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Development of an automated system of aeration for grain storage

Arlindo Modesto Antunes*, Ivano Alessandro Devilla, Antônio Cruvinel Borges Neto, Beethoven Gabriel Xavier Alves, Guiliano Rangel Alves and Mateus Morais Santos

Department of Agricultural Engineering, State University of Goiás, 75132-400, Anápolis – GO, Brasil.

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Stored grain should be preserved as much as possible during storage process, because of the occurrence of chemical, biochemical, physical and microbiological changes. The grain storage process consists of storing this material for a later use after a certain period. This study aims at to develop a prototype for grain aeration; to develop a software to control aeration strategies; and to evaluate the development of strategies for controlling the aeration of stored corn. The metallic silo is built in a cylindrical shape (0.9 m diameter and 3 m high), with a fully perforated bottom, which was adapted to an aeration system (plenum, axial fan, with three-phase motor of 1.47 kW and PVC pipe Ø 0.10 m). The silo was externally isolated using glass wool (0.06 m) thick, and the airflow controlled and determined in 0.1 m^3 min^{-1} t^{-1}, where t is ton of grain. To work with data relating to the experiment, it was necessary to use sensors, positioned at the center of the silo (spaced 0.5 m), from the plenum. The sensors were connected to an Arduino board, in order to register the temperature of grain mass. After the installation of the sensors in the silo, this was loaded and the surface of the grain mass was leveled. Control strategies were implemented: Continuous aeration; control of dry bulb temperature; control via timer and temperature control via temperature difference between the grain and the ambient air. Operating results obtained with the software developed, were effective for control of grain aeration processes stored in the prototype. In conclusion, the system for automated aeration of stored grain was effective in the storage of grain and the control strategy, aeration of grain via the temperature difference between the grains and the environment and night aeration were the best for the aeration process in region of Anápolis - GO.

Key words: Storage, grain cooling, prototype, Arduino.

INTRODUCTION

The grain storage date centuries, with biblical references when Joseph advised Pharaoh to store all grain produced in Egypt in times of plenty, to ensure the supply of these grains in the Egyptian cities in extreme drought time. The

*Corresponding author. E-mail: arlindo.modesto1@hotmail.com

grain storage is then used to store the product for consumption after a certain time period (Araújo et al., 2012).

It is known that after harvesting the grains pass through a series of processes until it reaches the final consumer. Some of these operations include: Receiving, cleaning, drying and storage, handling, among others. According to Baal (2014), these operations are called pre-processing of grain, and the places where they are held are called grain packing houses. Usually grain processing sites are also composed of storage structures, so these sites can be called units processing and grain storage.

Stored grain should be preserved to the maximum during storage, due to the occurrence of chemical, biochemical, physical and microbiological changes. The speed and intensity of these processes depend on the intrinsic quality of the grain, the pre-processing operations, the storage system used and the prevailing environmental factors during the storage period (Alencar, 2006).

The main influential factor in any process of storage, is the grain water content. Deterioration reactions occur at high humidity levels, especially enzymatic hydrolysis and oxidation of lipids, however, these reactions occur less frequently with low water content. Because of this, the water content of the grains should be controlled in storage (Furquim et al., 2014).

Moisture migration varies with respect to the season. During periods of winter and autumn, the beans located near the silo walls and on top of the grain mass are cooled more easily than those located at the bottom of the silo. After some time due to the mass of the temperature gradient grains, convective currents are generated. That is, the air cold and dense intergranular located near the bin wall is pulled down, flowing through the center of the silo and driving up the warm, less dense air initially locating in this region. Already in the spring and summer, the temperature of the grain near the walls of the silo and increase grain located in the center of the facility remain cold. In these periods the convective currents change their direction. The cold, denser air, located in the center of the silo, flows down, resulting in a movement of the convective currents from the silo center towards their side (Muir and Jayas, 2014; Vasconcellos, 2012)

Currently, aeration is the most widespread control method employed in the preservation of stored grain. Aeration is the forced passage of the ambient air through the grain mass in such a way as to modify the microclimate intergranular voids, creating unfavorable conditions for the development of organisms that influence the preservation of the quality of grain. However, if the aeration is not well managed it can cause loss of heating, fermentation and excessive loss of water content, and it is highly dependent on local weather conditions. Thus, the efficiency of an aeration system is centered on obtaining a uniform air flow in all regions of the silo. Another objective of aeration is to prevent migration and condensation of moisture that occurs whenever there is a heating at some point of the grain mass (Luiz, 2012).

The management of aeration should be implemented from the comprehensive studies on the devices to be used. The management of aeration is directly related to a control strategy, as is the drive fans based on temperature and humidity of grain and air (Lopes, 2006; Lopes et al., 2008).

Faced with the need to control and optimize the process of aeration of stored grain, activities are being developed, aiming at automating the data acquisition system and consequent reduction in the cost of the grain storage process (Kaliyan et al., 2007; Lawrence and Maier, 2011; Rigo et al., 2012).

Finally, this study is aimed at developing a computer program developed in PHP platform for control of aeration processes, build a prototype for aeration of stored grain, evaluate strategies for aeration control corn grain stored and collect cooling data and water content of corn grain stored in metal silos with different strategies of aeration being used.

MATERIALS AND METHODS

This work was developed in Drying Laboratory and Plant Products Storage, Campus of Exact Sciences and Technology, Henry Santilo, the State University of Goiás in Anápolis - Goiás. The laboratory is located in the Brazilian Central Plateau,with latitude 16°19' 36'' S and longitude: 48° 57' 10'' and altitude 1.017 m, with tropical weather and temperatures ranging from 18 to 36ºC (IMB, 2012).

In the experiments we used corn kernels (Zeamays L.), with initial moisture content of 12.6% (B.U.), acquired by the State University of Goiás in local trade. The treatment plant of corn kernels was conducted with the use of phosphine, before starting the experiment to control pests.

We used a cylindrical metal silo (0.9 m diameter and 3 m high), made of smooth material, capable of storing 1500 kg of corn grain with specific weight of 750 kg m^{-3}.

The plenum is constructed using construction materials like brick, cement and sand. Its construction is designed to enable air to enter the silo, its dimensions were (0.30 × 1.2 × 1.2 m).

When the silo Plenum, an aeration system was adapted, it consisted of radial centrifugal fan blades, with three-phase motor 1cv, consisting of sheet metal and dimensioned to provide the air flow of 6 m^3 min^{-1}. The same was placed in a device to restrict the entry of air, hence achieving the aeration air flow 0.10 m^3 min^{-1} t^{-1}.

For determining the air flow, we used the methodology described by Delmée (1982), which was used in the Pitot tube for determining the air flow in pipes. Control of fan air flow, was given by a diaphragm positioned in the suction inlet (Figure 1).

In order to achieve the temperature of the grain after the drying process, around 30°C, a device was developed for heating of stored grains (Lawrence and Maier, 2011).

The device consisted of a metal box with dimensions of 0.50 × 0.30 × 0.35 m (Figure 2). Two finned resistors (type U) with dimensions 0.45 × 0.06 m and 1 kW were installed in the metal box so that there were no losses in the water content of the grains to the external environment. A closed system was developed with the objective of recirculated air aeration and consequent gradual

Figure 1. Diaphragm coupled to the fan for restricting the flow of air.

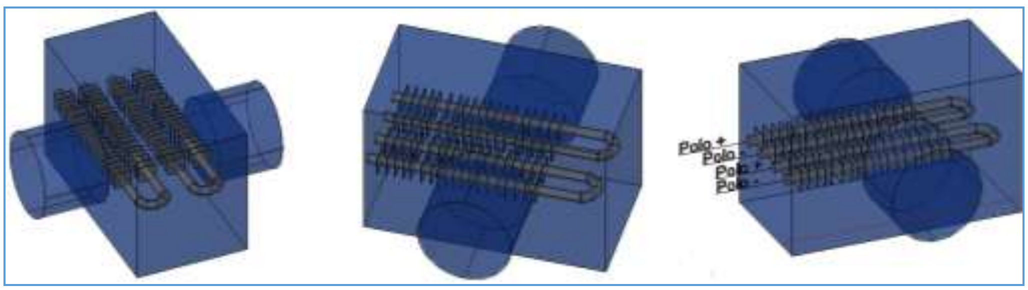

Figure 2. Device used to heat the grain mass.

increase in temperature (Lawrence and Maier, 2011). Control of the aeration system was designed by SHT 75 sensors (temperature and relative humidity) spaced 0.5 m in the grain mass with microcontroll Arduino Nano boards, relays, contacts and thermal relay, microcomputer and ventilator.

The main structure for the fan drive is guided in the components of the Arduino Nano board and Arduino 1.0.1 system, installed in the microcomputer, which controls the temperature sensors and humidity.

From the drive and return of the information from the sensors, which occurs every minute, the system turns on the fan through the relay board, which meets the criteria set out in topic 3.6 Validation of the computer program.

The Figure 3 shows the operating steps of the control system and data acquisition used to evaluate the different strategies of grain aeration process.

Reviews of developed software were performed according to the following aeration system control strategies: Continuous aeration, aeratoron 24 h, ambient air temperature control (T_{air} < 22°C ± 0.9), control via timer (aerator on from 21:00 pm to 10:00 am) and temperature control via temperature difference between the grain and the ambient air (T_{DIF} = 3°C).

RESULTS AND DISCUSSION

The storage capacity of the built silo was 1500 kg of corn grains (Zeamays L). Thus, this work was stored in 30 bags of 50 kg of maize, which were discharged vertically into the silo. The upper part of the silo has been accessed with the help of a metal ladder.

The results of the determination of the fan air flow, the pitot tube method are shown in Table 2. The average flow provided by the fan was [0.00152 ± 0.00158] $m^3 s^{-1}$. At the center pipe of 0.2 m the collected mean values were [0.00198 ± 0.0001] $m^3 s^{-1}$, as desired values (Silva et al., 2000).

The pitot tube was placed at various depths within the tube (PVC) of 0.2 m, which is being shown in Table 1 in reading position. As Macintyre (1990), the readings were spaced at 0.02 m.

The device comprises two finned resistors (type U) of 1 kW work properly when the resistors are arranged in series and connected to a cable 2.5 mm in diameter. The heating system resulted in temperatures up to 40°C, and monitored by digital thermo-hygrometer Cycloar arranged after the air outlet of the heater device.

In Table 2, to start the process, the average initial temperatures were not fixed, only the final average temperature, 30.0 ± 2.0. The various heights of the silo

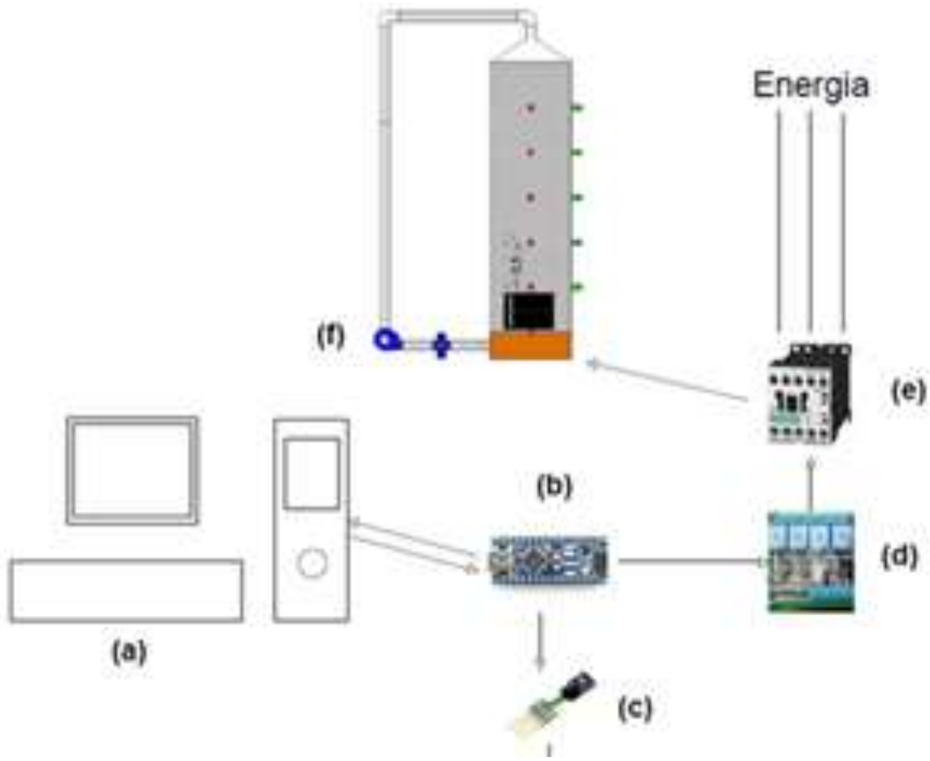

Figure 3. Control system diagram and acquisition aeration data follows the flow (a) Microcomputer (b) nano Arduino, (c) sensors, (d) relay board, (e) Contactor (f) of the fan motor.

Table 1. Means and standard deviation of speed, gauge air flow and height in different positions of the pitot tube.

Readings	Reading position (m)	Height gage (Pa)	Speed (m s^{-1})	Flow rate (LPM)	Flow rate (m^3s^{-1})
	0.02	0.980 ± 0.0	0.04 ±0.0	83.366±0.0	0.0014 ±0.0
Top edge	0.04	1.883 ± 0.107	0.06±0.002	115.477 ± 3.314	0.0019 ±0.0001
	0.06	1.687 ± 0.407	0.06±0.007	108.570±14.411	0.0018 ±0.0002
	0.08	1.765 ± 0.0	0.06±0.0	111.847 ±0.0	0.0019 ±0.0001
	0.10	1.295 ± 0.429	0.05±0.008	94.758±15.599	0.0016 ±0.0006
	0.12	0.981 ± 0.0001	0.04±0.0001	83.366 ±0.0001	0.0014 ±0.0
Center	0.14	0.981 ±0.0	0.04±0.0	83.365 ±0.0001	0.0014 ±0.0
	0.16	0.981 ±0.0	0.04±0.0	83.365 ±0.0001	0.0014 ±0.0
	0.18	0.666 ±0.161	0.04±0.004	68.318±8.553	0.0011 ±0.0001
Lower border	0.2	0.883 ±0.098	0.04±0.002	78.989 ±4.400	0.0013 ±0.0001
	Average	1.210±0.42	0.049±0.008	91.377±0.0002	0.00152±15.80

Table 2. Initial average temperature (TMI), final average temperature (TMF) and heating time for each airing strategy.

Strategy	TMI (°C)	TMF (°C)	Time (h)
a	28.5±1.22	30.98±1.33	2.5
b	25.5±0.62	33.6±0.65	8.0
c	27.2±0.35	31.2±1.41	5.2
d	27.3±0.82	31.5±1.01	6.0

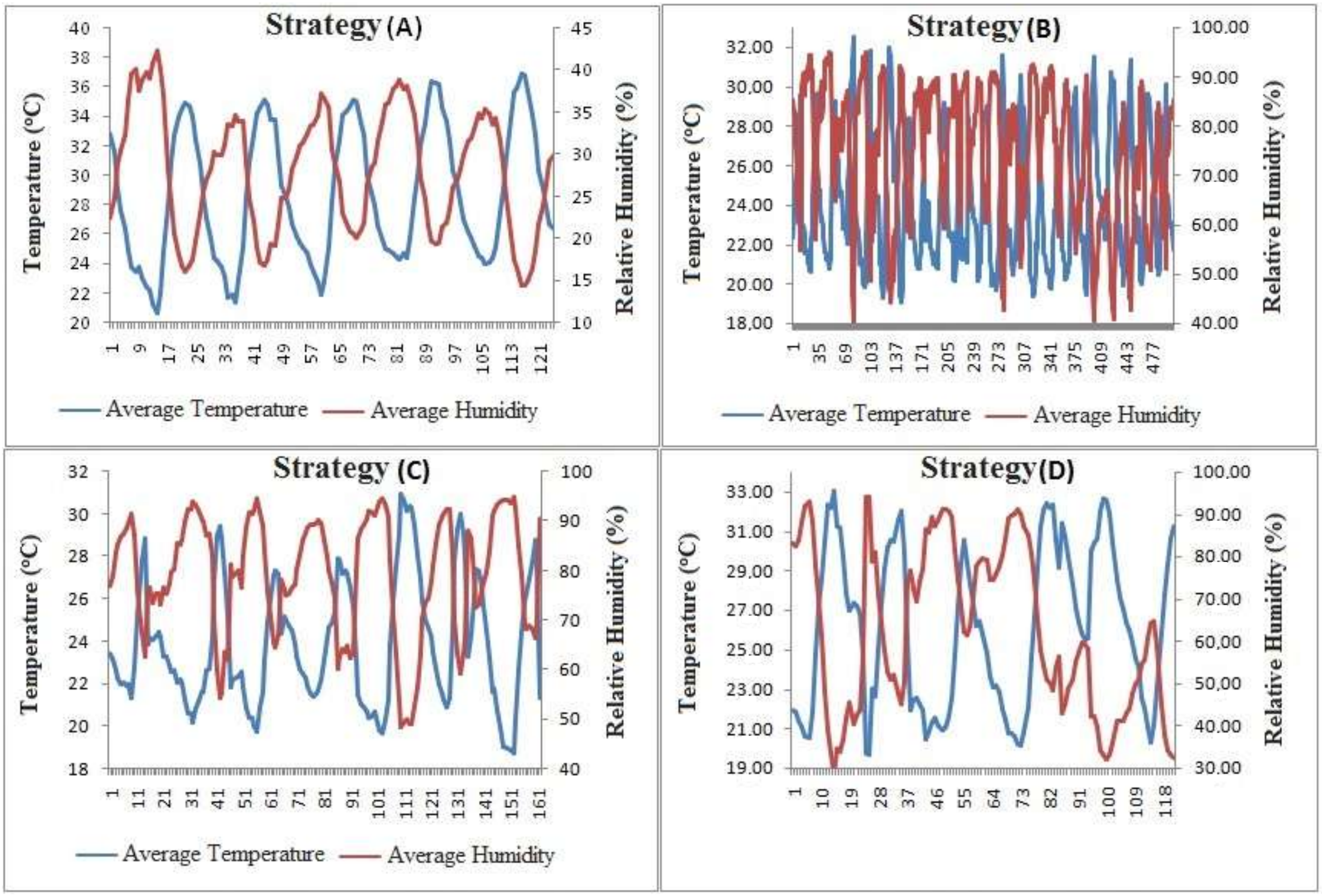

Figure 4. Averages of the ambient temperature and relative humidity during aeration strategies, b, c and d, in hours.

led different times to achieve TMF.

The heating process of the grain mass was faster in continuous ventilation strategy (a), since the initial temperature of the grain mass was 28.5°C. The total elapsed time for heating and air recirculation was 2.5 h to warm 2.4°C.

Heating the grain mass in strategy b the ambient air temperature control (T_{ar} < 22 ± 0.9°C) was conducted for a prolonged period of time due to the outside ambient temperature of 23°C. To complete the heating process, it was necessary to have 8 h to warm 8°C, since the initial average temperature of the grain mass was 25.5 ± 0.62°C.

The uniform heating of the grain mass was possible because of the prototype recirculation developed for the experiment. Figure 3 shows that the PVC pipe was connected to the fan and the top of the silo. The ventilation air outlet and the heater was placed immediately after a tubing connected to the plenum, allowing the recirculation of air.

As for the controller, it was observed that the use of Arduino was adequate for the process, since during the period of aeration of the mass of grains, the microcontroller remained in perfect operation, controlling the cooling of the grain mass, as strategy pre established. Other authors such as Cavalcante et al. (2011), Evans et al. (2013), Dilly and Mendes (2015), also cite the Arduino as functional for the acquisition of temperature and humidity data.

The strategies, during storage, environmental data and storage in silo prototype were collected to evaluate the aeration process. It was observed that the four aeration strategies, regardless of the storage time, there was cooling the grain mass, considering that all the simulations started from temperatures in the grain mass in the range of 30 to 32°C. Thus, the study corroborates other authors who also found the same cooling trend of the grain mass (Rigo et al., 2012; Lawrence and Maier, 2011).

Figure 4 shows the environmental meteorological data collected during testing of control strategies studied. Note that, the city of Anapolis - GO, with tropical climate, has striking feature, as it relates temperature and relative humidity. At night-time, it was possible to note an ambient

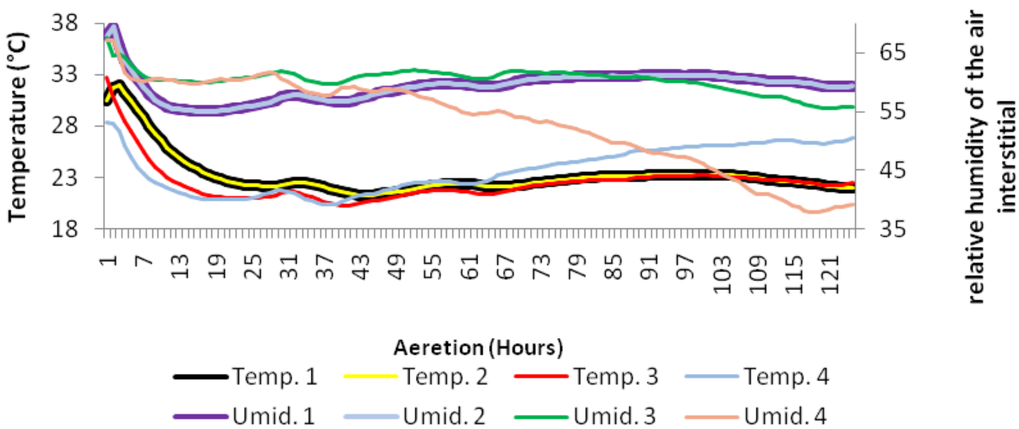

Figure 5. Means of temperature and relative humidity of the air interstitial grain silo heights in four (1, 2, 3 and 4) during continuous aeration control strategy.

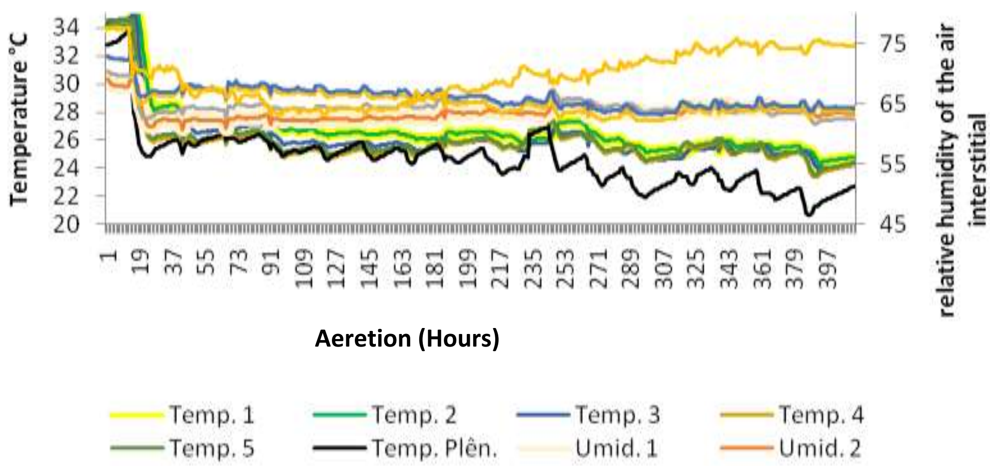

Figure 61. Medium temperature and relative humidity of interstitial air grain silo in six heights (1, 2, 3, 4, and 5 Plen) for ambient air temperature control strategy.

temperature reduction, combined with an increase in relative humidity. This characteristic shows the need for an efficient control of the aeration process of the stored grains (Lopes et al., 2015).

Control strategy, continuous aeration (a), ambient temperature ranged from 20.3 to 39.0°C and relative humidity of 12.74 to 43.7%, a fact which differed from other strategies, where their averages ranged from 18 to 32°C and relative humidity 30 to 95%, which can be explained by the beginning of the rainy season in the region.

Regarding the temperature in the grain mass, it was noted that at the beginning of the period in which the system has been in operation there occurred sudden changes in temperatures that were observed in the silo due to internal gradients, the temperature difference between the inside and the outside of the silo and a probable insect action. These temperature variations in the grain mass were observed in all strategies (Figures 5 to 8).

In the process of continuous aeration, aeration was done by a period of six days, reaching an average temperature of the grain mass is 23.3 ± 0.54°C. Temperatures lower than this could not be achieved, given the fact that ambient temperatures during the aeration process continued with a minimum of 20.5°C and maximum 39°C.

In continuous aeration strategy (a) and the room air temperature control (b) the mass of the cooling process grains can be seen intensely from 24 to 48 h of aeration. Devilla et al. (2004) and Nascimento and Queiroz (2011) also found this feature in the study of aeration of corn grain stored.

As in Figures 5 to 8, it is possible to note that in all tests the aeration mass of the cooling direction is vertically upward in the silo way, corroborating Lawrence and

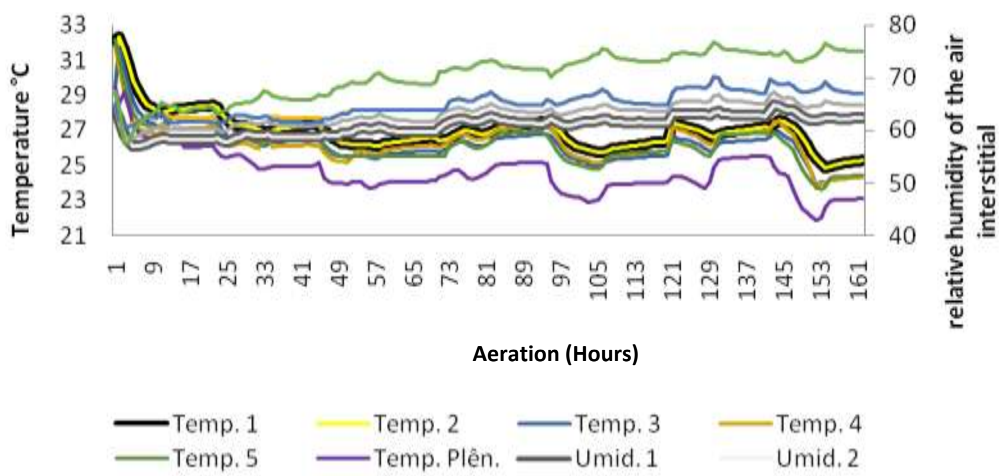

Figure 7. Means of temperature and relative humidity of the air interstitial grain silo in six times (1, 2, 3, 4, and 5 pollen) over night aeration control strategy.

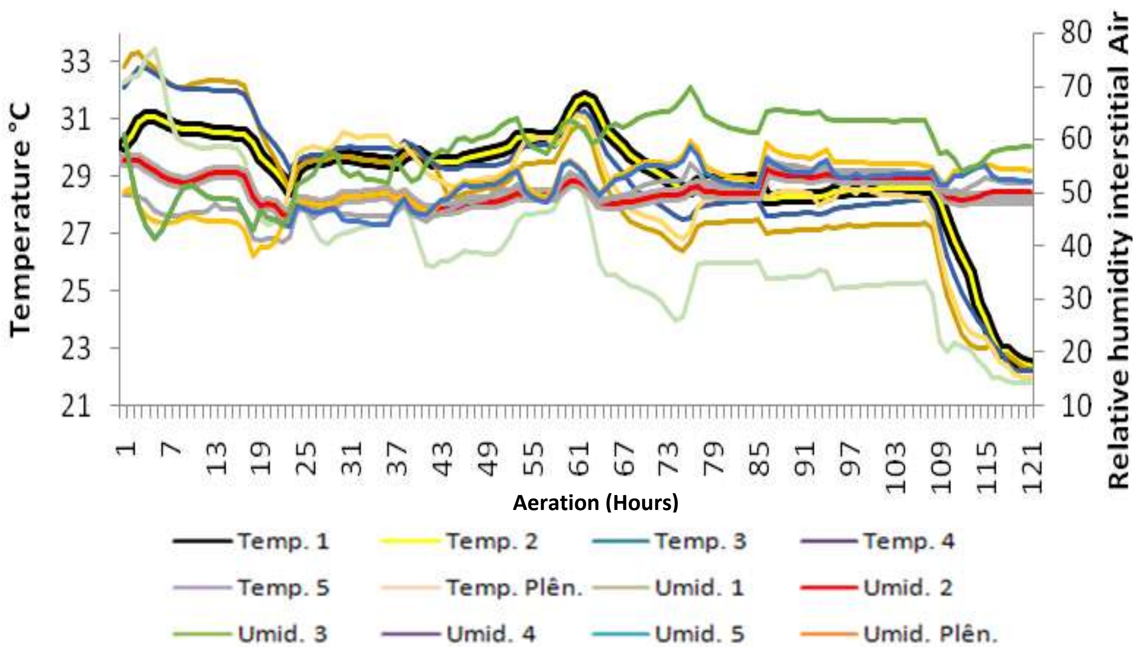

Figure 8. Means of temperature and relative humidity of the air interstitial grain silo in six times (1, 2, 3, 4, and 5 pollen). For temperature control strategy via the temperature difference between the grain and the ambient air.

Maier (2011) who also observed this fact when studying fifteen grain aeration strategies. Thus, it appears that the front of the cooling mass of the grain silo base to 1.5 m in height, making it slower subsequent to this point.

In Figure 7, it was possible to assess that when controlled aeration via timer, at night, 22 to 10 h the next day, there is a greater control of the temperature gradient of the grain mass, lengthening this way, the period of aeration is nine days. This was also by lifting by Lopes et al. (2010) when studying the effects of different control strategies in the aeration environment.

It was found that during the aeration process for all simulations, the heights (1 and 2) within the silo, showed similar temperature and relative humidity during the process. It is known that the deepest parts of the silo tend to warm very slowly, because of its low thermal conductivity (Elias, 2002; Santos, 2002; Quirino et al.,2013), however, it is known that for the upper parts of the silo is higher the influence of environment in storage.

Figure 8 relates to aeration control strategy via the temperature difference between the grain and the environment. This can be seen that in six days the grains

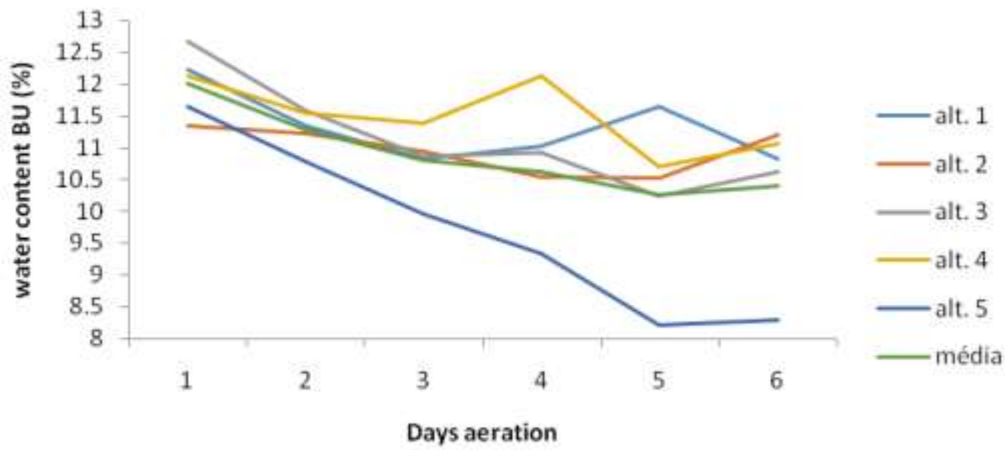

Figura 9. Grain water content em % B.U. related to six times and days in the silo aeration during continuous aeration control strategy.

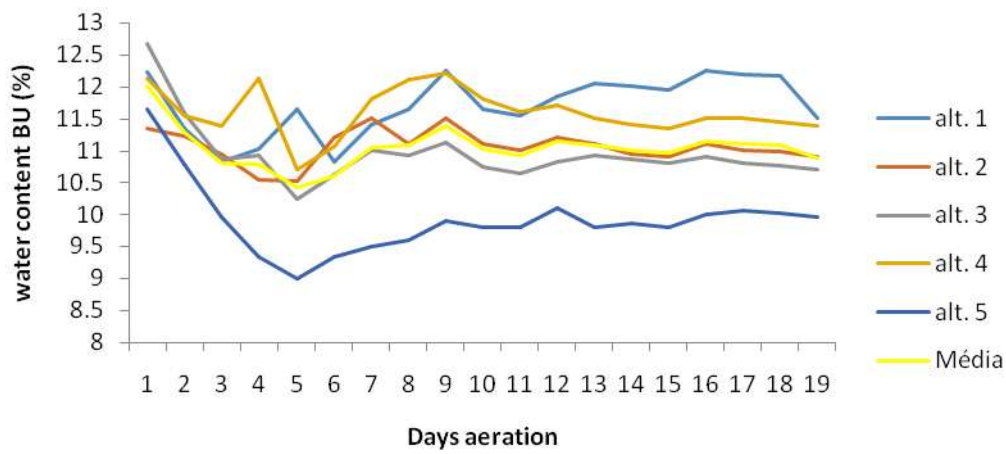

Figura 10. Water content of the grains in percentage, related to six times in the silo and days of aeration for ambient air temperature control strategy.

are cooled, which may be due to the long periods of low ambient temperature and the control strategy has been shown effective (Lopes et al., 2010).

In Figures 9 to 12 the variation of the grain water content in "% B.U." in six different heights in the storer prototype grain during test period are shown.

Based on Figure 9, continuous aeration, it is observed that there is super drying the lower profile of the grain mass, near the base of the silo, however, during the aeration process, the beans lost on average 1.6% B.U. finalizing the process with (10.39 ± 1.2)% B.U.

Note that if the top of the silo heights 1 and 2, the climatic conditions are fully exposed, win or lose water due to direct contact with the environment.

It was noted that the aeration night was the best preserved in the average grain moisture content, ranging 11.2 ± 0.64 to 11.4 ± 0.33% B.U. the end of the aeration process. Justified by environmental conditions (low night time temperatures combined with relative humidity between 50 and 65%).

In control via temperature difference between the beans and the ambient air the aeration process began with an average water content of [10.55 ± 0.8]% B.U, and was completed with 11.22 ± 1.0% B.U. Already airing via the external environment temperature control, allowed an average variation in grain moisture content of 12 ± 0.51 to 10.88 ± 0.62% B.U.

Through the strategies for, climate control of air (b), night aeration (c), and control via the temperature difference between the grains and the environment (d), it was possible to reach temperatures significantly affect the proliferation of insect pests in grain mass stored (Table 3).

It is known that temperatures between 27 and 34°C are permissible proliferation of most insect pests of stored grains in tropical and subtropical regions (ARO, 2014).

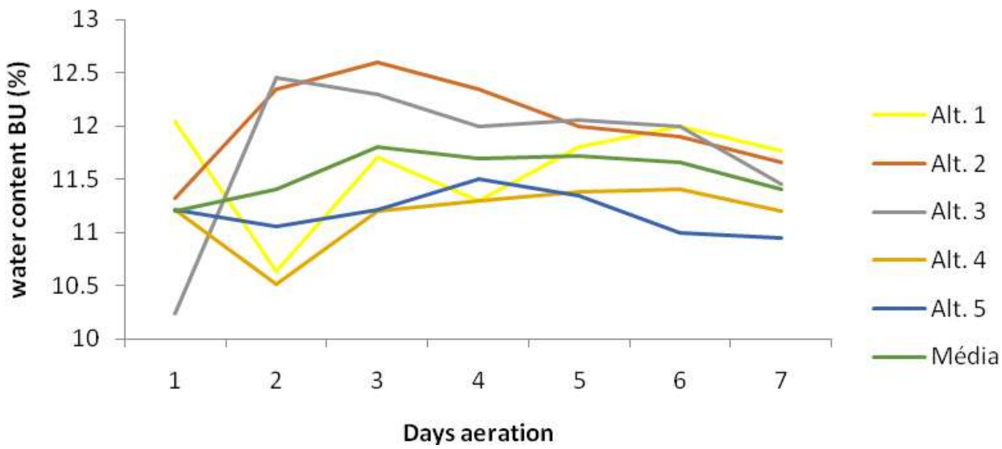

Figura 11. Grain water content in percentage, related to six times and days in the silo aeration, aeration during night time control strategy.

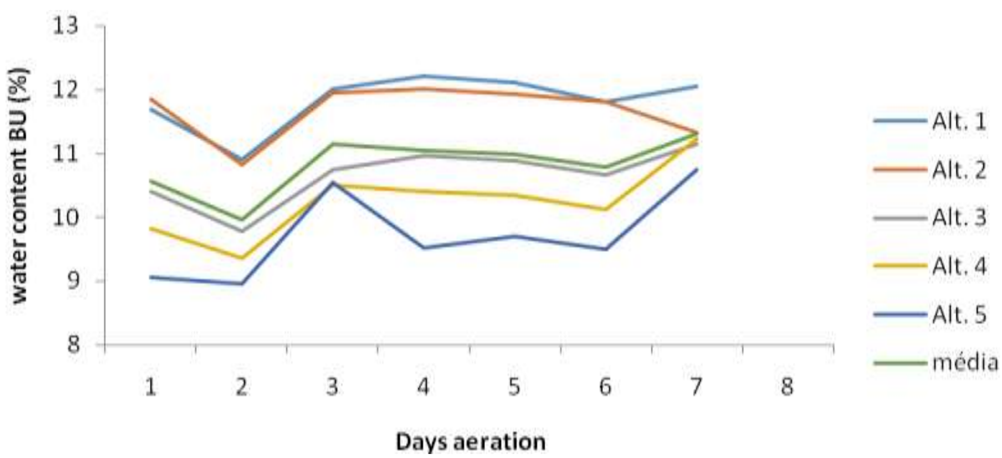

Figura 12. Grain water content in percentage, related to six times and days in the silo aeration for temperature control strategy via the temperature difference between the grain and the ambient air.

Table 3. Means and standard deviation of temperature in the strategies a, b, c and d related heights in silo.

Strategy	Height in silo						Mean
	1	2	3	4	5	Alt. Plen.	
a	23.6±1.99	23.6±1.99	23.3±2.17	22.5±1.60	-	-	23.3±0.50
b	24.0±1.91	23.8±1.92	23.9±1.77	23.3±1.87	23.5±1.76	20.6±2.21	23.2±0.85
c	24.8±1.06	24.8±1.06	23.2±0.95	23.8±1.06	23.5±1.05	21.9±1.94	23.7±0.85
d	22.4±1.51	22.4±1.51	22.2±1.43	22.3±2.12	22.0±1.98	21.8±2.31	22.2±0.95

However, the growth is suppressed by such temperature of 17 to 22°C (Garcia et al., 2000; Navarro and Noyes, 2010). Thus, it was found that the strategy d, temperature control between the grains, and environment <3 degrees Celsius was the best strategy, then the strategy B, temperature control air.

Figure 13 shows the period of operation of the aeration blower, wherein the aeration strategy d, controlling the aeration means of temperature difference between the grain and the ambient air was more economical in terms of consumption of electric power, and seen that for the mass of cooling grain using the "d" strategy was

Table 3. Means and standard deviation of temperature in the strategies a, b, c and d related heights in silo.

Strategy	Height in silo						Mean
	1	2	3	4	5	Alt. Plen.	
a	23.6±1.99	23.6±1.99	23.3±2.17	22.5±1.60	-	-	23.3±0.50
b	24.0±1.91	23.8±1.92	23.9±1.77	23.3±1.87	23.5±1.76	20.6±2.21	23.2±0.85
c	24.8±1.06	24.8±1.06	23.2±0.95	23.8±1.06	23.5±1.05	21.9±1.94	23.7±0.85
d	22.4±1.51	22.4±1.51	22.2±1.43	22.3±2.12	22.0±1.98	21.8±2.31	22.2±0.95

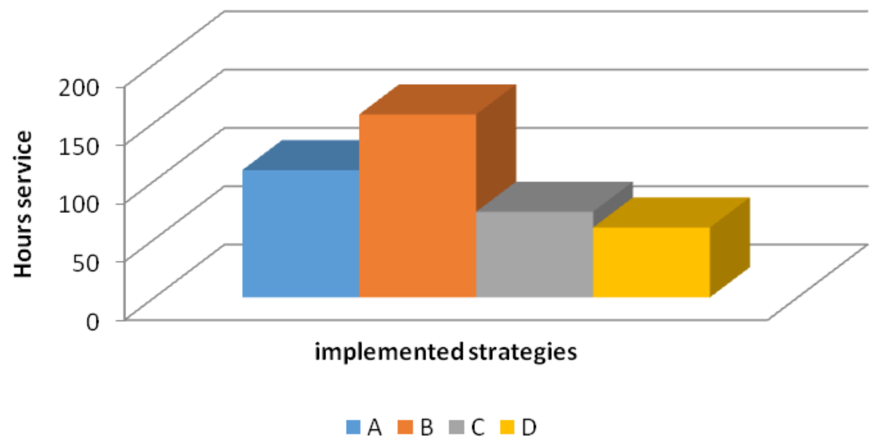

Figura 13. Number of hours with the fan on in the different evaluated aeration strategies.

completed with 60 h of ventilation. Then, the night aeration strategy was also economical, spending 73 h to cool the grain mass. Similar results were found by Lawrence and Maier (2011), when evaluated several controls for aeration of stored grains and concluded that flow rates of 0.1 $m^3 min^{-1} t^{-1}$ combined with temperature control strategies culminate in lower power consumption.

Conclusion

According to the results obtained and the conditions in which it was developed this work, it can be concluded that:

1. Operational results obtained with the software developed, were effective for control of grain aeration processes stored in the prototype.
2. The prototype for storage and control of aeration of stored grain was efficient in grain storage control process.
3. The control strategies, aeration of grain via the temperature difference between the grains and environment (TDIF = 3°C) and night aeration (21 to 10 h next day), were effective for the aeration process in Annapolis- GO.
4. Temperature and humidity data related to corn grain storage were collected and proved the efficiency of computational and structural system.

Conflict of Interests

The authors have not declared any conflict of interests.

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