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Determining and modeling the physical, thermal and aerodynamic properties of Pinto beans with different water contents

Mateus Morais Santos, Ivano Alessandro Devilla, Cristiane Fernandes Lisboa*, Pâmella de Carvalho Melo and Arlindo Modesto Antunes

Department of Agricultural Engineering, State University of Goiás, 75 132- 400, Anápolis – GO, Brazil.

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The present study aimed to determine and model the physical (orthogonal axes, circularity, sphericity and apparent specific mass), thermal (thermal conductivity, specific heat and thermal diffusivity) and aerodynamic properties (thermal experimental speed) of beans grains with different water contents. BRS cultivar were used as test crop and properties were investigated with seven water contents (32.9; 28.1; 24.9; 21.9; 18.9; 16.2; 13.6% dry base- d.b.). After data collection, mathematical models were set as experimental data. At the moment of choosing the best model, the following were taken into account: the adjusted coefficient of determination (R^2) and average relative error (P). The outcome analysis showed that the orthogonal axes and beans grain circularity are directly proportional to water content reduction. Apparent specific mass decreased and sphericity remained constant, with increase in water content. Thermal conductivity, specific heat and thermal diffusivity decreased by 22.7; 12.7; 14.3%, respectively, when water content decreased from 32.9 to 13.6% d.b. The experimental terminal speed was increased by 15.3% when water content increased.

Key words: Size and shape, thermal conductivity, terminal speed, *Phaseolus vulgaris*.

INTRODUCTION

Beans (*Phaseolus vulgaris* L.) is a vegetable species from Fabaceae family, which is extremely important as human feed, easy to find and an important source of protein, minerals, vitamins and phenolic compounds (Díaz et al., 2010). Its production and consumption are observed mainly in South America, The Caribbean, Central America and Africa (Luna-Vital et al., 2015), consisting of one of the most widely harvested crops in Brazil and the world (Zucareli et al., 2015).

The beanstalk is cultivated in various Brazilian regions

*Corresponding author. E-mail: cflisboa.engenharia@hotmail.com.

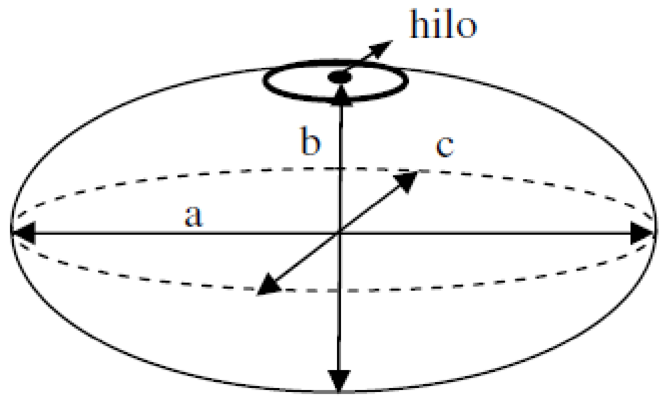

Figure 1. Schematic drawing of a bean grain with its characteristic dimensions.

with different handling types and weather conditions, favoring the deployment of new and more resistant cultivars and with desirable features to fit the final consumer (Pereira et al., 2009). Brazil is one of the main worldwide producers of this crop, with 3,182.7 thousand tons produced during the harvest of 15/16, and it is one of the major foods which follow the Brazilian basic consumption (CONAB, 2016).

The production of grain with high quality demands among other recommendations that the product is harvested safely and beforehand, aiming to decrease losses which occur in the field by insect and microorganism attack. This way, due to a high content of humidity of beans, after harvest, it is essential that the grain is dried, so its storage could be extended (Doymaz et al., 2015).

In post-harvest phase for beans, drying is the most used process to assure its quality and stability, because the decrease in water content diminishes biologic activity and the chemical and physical changes that occur within the grains throughout storage period (Resende et al., 2008). Because of this, there is a necessity of gathering information regarding physical, thermal and aerodynamic properties which are of utmost importance to aid post-harvest process, besides delivering a group of data for engineers and devisors, which will be the basis for machinery designing, structures, control processes and deliver a better efficiency of a piece of equipment or operation (Araujo et al., 2014).

The adjustment of mathematical models to experimental data is essential to forecast and simulate grain behavior, which are submitted to a certain process. Therefore, the use of mathematical models during drying, contributes to the execution of projects and equipment dimensioning, as well as the comprehension of related processes (Corrêa et al., 2011).

Regarding the aforementioned, this study aimed to determine the physical, thermal and aerodynamic properties of pinto beans grains in different water contents during drying process, in such a way as to contribute to their suitable processing.

MATERIALS AND METHODS

The experiments were performed in Laboratory of Drying and Storage of Vegetable Products of the State University of Goiás, Anápolis, GO. The geographical coordinates of the county is at latitude 16º 19’ 43” south and longitude 48° 57’ 12” west, in the State of Goias.

The pinto beans grains (*Phaseolus vulgaris* L.), cultivar BRS Estilo, produced by Embrapa rice and beans, located in Santo Antonio de Goias, were used in this study. The grains were stored with initial water content at 32.9% dry base (d.b.), polyethylene bags and stored in a freezer at 8°C until the beginning of experiments. The initial water content was determined by the standard hothouse method, at temperature of 105 ± 3°C, during 24 h, with three replications (BRASIL, 2009).

Samples of approximately 0.8 kg of grain were put into nets, and taken to a hothouse with forced air circulation, at constant temperature of 35 ± 1°C. The reduction in water content throughout drying was followed by gravimetric method, with the aid of an analytical scale with 0.01 g precision. The grains were dried until they have reached the following water content (28.1; 24.9; 21.9; 18.9; 16.2 and 13.6% d.b.). For each water content obtained, the product was homogenized and the physical, thermal and aerodynamic properties were determined.

Physical properties

To determine the beans grain size, considered as oblate spheroids, the dimensions of the orthogonal axes were measured (length (a), width (b) and density (c)), (Figure 1), for this determination, three 50-grain samples were used for each analyzed water content, with the aim of a digital equipment with precision 0.01 mm (Siqueira et al., 2012a; Araujo et al., 2014).

Table 1. Averages and deviations from the values of the orthogonal axes (length (a), width (b) and density (c)), apparent specific mass, sphericity and grain circularity form Pinto beans, cultivar BRS Estilo, in different water contents.

Water content (%d.b.)	Axis a (10^{-3} m)	Axis b (10^{-3} m)	Axis c (10^{-3} m)	Specific Mass (Kg m^{-3})	Sphericity (%)	Circularity (%)
32.9	10.96±0.12	7.02±0.08	5.39±0.08	729.2±10.8	68.06±0.18	64.06±0.03
28.1	10.74±0.27	6.81±0.10	5.03±0.15	758.8±4.1	66.69±0.22	63.36±0.75
25.0	10.53±0.24	6.70±0.12	5.06±0.11	768.4±3.3	67.42±0.90	63.69±1.01
21.9	10.38±0.06	6.57±0.08	5.20±0.08	769.6±2.2	68.18±0.37	63.29±0.47
19.0	10.11±0.08	6.34±0.05	5.08±0.04	788.8±4.4	68.03±0.13	62.64±0.47
16.3	10.18±0.23	6.44±0.15	5.00±0.16	790.8±4.8	67.72±0.25	63.22±0.08
13.6	10.03±0.27	6.29±0.14	5.04±0.12	814.0±5.5	68.03±0.17	62.72±0.29

The form for beans grain was determined, in three 50-grain repetitions for each water content, with sphericity estimated from values retrieved from the measures of the orthogonal axes, according to the following equation suggested by Mohsenin (1980):

$$S = \frac{(a.b.c)1/3}{a}.100 \quad (1)$$

Where, S = sphericity, %; a = measure of the greater axis, meter (m); b = measure from the normal axis to a, m; c = measure from the normal axis to a and b, m.

Circularity of beans grain was estimated by Equation 2, considering the natural resting position of the grains.

$$C = \frac{di}{dc}.100 \quad (2)$$

Where, C = circularity, %; di = diameter of the largest inscribed circle (b axis), meter (m); and
dc = diameter of the smallest circumscribed circle (a axis), m.
Determination of the apparent specific mass (ρ_{ap}), expressed in kg m^{-3}, was performed in five replications for each water content, using a hectoliter scale, with capacity of $\frac{1}{4}$ L.

Thermal properties

To determine thermal properties, the beans grains were initially removed from the freezer for six hours, so the temperature could reach balance with room temperature. Thermal properties were determined in 5 replications for each water content. Samples were homogenized and put into a beaker. Afterwards, the equipment, KD2-PRO was used, with a probe of parallel rods. The probe was introduced in the middle of the grain sample and after 10 min, the results for conductivity, thermal diffusion and specific heat were obtained.

Aerodynamic properties

To determine the experimental terminal speed of the beans grains, the equipment used was composed of a centrifugal fan, connected to a transparent acrylic tube, with diameter of 0.15 and 2 m of length. At 1 m from the surface part, a perforated screen was set, so that the product could be placed and at 1.75 m a crosslinker was connected, so that the distribution of air speed into the transversal section of the tube could be uniform. The fan was propelled by a three-phase engine of 0.735 Kw and flow control of air was performed by a frequency inverter.

The terminal experimental speed was determined with six replications for each water content. In the central part of the perforated screen, approximately 50 g of beans was placed, right after the equipment was set up to the moment the air flow started the process of fluctuation of the product. At this moment, a reading was performed for air speed, through a digital anemometer, placed at the surface and central part of the acrylic cylinder.

For the experimental data of the physical, thermal and aerodynamic properties of the pinto beans, cultivar BRS Estilo, linear regression equations and polynomial of second grade were set, using STATISTICA 12.0 software. For the choice of the best model, the magnitude of the adjusted determination coefficient (R^2) and relative error (P) was considered (Equation 3).

$$P = \frac{100}{n}\sum_{i=1}^{n}\frac{|Y - Y_0|}{Y} \quad (3)$$

Where: Y is the value observed experimentally; Y_0 is the value calculated by the model; n is the number of experimental observations.

RESULTS AND DISCUSSION

Physical properties

In Table 1, the average values and the deviation from orthogonal axes (a, b, c), specific mass, apparent specific mass and grain circularity from Pinto beans, cultivar BRS Estilo, in different water contents are depicted.

According to Table 1, a decrease of 8.49, 10.39 and 6.49% for axis length (a axis), width (b axis) and density (c axis) can be observed for beans grains, respectively, in relation to its initial dimensions, with water content reduction of 32.89 up to 13.62 (%d.b.). This way, it can be verified that beans grains presented disuniform

Table 2. Adjusted equation, determination coefficients (R^2, decimal), relative average errors (P, %), for the analyzed physical properties, in the different water contents for the pinto beans, cultivar BRS Estilo.

Propriedades Físicas	Modelos	R^2	P (%)
Apparent Specific Mass	ME= 861.4-3.89*U	0.96	3.15
Axis (a)	Axis (a)= 9.30+0.05*U	0.96	5.05
Axis (b)	Axis (b)=5.74+0.04*U	0.94	5.06
Axis (c)	Axis (c)=4.81+0.01*U	0.54	5.18
Sphericity	E=70.29-0.21*U+0.004*U²	0.37	4.90
Circularity	C=62.55+0.001*U+0.001*U²	0.72	4.89

variations in the various axes, as verified in other studies (Siqueira et al., 2012b; Oliveira et al., 2014; Ren et al., 2014; Izli, 2015). From the determination of these variants of the product with water content reduction, the work performed by drier devisors is optimized, and it is feasible for them to enhance the drying system, taking into account factors such as air flow direction, product movement into drier, among other parameters and related processes (Araujo et al., 2015).

Also, in Table 1, one can verify that circularity is directly proportional to water content, with a reduction of 2.1% with a variation of the initial water content towards the end. Jesus et al. (2013) observed a similar behavior working with Pontal beans cultivar. This tendency of reduction in circularity and water content was observed by Isik and Unal (2011) with beans grains; Goneli et al. (2011) with castor; Araujo et al. (2015) with peanuts; Izli (2015) with Kenaf seeds. Now, other authors stated that the increase in water content resulted in a decrease in this feature as in Lanaro et al. (2011) and Resende et al. (2005) with beans. According to Araujo et al. (2014), with the fact that sphericity and circularity maintained their values under 80%, the inability of classification of these grains into spherical and round, apart from the water content presented is evident.

Regarding apparent specific mass, it is possible to notice an increase of 10.44%, while the water content in beans grains decreased. According to Ribeiro et al. (2005), this increase is observed for the majority of farm products, for porosity decreases when water content diminishes, independent from which methodology was used. The same behavior was observed for various products, such as: crambe fruit, analyzed by Costa et al. (2012); lentil seeds, investigated by Amim et al. (2004); beans grains, observed by Jesus et al. (2013), Oliveira Neto et al. (2012), Lanaro et al. (2011), Isik and Unal, (2011), Resende et al. (2005, 2008); soy grains, investigated by Ribeiro et al. (2005). This is contrary to results found by Siqueira et al. (2012c) for jathropa seeds, where the decrease in apparent specific mass was observed with water content reduction. The reduction of apparent specific mass of beans with the increase in water content in the grains shows that the increase of mass in the sample in function of increase in the mass of water was proportionally smaller than its volumetric expansion (Sologubik et al., 2013). As reported by Botelho et al. (2015), specific mass is a physical feature that is frequently used to evaluate mass quality of grains, in a way that, normally, for specific water content, the greater is its magnitude, the better is product quality.

In Table 2, the statistic parameters and adjusted models used for the determination of physical properties are found, in the various water contents, for Pinto beans, cultivar BRS Estilo.

According to Table 2, in relation to the apparent specific mass, axis (a) and (b), the models presented themselves appropriate to estimate these physical properties in the beans grains, featuring a high determination coefficient (R^2) and low relative average error (P). For the model of apparent specific mass, this negative linear relation existing between it and the water content was also found by other researchers who worked with grains (Isik and Unal, 2011; Barnwal et al., 2012; Sologubik et al., 2013; Sharanagat and Goswami, 2014).

Regarding axis (c), sphericity and circularity, the models did not present a high determination coefficient (R^2), not having a good adjustment to experimental data when this parameter is analyzed, however there has been a low outcome for average relative error (P). According to Segundo Madamba et al. (1996), a parameter alone is not a good criterion for model selection, for this reason, the relative average error (P) was chosen as a main selection parameter. According to Mohapatra and Rao (2005), the relative average error values below 10% are recommended for model selection. For all studied variables, these models presented themselves predictable taking into account the relative average error (P).

Thermal properties

In Table 3, the average values for thermal conductivity, specific heat and thermal diffusivity for Pinto Beans cultivar BRS Estilo, are depicted for different water contents, as well as their respective deviations.

It can be verified, according to Table 2, that thermal conductivity, specific heat and thermal diffusivity decreased by 22.7; 12.7; 14.3%, respectively, alongside water content drop-off from 32.9 to 13.6% d.b. The same behaviors were also observed by Legrand et al. (2007)

Table 3. Averages and deviations for values of thermal conductivity, specific heat and thermal diffusivity for Pinto Beans, cultivar BRS Estilo in different water contents.

Water content (% d.b.)	Thermal conductivity ($W\ m^{-1}\ ºC^{-1}$)	Específic heat ($MJ\ m^{-3}K^{-1}$)	Thermal diffusivity ($mm^2\ s^{-1}$)
32.9	0.2698±0.02	1.97±0.16	0.14±0.010
28.1	0.2350±0.03	1.61±0.19	0.15±0.008
25.0	0.2572±0.05	1.91±0.29	0.14±0.018
21.9	0.2304±0.03	1.73±0.22	0.13±0.003
19.0	0.2136±0.06	1.84±0.47	0.12±0.008
16.3	0.1982±0.02	1.73±0.14	0.12±0.009
13.6	0.2084±0.03	1.72±0.22	0.12±0.007

Table 4. Adjusted equation, determination coefficients (R^2, decimal), relative average errors (P, %) in the analyzed thermal properties, for different water contents, from Pinto beans, cultivar BRS Estilo.

Thermal properties	Equations	R^2	P (%)
Thermal conductivity	K= 0.150+0.004*U	0.91	7.68
Specific heat	C= (1.923-0.021)*U+0.001*U²	0.20	7.31
Thermal Diffusivity	D= 0.095+0.001*U	0.83	5.18

on Red beans; Shrestha and Baik (2010) on saponaria vaccaria seeds and Yu et al. (2015) on canola seeds.

Thermal conductivity and specific heat presented the same tendency of other products, such as: quinoa grain (Nunes, 2009); wheat grain (Ribeiro et al., 2007); corn grain (Andrade et al., 2004); millet and birdseed grain (Corrêa et al., 2004); soy grain (Ito, 2003); cherry coffee (Borém et al., 2002). The fact that thermal conductivity presents a higher average value for a higher water content, is directly associated with the increase in porosity, once water content in the product increases, because, according to Incropera and Witt (1996), thermal conductivity of a material is the measure of its capacity to conduct heat; for foods, it depends on, mainly, of composition, but also of the presence of empty spaces and its homogeneity. Now specific heat is essential to determine the quantity of energy required in the heating and quenching processes of the foods, which by definition, is related to heat energy needed to heat up the samples up to a desirable temperature (Yu et al., 2015).

The behavior observed for thermal diffusivity, corroborates with what was described by Borges et al. (2009), for soy grain. It has been observed that as water content decreases, the value for thermal diffusivity diminishes. The data found in this study for thermal diffusivity, differ from the ones observed by Corrêa et al. (2004) for millet and birdseed; Ribeiro et al. (2007) for wheat grain and Jian et al. (2013) with canola, in which thermal diffusivity increased with water content decrease in the grains. In other works, a great variant in thermal diffusivity values for the mass of different variety of grains, in function of water content can be verified. Ribeiro et al. (2007) verified that various factors influence heat quantity that goes through granular mass, this way, thermal diffusivity values can vary among products and varieties due to, mainly, its composition, specific mass, porosity and water content., the statistical parameters and the adjusted equations used in the determination of thermal properties, in the various water contents for Pinto beans, cultivar BRS Estilo is shown in Table 4.

In other works, a linear relation is reported between the property of specific heat and water content; however, this was not observed in this study, presenting a non-linear relation, which corroborates with what was observed by Razavi and Taghizadeh (2007), for pistachio grain. In relation to specific heat, the determination coefficient (R^2) and (P) were respectively 0.20 and 7.31. For all studied variables, these models presented themselves predictable, taking into account the relative average error (P).

Aerodynamic properties

In Table 5, the averages and standard deviations of the values for terminal experimental speed, for different water contents for Pinto beans, cultivar BRS Estilo is shown.

One can notice the increase of 15.3% in experimental terminal speed in function of the increase in water content. The same tendency was found for quinoa grain, observed by Nunes (2009); beans grain, observed by Isik and Unal (2011); Gharibzahedi et al. (2011) working with castor; Shirkole et al. (2011) with soy; Yilmaz et al. (2012) with sesame; Izli (2015) with Kenaf seeds. This is the behavior observed for the majority of the grains, once the increase in terminal speed with water content increment within the break in the study can be attributed

Table 5. Averages and deviations of the values of terminal experimental speeds, for Pinto beans, cultivar BRS Estilo, for studied water contents.

Water content (% d.b.)	Terminal Speed (m s^{-1})
32.9	4.64±0.04
28.1	4.18±0.06
25.0	4.29±0.03
21.9	4.27±0.02
19.0	4.11±0.11
16.3	4.14±0.05
13.6	3.93±0.09

Table 6. Adjusted equation, determination coefficients (R^2, decimal), relative average error (P, %) for experimental terminal speed, in different water contents for Pinto beans, cultivar BRS Estilo.

Aerdynamic property	Equation	R^2	P (%)
Terminal speed	Vt= 3.59+0.03*U	0.83	3.34

to the increase in the grain mass per unit of frontal area submitted to air flow.

One can say that, terminal speed is influenced by product shape, water content, size, orientation, viscosity within, and by specific masses of the particles and of the fluid (Treto, 2012). Other reason for this increase in the experimental terminal speed with the increase in water content is that the drag force is affected by water content of the particles (Ahmadi and Siahsar, 2011).

In Table 6, there are statistical parameters and adjusted equation from experimental terminal speed, for the various water contents of the Pinto beans, cultivar BRS Estilo.

It is shown in Table 6 that the linear model, adjusted itself properly to the data of the experimental terminal speed, with a good determination coefficient (R^2), and low relative average error (P), below 10%, the same tendency was found by other authors working with other grains, such as the ones observed by Ahmadi and Siahsar (2011) and Izli (2015).

Conclusions

According to the outcomes and under the conditions in which this study was developed, it can be concluded that:

1. Length (axis a), width (axis b), dimension (axis c), circularity, thermal conductivity, specific heat, thermal diffusivity and experimental terminal speed of the beans grain, are directly proportional to water content.
2. Sphericity was kept practically unchanged with the variation in water content of the grains.
3. Apparent specific mass is inversely proportional to water content in the grains.

Conflict of Interests

The authors have not declared any conflict of interests.

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