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Biosystems Engineering

Research Paper: PH—Postharvest Technology

Management of stored maize by AERO controller in five Brazilian locations: a simulation study

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ARTICLE INFO

Article history:
Received 11 June 2008
Received in revised form
22 July 2008
Accepted 2 September 2008
Published online 26 October 2008

A simulation model was used to quantify the effect of the AERO controller on dry matter loss, moisture content, grain temperature and required aeration time for five Brazilian States during one year. The application focused on maize because it is the dominant crop in the regions studied, but the analyses can be applied to other grains and locations as well. Decision making of the AERO controller is based on simulation of the aeration process and on real time data acquisition. It proved to be an effective strategy and showed its significant potential as a non-chemical preventative practice for safe storage.

1. Introduction

When grains are placed into storage they are exposed to a broad range of complex ecological factors that work against the stored grain manager's objective of maintaining grain quality. Grain temperature is important because it directly affects grain quality, development of pests and dry matter losses (Maier *et al.*, 1996). But the moisture content is also a significant factor since the lower it is, less susceptible grains are to spoilage by insects, mites or fungi (Longstaff, 1994).

It is usual practice to implement preventive management, rather than to solve specific storage problems once they have occurred. Aeration is a well-known and proven Integrated Pest Management tool for controlling the quality of stored grain. The two primary objectives of aeration are to maintain uniform temperatures inside the bin and keep temperatures below the limits for insect and fungal development (Navarro and Noyes, 2001). However, this technique remains an underused tool in some situations, particularly in warm climates such as in Brazil. Thus, the development of appropriate control strategies will enable aeration to be more widely and efficiently used in these regions.

When ambient aeration is used, it is very important to operate the system during appropriate conditions for efficient storage management. The AERO controller is a promising strategy which was developed with the objectives of maintaining grain quality with minimal energy input, automatically adjusting its set points according to different climates and storage systems based on real time data acquisition and on simulations of the aeration process (Lopes, 2006).

As simulation of a grain storage ecosystem is less expensive and a time-saving alternative to field research, in this study simulations were carried out to evaluate the effectiveness of AERO control strategy for maintaining safe storage of maize in five Brazilian locations.

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1537-5110/$ – see front matter
doi:10.1016/j.biosystemseng.2008.09.001

Nomenclature

c_a	specific heat of air (J kg^{-1} °C^{-1})
c_g	specific heat of dry grain (J kg^{-1} °C^{-1})
c_w	specific heat of water (J kg^{-1} °C^{-1})
h_v	latent heat of vaporization of water (J kg^{-1})
h_s	differential heat of sorption (J kg^{-1})
U	grain moisture content (% d.b.)
m_s	dry matter loss of grains (%)
Q_r	heat of oxidation of grain (J s^{-1} m^{-3})
T_a	air temperature in equilibrium with the grain (°C)
T	time (s)
u_a	aeration air velocity (m s^{-1})
R	humidity ratio of air (kg kg^{-1})
Y	vertical coordinate (m)
ε	grain porosity (decimal)
ρ_a	density of intergranular air (kg m^{-3})
ρ_b	bulk density of the grain (kg m^{-3})
θ	grain temperature (°C)
M_M	moisture modifier (dimensionless)
M_T	temperature modifier (dimensionless)

Fig. 1 – Geographical location of Brazilian States considered in this study.

2. Methodology

The simulation model used in this work can be applied to several grains and aeration systems. This study focused on maize because it is one of the crops whose production has increased most in Brazil during recent years. In 2007 the area planted with maize was 14.3 million hectares and the national production was 52.3 million tonnes (Conab, 2007).

In Brazil, the first crop of maize is grown during the rainy season, between September and November, and represents 75% of the national production of this cereal. Of this, the South region contributes 40.0% followed by Southeast and Mid-West which represent 34.7% and 12.0%, respectively. State of Paraná is the largest maize producer in Brazil. This State is located in the South region and represents 23.1% of the national production. In Southeast the major producers are the States of Minas Gerais and São Paulo, which represent 22.3% and 11.9% of the Brazilian maize production, respectively. In Mid-West, the States of Mato Grosso and Goiás produce 1.9% and 7.9% of the maize grown in Brazil (Embrapa, 2007).

Thus, simulations were carried out for Paraná (PR), Mato Grosso (MT), Goiás (GO), Minas Gerais (MG) and São Paulo (SP). These Brazilian States (Fig. 1) were represented by the cities of Nova Cantu, Cuiabá, Jataí, Araxá and Taquarivaí, respectively. Cities were selected based on their maize production, as related by Ibge (2008), and on the availability of weather data obtained from Cptec (2008).

Nova Cantu is located at an altitude of 555 m, 24°40′22″ S latitude and 52°34′08″ W longitude. Iapar (2000) classifies the weather of this city as Cfa according to Koppen climate classification. It is humid subtropical with an average temperature in the coldest month less than 18 °C (mesotherm) and in the warmest month greater than 22 °C. Frosts are not frequent and summer is hot and rainy.

Taquarivaí is located at 682 m altitude, 23°55′28″ S latitude and 48°41′35″ W longitude. According to Ferraro (2006), the weather at this location is Cfb by Koppen classification. It is dominated throughout the year by the polar front, leading to changeable, often overcast weather. Summers are cool due to cloud cover, but winters are milder than other climates at similar latitudes. This city has average annual maximum and minimum temperatures around 26 °C and 14 °C, respectively.

Araxá, Jataí and Cuiabá are predominantly Aw Koppen type, presenting two well-defined seasons: a rainy summer and a dry winter. Araxá is located at 1000 m altitude, 19°35′33″ S latitude and 46°56′26″ W longitude. As related by Rocha and Rosa (2007), in this city every month has an average temperature of 21 °C. Jataí is located at 696 m altitude, 17°49′46″ S latitude and 51° 46′ 29″ W longitude. Sousa *et al.* (1997) affirmed that minimum temperatures are around 15 °C during winter and maximum temperatures are greater than 22 °C. According to Curi and Campelo Júnior (2001), Cuiabá is located at 176 m altitude, 15°35′52″ S latitude and 56°5′27″ W longitude with average monthly temperatures ranging from 22 °C to 27 °C.

Ambient dry bulb temperatures and relative humidities of the five Brazilian locations were collected every 3 h, from March 2007 to February 2008 according to data obtained from the Cptec (Centro de Previsão de Tempo e Estudos Climáticos – Center for Weather Prediction and Climate Research), which has 620 automatic meteorological stations located in different Brazilian cities.

Simulations started in March as this is the month in which most of the first maize crop is stored. One year of storage was simulated, corresponding to 8760 h. During simulations the use of the AERO controller was considered for each location. This strategy was developed based on the recommendations presented by Navarro and Noyes (2001), Lacerda Filho and Afonso (1992) and Martins *et al.* (2001). Four conditions are analyzed for the AERO controller using the simulation results to determine fan operation based on real time data acquisition. According to these conditions the aeration system can be turned on, turned off or maintained its previous state.

The first condition evaluated by AERO indicates turning the fan on if the dew point temperature of the aeration air is lower than the minimum grain temperature, thus minimizing the possibility of condensation in the grain bulk. According to the second condition, the fan can be turned on if the difference between the simulated grain moisture content and the safe one is less than 0.5 percentage points or is smaller than the actual one. Thus, the moisture content of grains is always kept at a safe level. Temperature management is based on two conditions. To equalize grain temperatures, the fan can be turned on if a difference greater than 5 °C is observed inside the bin and if the simulated difference is smaller than the real one. The fan can also be turned on if the simulated temperature for one of the grain sections is smaller than the real one equivalent to it or if the simulated average grain temperature is smaller than the real one, assuring cooling whenever it is possible (Lopes *et al.*, 2008).

Other input data for the simulations were grain bulk density (746 kg m^{-3}), initial grain temperature (30 °C), moisture content (13.5% w.b.), bin diameter (12 m), grain mass depth (10 m), aeration airflow (0.0012 m^3 s^{-1} m^{-3}) and altitudes of the locations. Initial grain temperature, moisture content and bulk density were selected based on average harvest conditions for Brazil and simulations used round upright bins.

A one-dimensional mathematical model based on psychometric relationships and on energy and mass balances was used to simulate the aeration process. This model was proposed by Lopes *et al.* (2006) based on that formulated by Thorpe (1997) and presented in more detail by Thorpe (2001). With this model it is possible to predict the distributions of temperature, moisture content and dry matter loss within the grain mass. The differential equations used by the model to describe the heat and mass transfer in an aerated bulk of grain are expressed as

$$\frac{\partial\theta}{\partial t}\left\{\rho_b\left[c_g + c_w U + \frac{\partial H_w}{\partial T_a}\right] + \varepsilon\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T_a}\right)\right]\right\} = \rho_b h_s\frac{\partial U}{\partial t} - u_a\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T_a}\right)\right]\frac{\partial\theta}{\partial y} + k_{eff}\frac{\partial^2\theta}{\partial y^2} + \rho_b\frac{dm_s}{dt}(Q_r - 0.6h_v) \quad (1)$$

$$\frac{\partial U}{\partial t}\rho_b = \rho_a D_{eff}\frac{\partial^2 R}{\partial y^2} - \rho_a u_a\frac{\partial R}{\partial y} + \frac{dm_s}{dt}(0.6 + U) \quad (2)$$

The simulation model also includes the method developed by Thompson (1972) and presented by Thorpe (2001) to determine the dry matter loss, as described by Eq. (3).

$$m_s = 8.83\times10^{-4}\left\{\exp\left(1.667\times10^{-6}\frac{t}{M_M M_T}\right) - 1\right\} + 2.833\times10^{-9}\frac{t}{M_M M_T} \quad (3)$$

The terms M_M (moisture modifier) and M_T (temperature modifier) can be calculated by empirical equations presented by Thorpe (2001) and Lopes *et al.* (2006).

During simulations, the grain bulks were divided into fifteen sections in the vertical direction and the grain moisture contents, temperatures and dry matter losses were calculated after a time interval of 1 h for each section in an iterative way by using numerical analysis.

The fan state (on or off) was checked for each time step according to the AERO control strategy. Thus, for each time step an additional simulation was executed to verify the effects of aeration with the fan turned on during the next hour. After analyzing the control strategy, the model was executed to simulate storage conditions considering the fan state indicated by the controller and results were used as actual data. When AERO indicated that the fan should be turned off, the airflow rate considered by the simulation model was set to a very low value (10^{-8} m^3 s^{-1} m^{-3}) indicating almost no airflow through the grain mass. When the fan was turned on, input airflow was used.

3. Results and discussion

Comparison of the effects of AERO in different Brazilian regions was based on the ability to minimize the potential for spoilage, fungi activity and insect development. These were defined by the accumulation of dry matter loss, moisture content control, grain temperature uniformity, grain cooling and required aeration time.

As shown in Fig. 2, all locations required similar aeration times. Of course presented values were influenced by the suitable daily aeration hours for cooling in each region. Also, the time required to cool grain depended greatly on the airflow rate.

It is to be expected that smaller airflow rates would increase the aeration time, which could prejudice the control of temperature and moisture of grain. On the other hand, increased airflow would result in proportional reduction in cooling time but would also increase the energy consumption. In this study, the number of aeration hours agreed well with those presented by Navarro and Noyes (2001) where several experimental trials were reviewed and their results were compared with mathematical calculations. These comparisons showed that, although the theoretical amount of aeration hours needed to cool the grain is much less, actual fan operation hours could be in the range of 500–600 h at an average airflow rate of 0.0013 m^3 s^{-1} m^{-3} when grain are submitted to suitable aeration control strategies due to weather fluctuations during experimental trials.

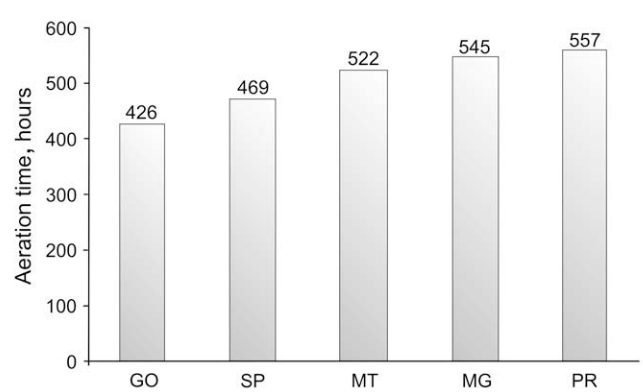

Fig. 2 – Simulated number of aeration hours required when using the AERO controller at five Brazilian locations.

Fig. 3 presents simulated dry matter loss for each location. Again for this case, the behaviours of the five States were similar. Dry matter losses were larger as the total duration of aeration was smaller. All regions reached maximum dry matter losses below 0.14%.

Dry matter loss results demonstrate that maize controlled by AERO can be stored for more than one year in the Brazilian regions studied without significant risk of spoilage. Simulated values were much less than 0.3%, which is considered a large enough deterioration to affect the final market value of grains in Brazil. These successful results can be explained by the capacity of AERO to reduce and equalize grain temperatures and also maintain safe moisture contents inside the bin, taking the greatest advantage of the available conditions in different regions.

As shown in Fig. 4, safe moisture contents were successfully maintained for all locations studied. During the whole period studied all simulated moisture contents ranged from 13.5% to 12.6% w.b., corresponding to equilibrium relative humidities between 55% and 70% when considering temperatures from 15 °C to 30 °C. As reported by Weinberg *et al.* (2008), under these conditions the development of microorganisms can be efficiently prevented.

From March to June, an average drop of 0.9 percentage points in simulated moisture contents was observed. During this period, the aeration system operation was more intense for all locations since the control strategy was performed to equalize grain temperatures progressively with decreases in ambient air temperature. So, aeration air absorbed energy from grain which decreased its relative humidity. With this, grain tended to equilibrate its moisture content with the air, which was at a lower level than the grain relative humidity.

Fig. 5 presents the average bulk temperatures throughout the whole simulated period. On an average, the AERO controller reduced grain temperatures from March to June from 30 °C to 16 °C. At the end of the simulated period, grain temperatures varied from 14.4 °C to 19.77 °C for the five Brazilian locations.

Warming of grain occurred mainly from March to May and from August to February, probably because low ambient aeration temperatures and suitable relative humidities were not available all the time. Thus, the initial high grain temperatures were reduced by stages during the coldest months and a progressive increase of them was noted during most of spring and summer. From this simulated data it is possible to verify that ambient aeration could be effective in cooling grain in different Brazilian regions and that it is being controlled by a suitable strategy.

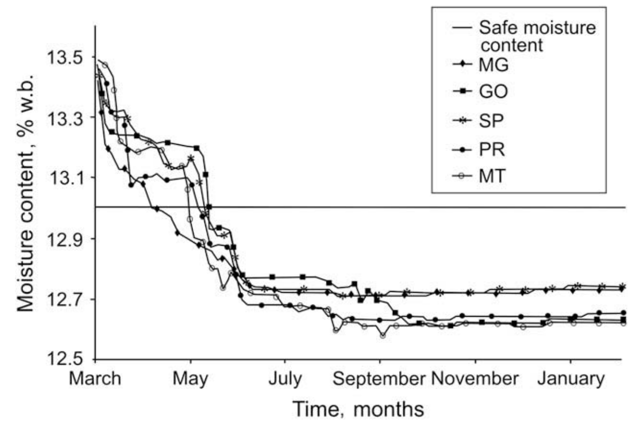

Fig. 4 – Simulated moisture contents when using the AERO controller at five Brazilian locations.

As shown in Fig. 6, stored grain in the five Brazilian locations maintained uniform temperatures (with differences between 3 °C and 5 °C or below 3 °C inside the bin) during most of the simulated time. This control is very important since it minimizes the risk of moisture migration and under-roof condensation. These results also confirm the effectiveness of the AERO controller in maintaining stored grain under safe conditions during long periods of time in different regions.

Of course, the energy costs associated with an aeration system depend on the grain type, bin size, fan horsepower, electrical cost and other. But, the results indicated that the use of the AERO controller is economically feasible. The energy consumption of the aeration treatments varied from 0.18 to 0.23 kWh/ t^{-1}, which corresponds to a cost of about 0.2 US\$ t^{-1}, considering an electrical cost of 0.10 US\$ kWh^{-1}. Beyond the electrical costs, it should be considered that, using the AERO controller, the need for fumigation will be minimized as well as the labour costs, making this system more competitive and economically attractive.

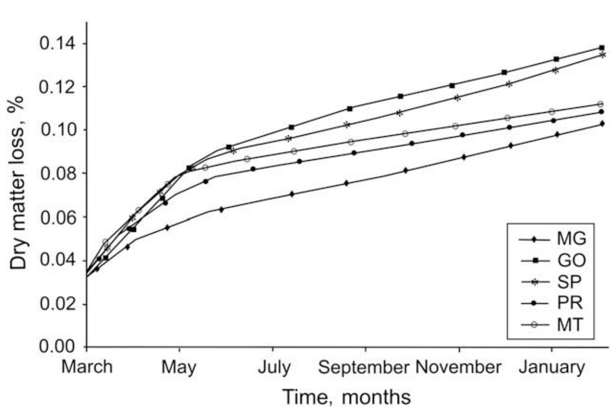

Fig. 3 – Simulated dry matter losses when using the AERO controller at five Brazilian locations.

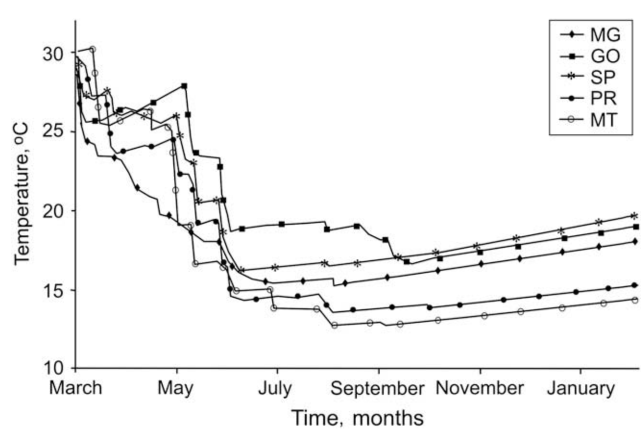

Fig. 5 – Simulated average bulk temperatures when using the AERO at five Brazilian locations.

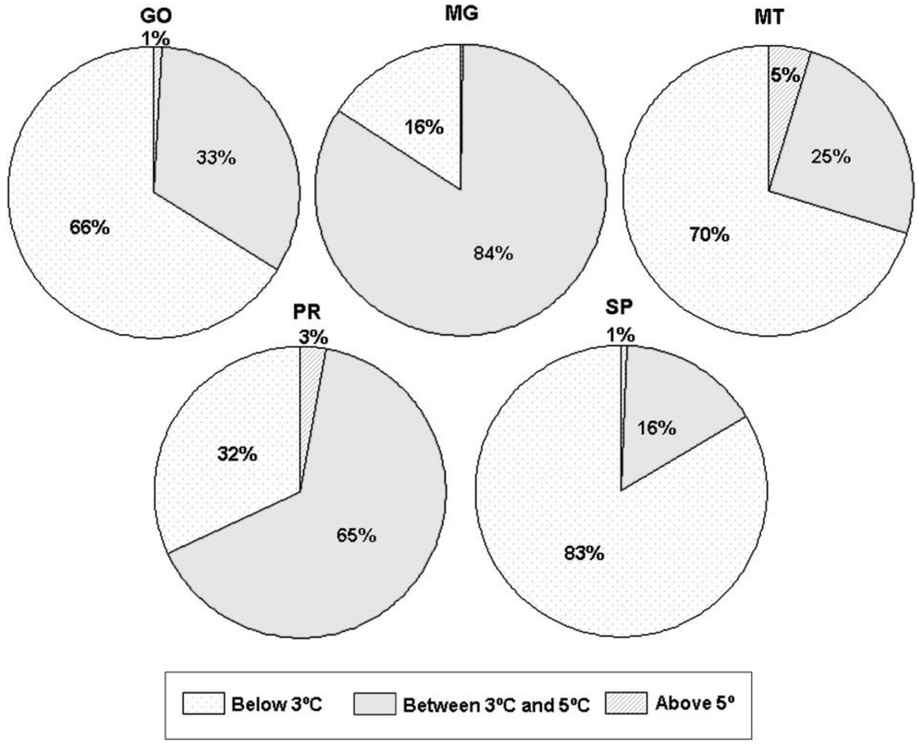

Fig. 6 – Percentages of grain temperature differences considering the whole simulated period and the AERO controller use at five Brazilian locations.

4. Conclusion

Results presented in this work confirm that the quality of the maize stored in different Brazilian regions can be efficiently controlled with the AERO strategy for long periods assuring safe storage conditions. The simulation model can also be applied to other grains and aeration systems. The software AERO is available for download at www.evandro.eng/agroinformatica. With this free version of the software it is possible to simulate different control strategies, including that discussed in this work, with different grain types and aeration systems designs. Also, it is possible to use variable ambient data as input data and simulate hot spots inside the bin.

Acknowledgements

Authors would like to thank the FAPEMIG (Fundação de Amparo à Pesquisa de Minas Gerais) for the financial support.

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