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Simulation of a Mathematical Model for the Temperature Profile in a Silo Bag for Bean

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Abstract. The problems encountered with storage of agricultural products has warranted studies related to finding alternative methods of grain storage, thereby avoiding unnecessary losses. Stored grain deteriorates quickly at high temperatures. The moisture content of the grain influences the respiratory process; therefore, when at the recommended humidity of between 11 and 13%, this rate remains low; it prolongs maintenance of the product quality. The silo bag being airtight enables the grain mass to consume the entire internal O_2 purse within it, and in that low or absent oxygen environment the grain mass saturates the CO_2 atmosphere, inhibiting the multiplication of insects and fungi, thus providing a controlled environment. This study aims at simulating; using Computational Fluid Dynamics (CFD), the time it would take for the entire grain mass contained in a silo bag to reach thermal equilibrium with the environment and analyzes the feasibility of the technique employed here. The simulations were performed based on the data of the average air temperature in the region at each harvest time and the average storage temperature of the bean mass (60°C). The results obtained from the simulations reveal that after one month of silo storage the entire bag remains in thermal stabilization, and four months later when it hits the entire mass, all the beans are in thermal equilibrium. Therefore, maintaining stable temperature and humidity within the recommended silo bag preserves the grain quality well.
Keywords: Storage; Thermal Conduction; CFD.

Introduction

Brazil is a country experiencing a highly diversified agricultural production, with the Mato Grosso state being responsible for a significant portion of this production. To ensure grain quality, the factors of storage and transportation become vital in the logistics of agricultural production; however, the infrastructural deficiencies can substantially reduce the competitive potential of these products in the Brazilian agribusiness (MILK, 2013).

The bean (*Phaseolus vulgaris L.*) is one of the most widespread legumes worldwide, being cultivated in several countries of tropical and subtropical climate. It is an excellent food that provides essential nutrients for humans, such as proteins, iron, calcium, magnesium, zinc, vitamins (especially B complex), carbohydrates and fiber. Besides being one of the most traditional foods in the Brazilian diet, it is considered the main source of proteins for low-income populations, resulting in a product of high nutritional, social and economic importance. As the contribution of calories, beans ranks third among food consumed, totaling 11.2% of the calories ingested per day (SOARES, 1996).

Post harvesting, the beans require proper storage to ensure retention in quality, because the process of grain respiration and other metabolic reactions continue to remain dynamic and can interfere with the final quality of the product. Such changes may occur due to high humidity, temperature and luminosity, over prolonged storage periods, resulting in dark and hardened grains. Consumers are extremely selective when choosing the product for their consumption, with of course, the grain integument representing the most important reasons for their choice, good color being associated with appropriate storage (LIMA, 2013).

Storage, using the dry grain in silo-bag, is a practical, economical and innovative means, which offers farmers a better storage method of their produce on the farm itself, than the conventional silos which are fixed, limited and expensive to maintain capacity, thus the reducing storage and high freight costs involved at the peak of harvest. The silo-bag allows greater flexibility because it suits the specific needs of each crop and is easily adjustable to any changes in production volume, thereby enabling the producer to reap, regardless of the lack of truck facilities or port availability during normal harvest times. Moreover, according to Resende (2006), grain storage under proper conditions allows the producer to increase the bean supply in times of scarcity, when the prices are more attractive.

The airtight silo or storage bag facilitates modification of the intergranular atmosphere, by converting the oxygen into carbon dioxide through the respiration of the biota within the storage ecosystem (DARBY & CADDICK, 2007). This system is widely used to preserve the characteristics of freshly harvested grain over prolonged time periods (SIGOU, 1980; LIMA, 1990; BROOKER et al., 1992). It is characterized by restricted gas exchange between the environment and the interior of the silo, thus inhibiting variation in the grain moisture, which prevents pest infestation. It also negates the costs of utilizing pesticides for grain conservation resulting in a healthier final product (ELIAS, 2002; RICKMAN, 2002).

Temperature, directly related to the final quality of stored grain and the relative humidity prevailing in the storage location are the main external factors that influence the ecosystem of the grain mass and it is these that affect the verification of the effectiveness of the silo bag. The combined effect of these two factors in a particular storage location determines the activity of all the biotic components in the system, which enables safe storage or result in product losses (ATHIÊ et al., 1998). Another important feature of stored grain is its thermal conductivity. In grains, heat is propagated by conduction, from grain to grain in contact with each other, and also by convection flow, producing the intergranular moving air. Investigations conducted in several countries reveal that grain mass is regarded as a material of low thermal conductivity, i.e., grains stored in silos or stacked bags do not easily exchange heat with the storage environment. This characteristic can prove dangerous if the grains have high humidity, although it can be advantageous in the preservation of properly stored products (BRAGANTINI, 2005).

An alternative technique for analyzing the temperature profile inside the silo bag is Computational Fluid Dynamics (CFD) - a branch of fluid mechanics based on analysis done through simulation computing systems involving consistent fluid flow, heat transfer and other related phenomena. Using this technique helps in obtaining estimates of the speed and distribution of indoor air temperature, enabling the prediction of product quality at the end of storage (AWBI, 1989), thus reducing the time and costs of new projects.

From the information given above, the objective of this paper was to simulate the time spent by the stored grains to achieve thermal equilibrium with the environment, in an attempt to evaluate this technique as a safe storage method for products fresh from the dryer.

Methods

Meteorological data

In the process of temperature simulations, the meteorological data of Sinop was used for the whole of 2013, at the weather station installed in the Federal University of Mato Grosso. Campus Sinop.

Initial condition and physical properties

The average temperature of the grain mass analyzed post drying was recorded according Gouveia et al., (2011) at 60°C on average.

The key to the implementation of the model physical and thermal properties was obtained for the bean according to the data of Botelho et al., (2007); however, the water content during the storage was assumed as 13% (db). Therefore, the bulk density obtained was 872.13 kg / m³, the specific heat obtained by the equation $y = 1.2076 + 2{,}8154x$ gave a value of 1.59 KJ / (Kg. °C) and the thermal conductivity determined by the equation $y = 0.102 + 0{,}1557x$ was 0.12 W / (m. °C).

Mesh geometry and boundary conditions

Fig. 1 presents the geometry and the coordinate system for the silo bag.

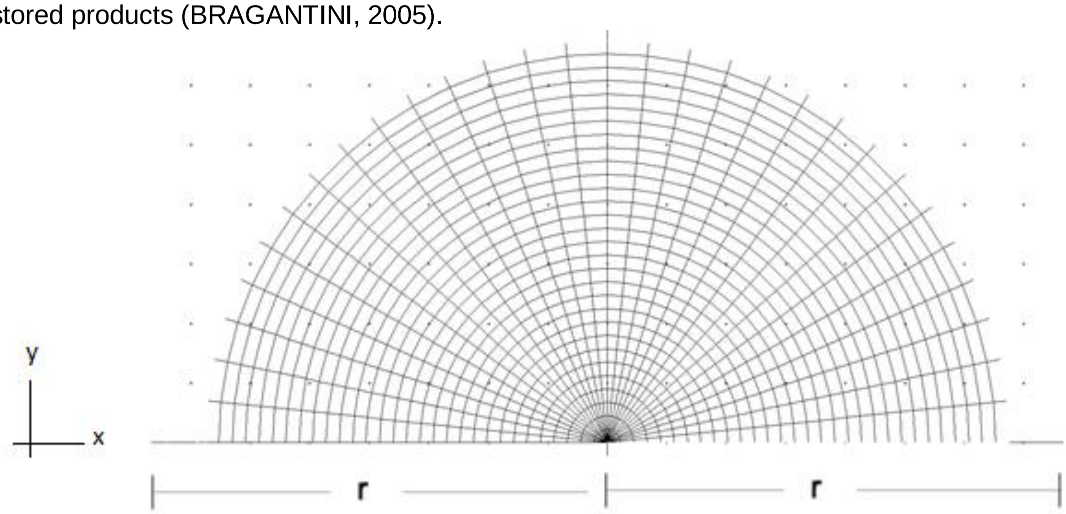

Figure 1. Coordinate system and mesh used for the numerical solution.

In Fig. 1 the geometry used in simulations is displayed. The form presented by the silo bag is a complete semicircle. In the simulation, two quarters of a circle of diameter equal to 2.7 m was used.

Considering the diameter of the silo bag, the mesh applied for the numerical solution was built with 30 volumes in each quadrant, and in each direction (x and y), proportionally spaced, totaling to 1800 differential volumes.

In the Cartesian plane (x and y axes) the boundary condition applied was zero heat flow. The outer surface of the silo convection boundary state on the surface was used.

Method and mathematical considerations

The differential equation that governs the thermodynamic process of heat transfer by conduction inside the silo bag can be directed by a two-dimensional model in the transient regime, where temperature T (r, Φ, t) is a function of the point coordinates and t the time considered, according to Equation 1:

$$1/r\ \partial/\partial r\ (kr\ \partial T/\partial r)+1/r^2\ \ \partial/(\partial \phi)\ (k\ \partial T/(\partial \phi \qquad =\rho cp\ \partial T/\partial t \qquad (1)$$

In that q, (W m³) is the internal rate of heat generation. The thermal conductivity is denoted by k, (W m-3 K-1). The radius is denoted by the re symbol and given in meters. The density is denoted by ρ (kg-m ³) and the specific heat C_P by symbol (J kg-1 K-1).

To use this equation, the following considerations were assumed:

- It is assumed that the grains bed formed during filling the silo bag has porosity equal to the chelates obtained in a sample subjected to the homogenizer;
- The heat and mass transfer in the direction is negligible compared to those in cross-section of silo bag. Therefore, a 2D plan was adopted;
- Inside the silo bag, the grains are in thermal equilibrium;
- The reduction of the volume by breaking grains is negligible;
- The internal rate of heat generation is negligible in products with low moisture content;
- The heat and mass transfer inside the silo bag by convection is negligible, as well as that by radiation;

Processing

Simulation were done using the Software CFD Studio, applying the method of finite differences between the volumes considered.

Simulations were performed for three existing bean crops during 2013, divided into five different grain storage periods of one day, one week, one month, two months and four months.

Results and discussion

The analysis of the temperature profile of the bean stored inside the silo bag, after the first 24 hours of storage, is shown for the simulated conditions, in which the first crop had an onset greater than the second and third stabilizations. Whereas each silo volume is 45 mm, 630 mm in the first season indicates the beginning of the process of stabilization with the environment, while in the other it was only at 405 mm that the beginning of this process commenced (Fig. 2).

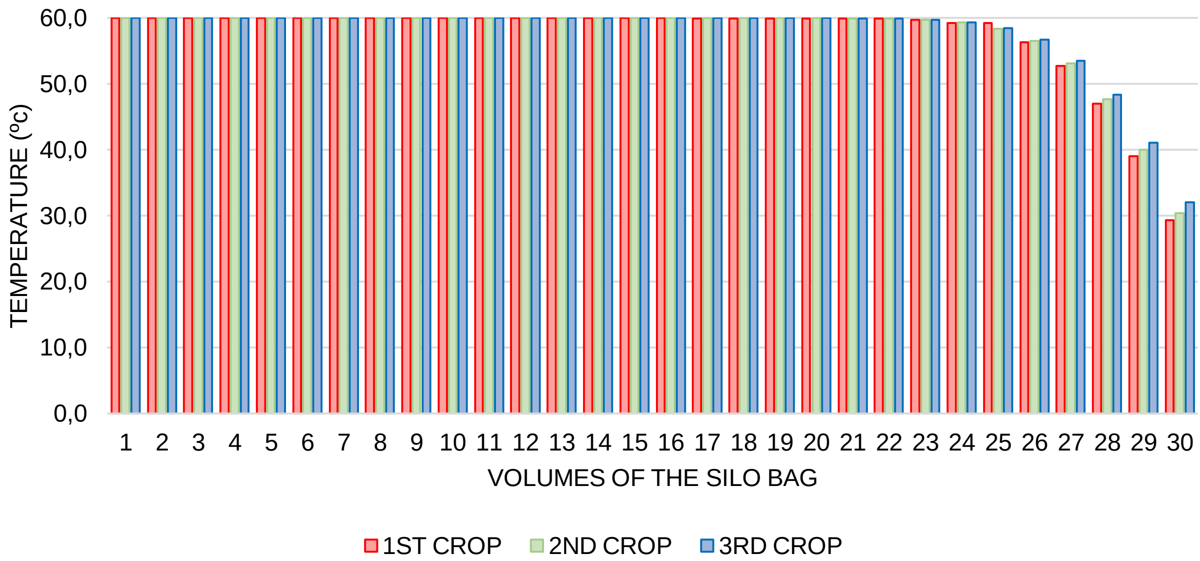

Figure 2 - Profile of the temperature distribution in the silo bag after 24 hours storage.

Despite the difference between the yields indicated, it is evident that all yields revealed significant falls outside the first volume with respect to the temperature of the product, and furthermore due to the boundary conditions the external volume used tended to reach room temperature, which was

24°, 24° and 26°, respectively, for each crop. It is also noted that the first 1035 mm of the grain mass from the center suffered virtually no action indicating that the heat transfer process had insufficient time to take place.

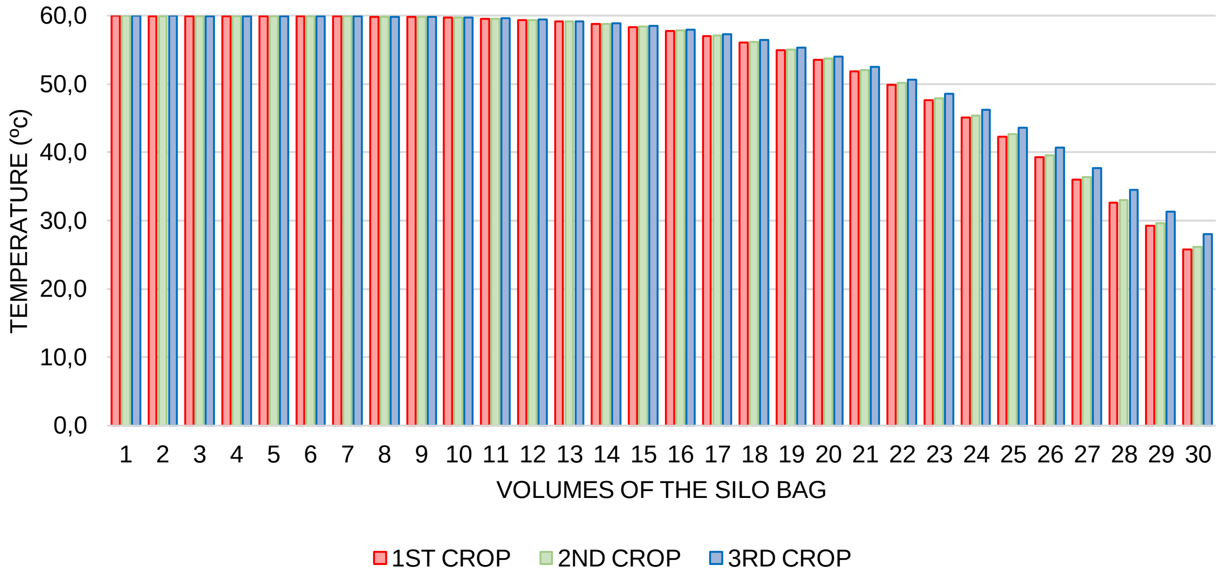

Figure 3 - The results obtained by the simulation after a week storage.

From Fig. 3, it becomes clear that after a one week storage period, over 495 mm of the grain mass commenced the process of stabilization in the first season, whereas for the simulated conditions, the second and third seasons it was 720 mm of the grain mass. In all the harvests about 83% of the entire silo bags were already conducting, regardless of the amount of heat transfer. The external volume for each season can be considered in thermal equilibrium because the maximum temperature difference of the grain mass is less than 4 (SILVA et al., 2008). However, this time period is insufficient for thermal stability of the total grain volume to be achieved.

After one of storage (Fig. 4), the entire silo bag begins the process of heat transfer, with no regions having an initial temperature. It is essential to emphasize that thermal exchanges occur inside the bean bag through the conduction process, even if the product has low thermal conductivity, as in the case of beans. According to Silva (2008) it appears that at 135 mm, from the outside to the center, the first, second and third harvests were already in thermal equilibrium, considering the condition of the thermal stability of the ambient air which was 25°, 25° and 26°, respectively.

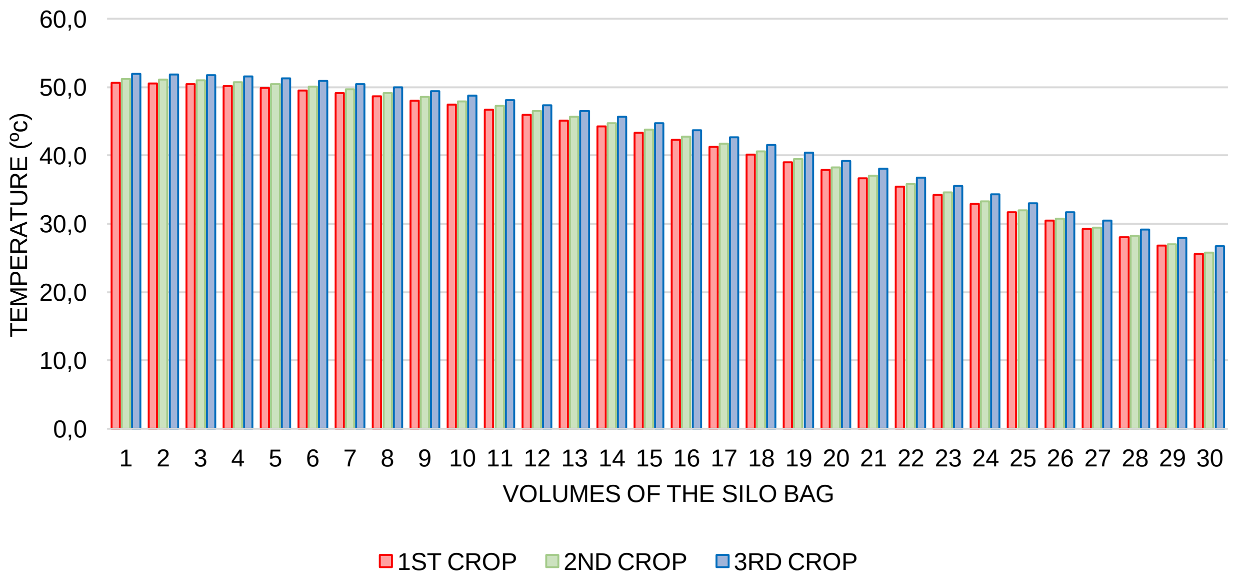

Figure 4 - Profile of the temperature distribution in the silo bag, one month after storage.

Fig. 5 shows the results obtained by simulating a period of two months of storage, where it checked for conditions that simulated 270 mm, from the outside towards the center from both crops which reached thermal equilibrium (SILVA et al., 2008).

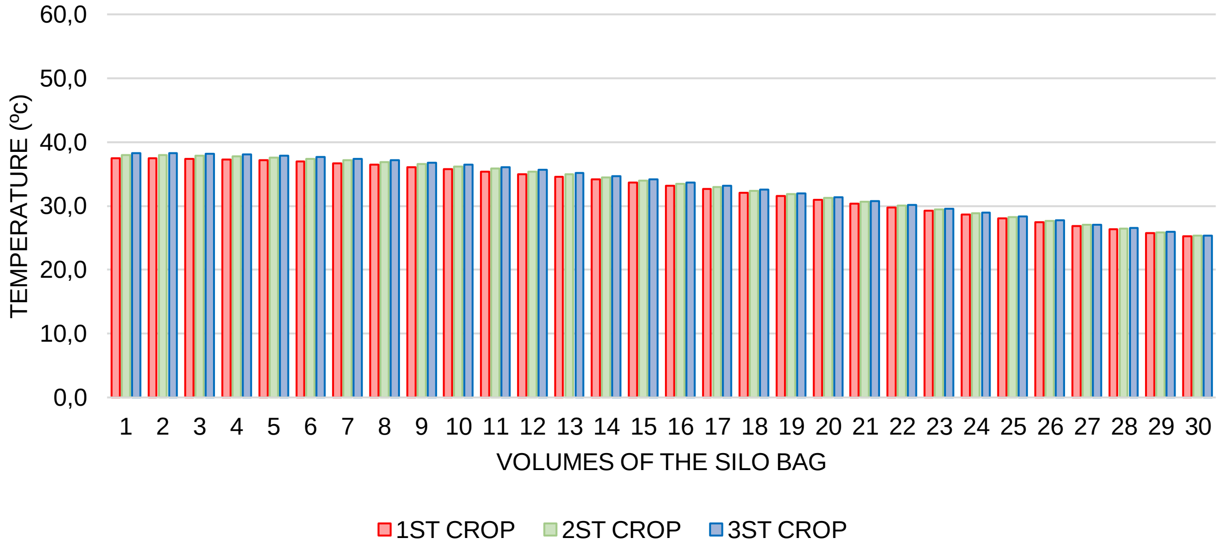

Figure 5 - Profile of the temperature distribution in the silo bag, two months after storage

Silva et al., (2008) state that the goal is not the effective cooling of the grain mass, but achieving a temperature that stays consistent. Variations in the temperature of the grain mass lower than 4°C are considered uniform. Fig. 6 reveals that all the volumes in the silo bag are in thermal equilibrium, considering that the condition of thermal stability in the ambient air was 25 for all the crops used in the simulation. By increasing the time spent during simulation, it appears that the only the difference between the temperature inside of the silo and that of the contour bag was greatly reduced from an average of 25.3 months in the first to the fourth month and was 3.1°.

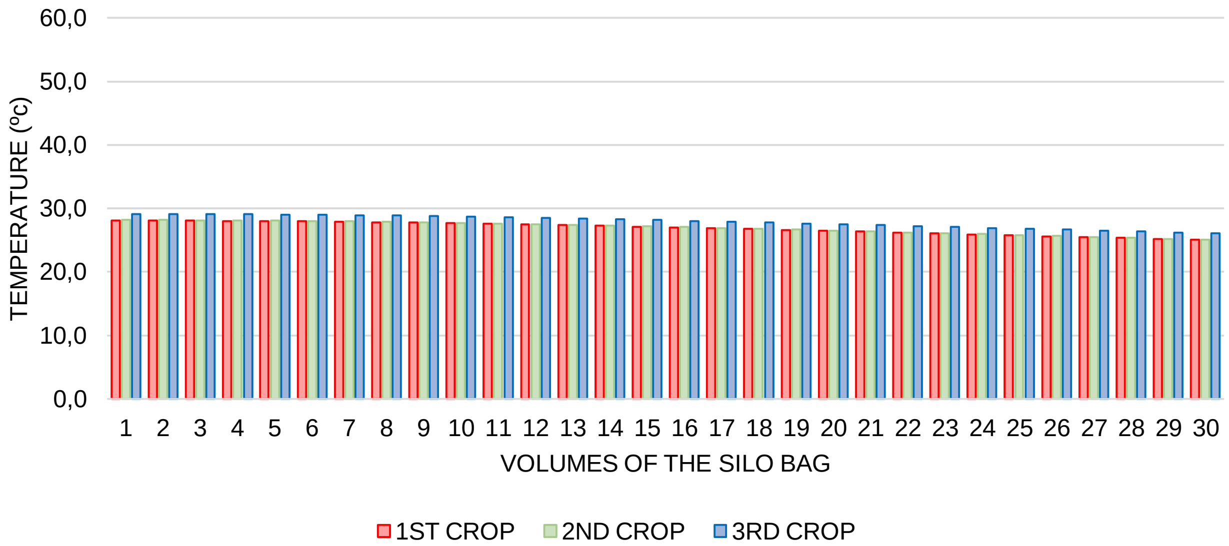

Figure 6 - Profile of the temperature distribution in the silo bag, four months after storage.

The first deleterious effects of storage on the physiological quality of the bean seeds are noticed by loss of vigor. Skowronski et al., (2004), while measuring the effect of storage on the bean seeds of different cultivars, identified the loss of force after six months in storage and discovered that some genotypes store better than others.

Hunt & Pixton (1974) found that the environmental factors of temperature and relative humidity influence grain storage, the goal being preservation of the product characteristics. The water content of the grains and their genetic constitution also exerts a great influence (VIEIRA & YOKOYAMA, 2000). These factors affect food, nutrition and the marketing qualities of the bean, such as the cooking time and appearance (SARTORI, 1988).

Vieira et al., (2005) evaluated bean storage in airtight polyethylene tubes. By coloring the outer wall white in color, the manufacturers claim that part of the sunlight gets reflected and, therefore, the silo prevents changes in the moisture content of the grain, avoiding contact with the same moisture from the outside air. Also, as the solar rays are blocked by the silo wall, the grains are kept completely in the dark. This contributes towards the delay in the browning of the integument. The authors concluded that the moisture content of the bean remains almost unchanged for 90 days in storage under these conditions.

Conclusion

Based on the data obtained, it can be concluded that the model used for the simulation it has adapted to the heat transfer by conduction, ensuring the convergence of data at the end of the simulated process. One can also conclude that the silo bag can be suitable storage method for beans intended for human consumption, however, for use as seed, this method can reduce the vigor of seeds on account of the high time taken for lowering the temperature of the mass.

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