design and contributes to the data enrichment physical properties of conilon coffee clones. Figure 14 illustrates the drag coefficient behavior by varying the water content. It has a nonlinear behavior by decreasing the drag coefficient with increasing water content in the coffee cherry. The model found to determine the drag coefficient enables the process of determining the terminal velocity of coffee fruit. This process previously needed to use trial and error procedures [1], using reported models in the literature for other different bodies to agricultural products with type of biological characteristics [13] or the product closer to a sphere and using the drag coefficient value of 0.44.

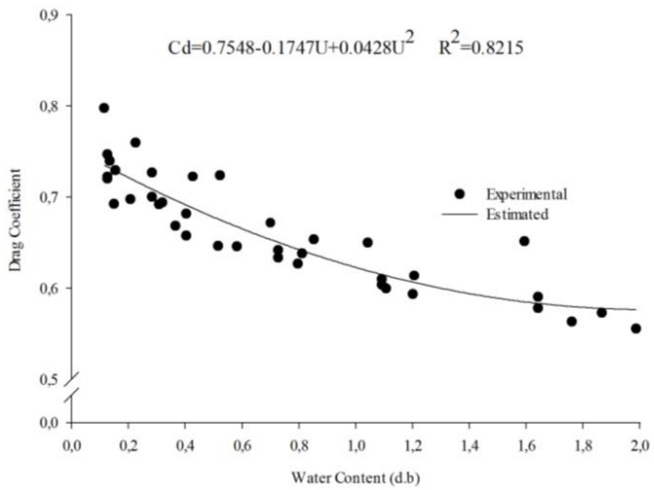

Figure 14 - Behavior of the drag coefficient for each value of the terminal velocity to reduce the moisture content during drying of all the clones analyzed.

IV. Conclusion

Considering the coffee fruit-shaped ellipsoid, it determined the influence of water content on the terminal velocity. By increasing the water content, the terminal velocity increases nonlinearly in all conilon coffee clones and maturation stages studied. A common terminal velocity model representing the variation across the drying was found for all clones studied with a significance level of 1% for the identity test. The drag coefficient of each clone was experimentally determined in a horizontal wind tunnel, and the common model that satisfies the phenomenon with a significance level of 1% for the identity test was found. The drag coefficient presented a non-linear behavior, decreasing with increasing Reynolds number. A general model was found to determine the drag coefficient that depends on the water content of the coffee fruit during drying which eliminates the previous tedious procedures of trial and error.

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