AUTOMATIC CONTROL SIMULATION FOR STORED GRAIN AERATION SYSTEMS USING MATLAB AND SIMULINK

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ABSTRACT

In several regions of the world both grain quality and quantity losses during storage may be prevented by means of aeration. However, it is important a correct management of the aeration systems to prevent over drying, condensation, or absorption. This management may be accomplished using an appropriate data acquisition and an automatic controller to operate the aeration system. In this work it is demonstrated by simulation that the **SIMULINK** toolbox, in conjunction with **MATLAB** functions, may be used to control the aeration process in a real world storage facility by real time data acquisition of the grain mass temperature, ambient air temperature, and relative humidity.

Notation

λ	heat of vaporisation, kJ/kg	G	flow rate, m^3/min.kg
h	air enthalpy, kJ/kg-dry air	ρ	density, kg/m^3
H	air relative humidity, decimal		**Subscripts:**
M	moisture content, %, dry basis	a	air
P	pressure, kPa	atm	atmospheric
T	air temperature, °C	e	equilibrium
t	grain cooling time, h	f	final
θ	grain temperature, °C	g	grain
W	weight, kg	i	inlet
w	air absolute humidity, kg/kg	o	initial
C	specific heat, kJ/kg.°C	v	vapour
k, n, c	Henderson equation parameters	vs	saturated vapour

1. INTRODUCTION

Agricultural grains are live biological materials and are, therefore, subject to transformations of diverse natures, originated from the technology applied to the storage and processing systems.

The main sources of both grain quality and quantity losses during storage are fungi, insects, acarus, and rodents. The respiration also may contribute for dry matter loss, although this loss is small when compared to those caused by live organisms.

The secret to maintain a stored grain in good conditions is to keep the grains under uniformly cool and dry conditions. This can be accomplished in several regions of the world by means of aeration: forced movement of ambient air through stored grain to decrease

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or increase the grain temperature to the desired level (Maier & Montross, 1997).

The aeration may have different effects on the grain mass depending, basically, on the ambient and product conditions. It is essential to make a prediction about the possible results before turning on the aeration system.

The use of aeration techniques on a storage system may attend several objectives, described as follows:

1. to establish conditions that allow for cooling of hot spots in the grain mass;
2. to equalise the temperature in the grain mass;
3. to prevent the heating and humidifying of the grains;
4. to promote drying within certain limits;
5. to remove odours from the grain mass.

When grain is dried slowly and/or aerated, its moisture comes into equilibrium with the interstitial air temperature and relative humidity (H) of the drying or storage environment. If air temperature increases at constant H, the equilibrium moisture content of the grain (EMC) will decrease. If H increases at constant temperature, the EMC will increase. Therefore, knowing the relationship between EMC and air conditions is important in properly managing aeration systems to prevent over drying, condensation, or absorption. This knowledge may be used as a managing strategy to develop and/or implement and automatic control system for the aeration process.

The objective of this work is to demonstrate by simulation that it is possible to develop an automatic controller for grain aeration systems based exclusively upon the external ambient conditions and the conditions inside the grain mass, without the need for historical meteorological data.

2. THE AERATION PROCESS

2.1. Aeration Background

The aeration process consists of forced movement of ambient air through stored grain to decrease or increase the grain temperature to the desired level. However, the main objective and major utility of the aeration is the cooling of the grain mass, as the microclimate formed inside the grain mass may bring up several benefits to the grain preservation process (Lacerda Filho & Silva, 1995).

After the grain have been dried, cooled and stored with a moisture content between 13 and 15% w.b. (wet basis), its temperature in tropical climates is frequently well above the ambient mean temperature. Therefore, the grains close to the silo walls and those on the surface start to cool until they reach a temperature below that of the interior of the grain mass. The resulting temperature gradient causes natural convection streams of hot and humid intergranular air that promotes moisture condensation on the surface of the colder grain mass. This process causes a moisture content increasing, resulting in crusting and moulding on a grain layer of 30-50 cm deep at the silo centre (Brooker et al., 1992). This is called moisture migration (Figure 1) and may be prevented by aeration.

The time necessary to cool a grain mass may be precisely determined by simulation. If the grain is stored in a silo with a perforated floor, the stationary bed model described by Brooker et al. (1992) may be used for the simulation. Appropriate thickness of the grain layer, initial temperature and grain moisture, selected airflow rates, and expected climate conditions (dry bulb and wet bulb temperatures) should be used. The solution of the model gives the time required for the aeration process to cool a grain mass to a temperature range of 3-5ºC, below the ambient temperature at a selected airflow rate, or for the cooling front to move completely throughout the grain mass. Due to the complexity of the simulation, a simplified method based on a simple heat balance is frequently used to estimate the aeration time required for reducing the grain temperature to a desired level by the following expression:

$$t = \frac{W_g\, C_g\,(\theta_o - \theta_f)}{G_a\, \rho_a\, C_a(\theta_o - T_i) + G_a\, \rho_a \lambda_g (w_i - w_f)} \quad (1)$$

2.2. Aeration Systems

An aeration system consists of a fan, an air supplying duct, aeration ducts (or perforated floors), and a fan controller (ranging from a simple on-off switch manually operated to a state-of-the-art computer-based system). The fan may be either of centrifugal or axial type, depending on the static pressure and airflow rate required by the storage unit (Maier & Montross, 1997). Details about projects of aeration systems may be found in the specialised literature such as Lacerda Filho & Silva (1995), and Lasseran (1981).

2.3. Aeration Controllers

The control of an aeration system on a silo or store is normally made by temperature measurements in the interior of the stored grain mass. When the temperature in the grain mass reaches a critical value above the ambient temperature, a control system (manual or automatic) turns on the fan which will furnish the sufficient amount of air throughout the grain mass to promote its cooling after a pre established period of time. Details may be found in the specialised literature such as Navarro et al. (1982), Brooker et al. (1992) and Maier & Montross (1997).

In order to perform the control task, aeration systems normally contain a monitoring system that indicates the internal and external ambient conditions of the grain mass. In some cases this system may be used to turn the ventilation system on or off according to the ambient conditions (Lacerda Filho & Silva, 1995; Brooker et al., 1992; Lasseran, 1981).

3. MATERIAL AND METHODS

3.1. Computer Program Development

A computer program was developed using **MATLAB/SIMULINK** language (Chen et al*.,* 1999; MATLAB, 1996; SIMULINK, 1996) to simulate the aeration process in a grain storage unit based on the relationships between the equilibrium moisture content (EMC) of the grain and air conditions.

The program-input parameters are the ambient temperature and relative humidity, the grain initial temperature and moisture content, and local atmospheric pressure.

The grain moisture content is supposed to be kept constant. Therefore, the maximum relative humidity of the air in equilibrium with the grain mass may be calculated using a specific equilibrium moisture content equation for the product. The modified Henderson equation for maize is used in this work (Brooker et al., 1992):

$$H = 1.00 - \exp\left[-k\left(T + c\right)M_e^n\right] \tag{2}$$

Knowing the maximum relative humidity inside the grain mass, and the outside ambient air temperature and relative humidity, an adiabatic equilibrium temperature inside the grain mass is calculated in order to maintain constant the grain moisture content. This is the equilibrium temperature achievable by the grain mass after it had been exposed to the ambient air under these conditions. This temperature may be above or below the ambient air temperature, depending on both the grain moisture content and the outside ambient conditions. This temperature can be calculated by an iterative method to find the root of the following equation:

$$w = \frac{h - 1.006T_e}{2501 + 1.775T_e} \tag{3}$$

To calculate T_e in Equation (3) the following auxiliary equations are necessary:

$$P_{vs} = 0.61078\left[10^{\left(\frac{7.5T}{237.3+T}\right)}\right] \tag{4}$$

for T > 0

$$P_{vs} = 0.61078\left[10^{\left(\frac{9.5T}{265.5+T}\right)}\right] \tag{5}$$

for T < 0

$$P_v = H \cdot P_{vs} \tag{6}$$

$$w = \frac{0.62198\,Pv}{P_{atm} - P_v} \tag{7}$$

$$h = 1.006T + w\left(2501 + 1.775T\right) \tag{8}$$

Considering that the grain moisture content must be kept constant, and the air dry bulb temperature and relative humidity are available at any time, the equilibrium relative humidity (H_e) can be calculated by Equation (2). Using the Equations (4) to (8) the enthalpy of the air can be calculated. Therefore, the iterative procedure consists in following the adiabatic line by keeping the enthalpy constant until finding a value for the equilibrium temperature that satisfies the condition H = $H_{e.}$ Iteratively calculating and recalculating H as a function of absolute humidity (w) and equilibrium temperature (Te) can perform this by using the following expression, until it converges:

$$H = \frac{P_{atm}\, w}{P_{vs}\left(0.618 + w\right)} \tag{9}$$

In each iterate the equilibrium temperature (T_e) is incremented or decremented accordingly by a pre-defined step value. In the first iteration T_e is equal the air temperature decremented by one step value.

3.2. Simulation and System Operation

The simulation model was developed based up on the relationships between the grain equilibrium moisture content and air conditions. The system operation must fulfil the condition established in the computer program, according to a pre-defined strategy, which may be modified at any time by the aeration expert.

The decision of to turn on or off the aeration system is made automatically by the computer program based on the strategy implemented by the expert technician. Therefore, within certain limits, almost any strategy may be implemented.

The strategy used in this work is to turn on the aeration system whenever the grain temperature reaches a value above the maximum in the range between the aeration temperature and the air temperature and turn it off whenever the lower temperature limit is reached. The cycle may repeat several times in a day if necessary to keep the grain temperature between the minimum and the maximum reachable temperature. However, any other feasible strategy could be implemented.

When the aeration system is off, the grain may naturally heat up and reaches the critical temperature again, and the cycle repeats.

To simulate the whole process the computer program reads the ambient air temperature and relative humidity, the grain temperature and moisture content from a file, and performs all the calculation mentioned previously and decides to turn on or off the aeration system. The main steps of the program are presented in the flowchart of Figure 2 and the complete **SIMULINK** Simulation Blocks in Figure 3.

The **SIMULINK** Simulation Diagram (Figure 3) is composed of the following blocks:

Tamb - Workspace vector containing the values of the ambient air temperature.

Hamb - Workspace containing the values of the ambient air relative humidity.

ATC - System function that performs all calculations necessary to determine the limit of the aeration temperature for controlling, using psychrometric equations and an equilibrium moisture content equation for the specific grain that has been considered.

CONTROL - System function used to perform the closed loop control, using the ambient air temperature, aeration temperature and generating the fan status.

Silo - SIMULINK block that simulates the evolution of the grain temperature.

Mux - Multiplexer block used to send the output variables to the workspace vector **y** and to an auto scale graph oscilloscope.

INITSIM - MATLAB script file used to initialise the simulation parameters.

SHOW RESULTS - MATLAB script file used to show the results on the screen.

4. RESULTS AND DISCUSSION

To test the simulation program, air temperature and relative humidity data registered during one day every 12 minutes, from 0:00 to 24:00h, obtained from Melo Jr. (1999), were used. The data are shown in Figures 4 and 5. In this case, these data were inputted in the computer program but could be directly read from a sensor in a real time experiment. The results would be similar for the same set of ambient conditions.

According to Equation (1), the time required for a grain mass to cool to a desired temperature depends on the amount of grain, initial and final grain temperature, grain and air specific heat, grain heat of vaporisation, airflow rate, and air humidity and density. During this time the fan remains continuously on until the grain mass reach the desired temperature. After that, the fan is turned on or off in order for the grain to follow this temperature. As an example, it was assumed maize with moisture content of 15% w.b. and initially at a temperature 2°C above the desired level. The results are shown in Figure 6.

It can be observed in Figure 6 that, initially, the aeration fan is turned on since the grain temperature is 25°C, above both the aeration temperature of approximately 23°C and the air temperature of approximately 19°C. It shall be noted that, for this case, to maintain the grain mass at a constant moisture content of 15% w.b. the aeration temperature is higher than the air temperature because the equilibrium relative humidity of the grain mass is lower than the ambient air relative humidity. This condition cannot be violated if the objective is to keep the grain mass at constant moisture content and sufficiently cool.

5. CONCLUSIONS

The equilibrium moisture content and psychrometric equations may be used to define a strategy to predict, based on actual ambient air and grain conditions, the aeration process of a stored grain mass.

The **SIMULINK** toolbox, in conjunction with **MATLAB** functions, may be used as a powerful tool to simulate the aeration process of a stored grain mass.

It may be inferred, based on the results, that the **SIMULINK** toolbox, in conjunction with **MATLAB** functions, may be also used to control the aeration process in a real world storage facility by real time data acquisition of the grain mass temperature, and the ambient air temperature and relative humidity (Mota et al., 1998a; Mota et al., 1998b).

After adequate real-world experiments, such real-time control system may easily be adapted to develop embedded aeration control systems.

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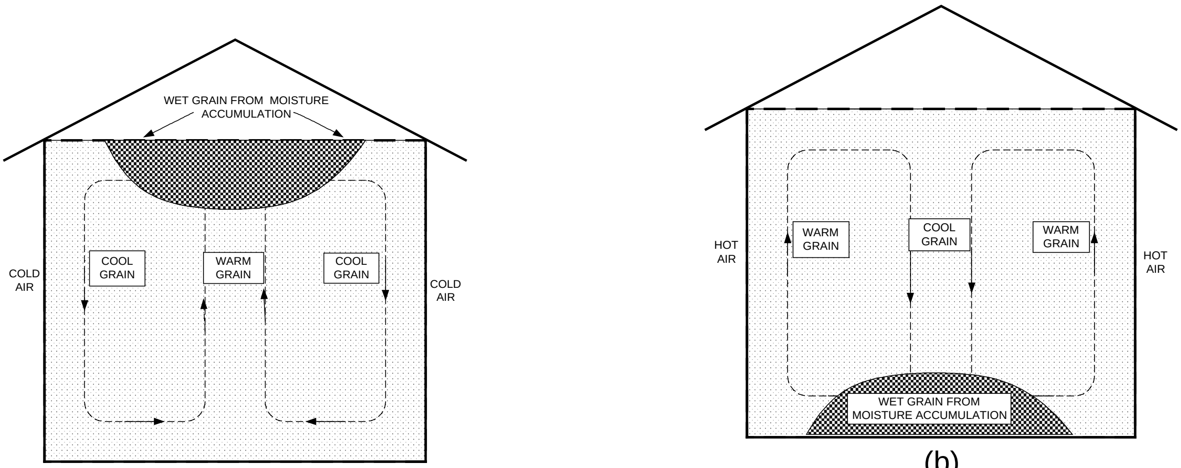

(a) (b)

Figure 1. Moisture migration in stored grains when (a) the external temperature is decreasing, and (b) when the ambient temperature is greater than the grain mass temperature.

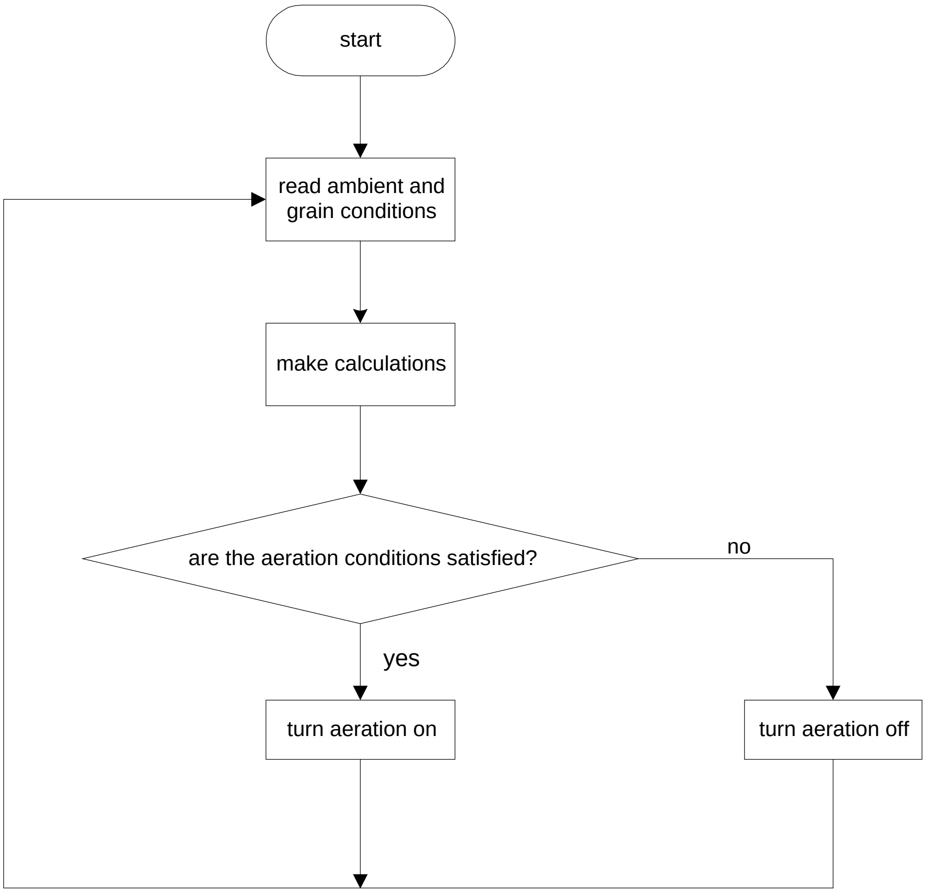

Figure 2. Simplified flowchart of the computer program.

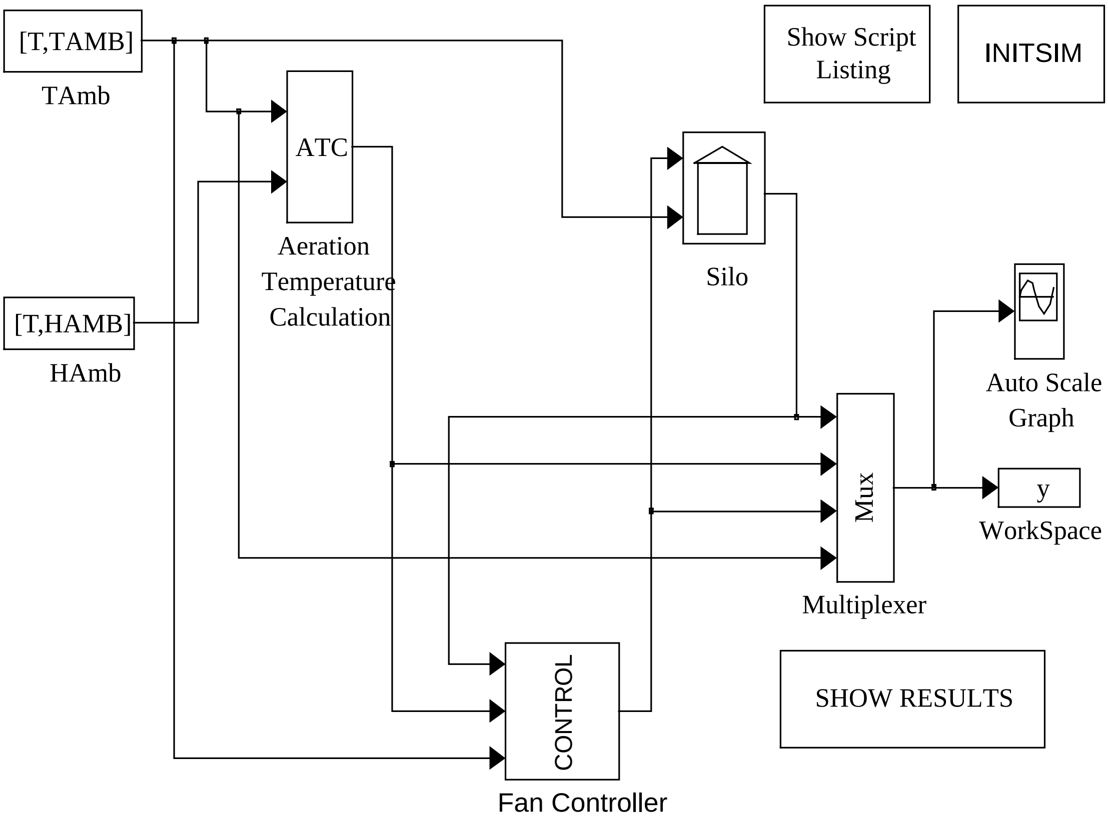

Figure 3. Complete **SIMULINK** Simulation Diagram.

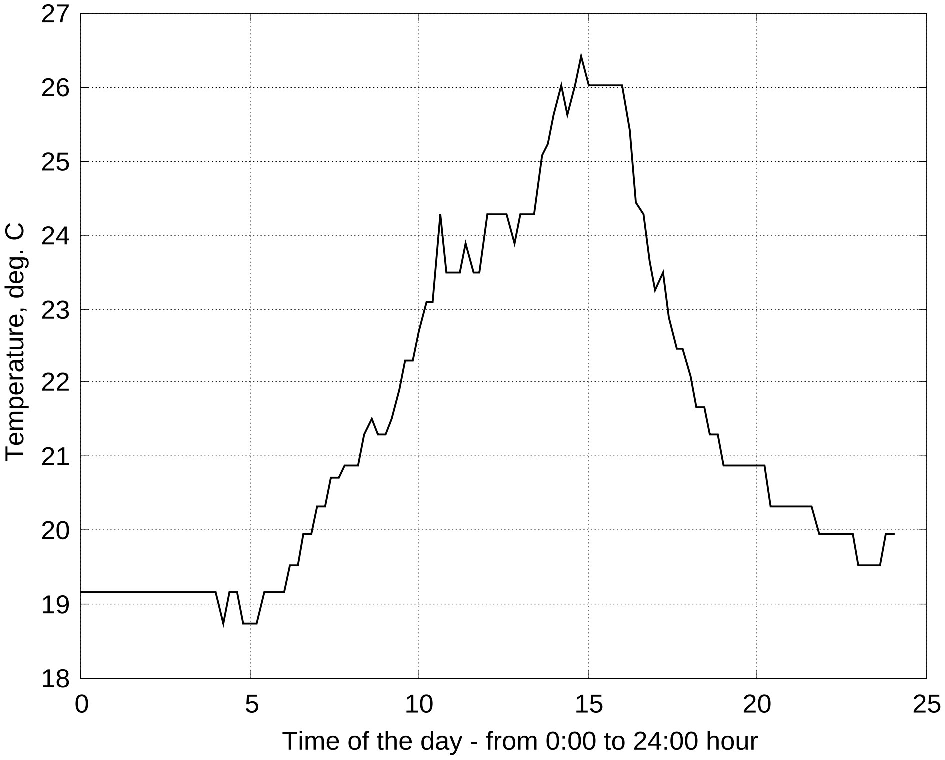

Figure 4. Temperature variation on November 9, 1999 in the city of Viçosa, State of Minas Gerais, Brazil (Melo Jr., 1999).

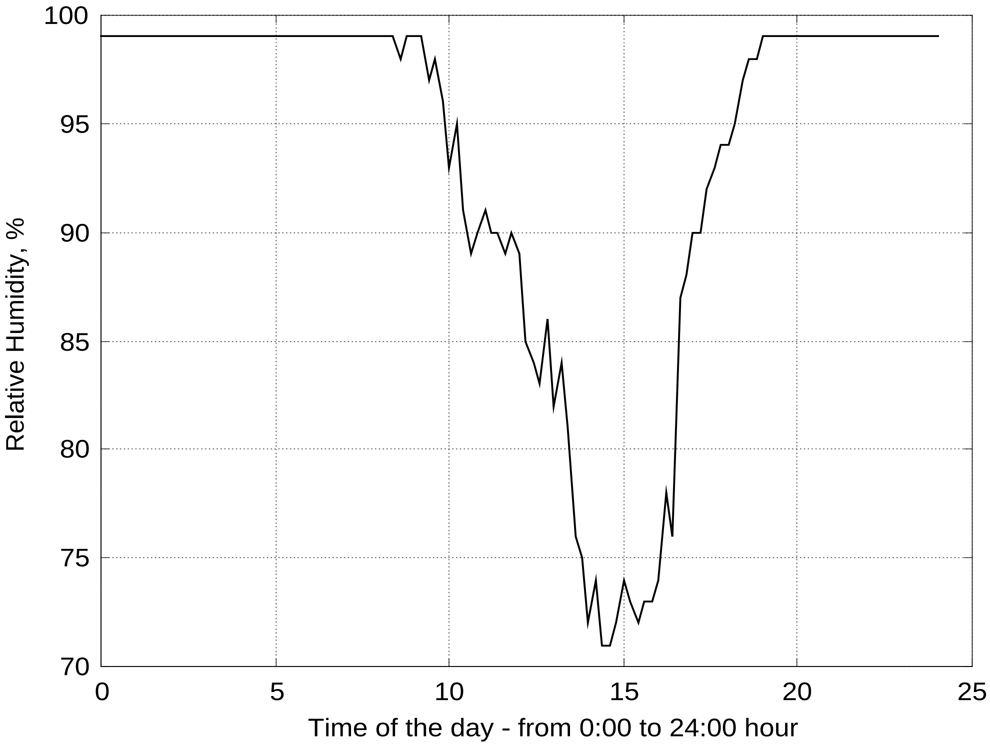

Figure 5. Relative humidity variation on November 9, 1999 in the city of Viçosa, State of Minas Gerais, Brazil (Melo Jr., 1999).

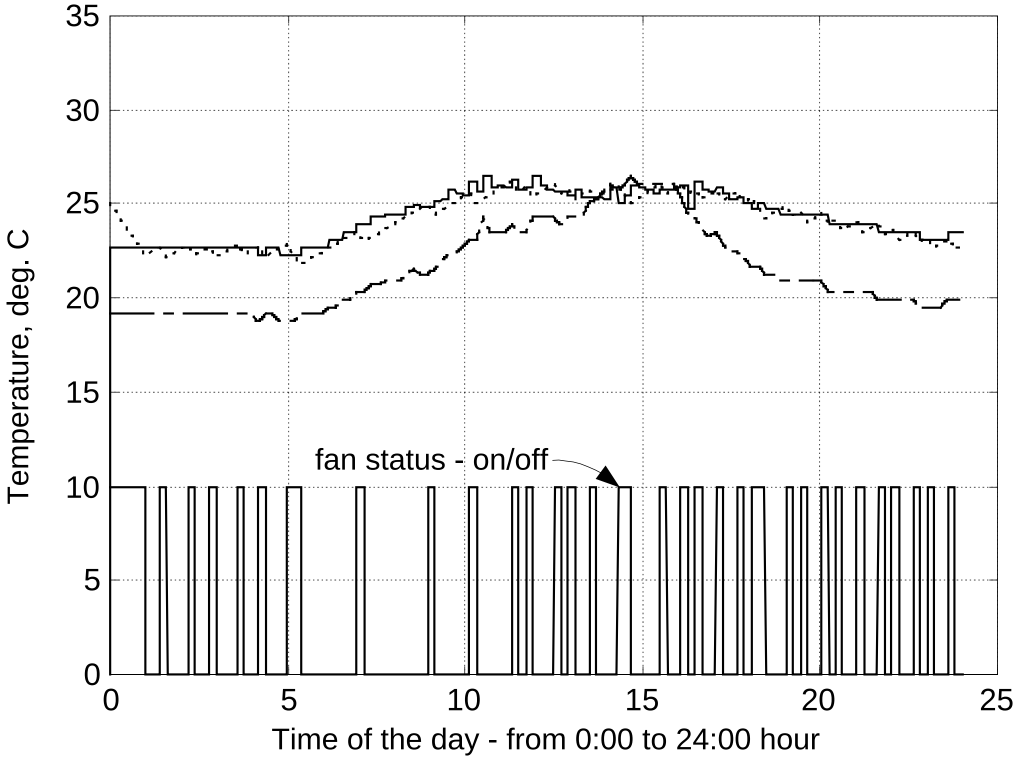

Figure 6. Variation of air temperature (— – —), grain temperature (· · · ·), aeration temperature (—), and fan status on November 9, 1999 in the city of Viçosa, State of Minas Gerais, Brazil.