AUTOMATIC CONTROL AND MONITORING OF STORED GRAIN AERATION SYSTEMS BY REAL TIME DATA ACQUISITION

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ABSTRACT

The time necessary to cool a grain mass by aeration may be precisely determined by simulation. However, 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. Therefore, by using real time data acquisition it is not necessary to predict in advance the cooling time, because all the calculations are executed by a computer program in real time and control actions taken immediately, based on some implemented strategy. So, the objective of this work is to develop, implement and test an automatic monitoring and control system for grain aeration process based on the external ambient conditions and the conditions inside the grain mass, using real time data acquisition. An experimental prototype, specially designed for the purposes of this work, was used to test the control hardware and software. Although the control system is working properly, research is been continued to improve the aeration strategy to be implemented in a real scale aeration system. It is also desirable to use reliable moisture content and relative humidity sensors inside the grain mass.

KEYWORDS: Automatic control; Aeration system; Real time data acquisition

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

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1. INTRODUCTION

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.

To maintain a stored grain in good conditions it is necessary to keep the grain mass under uniformly cool and dry conditions. This can be accomplished in several regions of the world by means of aeration: the forced movement of ambient air through stored grain to decrease or increase the grain temperature to the desired level (Maier & Montross, 1997).

The aeration may affect the grain mass in different ways depending, basically, on the ambient and product conditions. Therefore, it is essential to make a prediction about the possible results before turning on the aeration system.

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 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, and the needs for process optimisation the development of a feasible monitoring and control system is very important.

Therefore, the objective of this work was to develop, implement and test an automatic monitoring and control system for stored grain aeration, based on the external ambient conditions and the conditions inside the grain mass, without the need for historical meteorological data.

2. AERATION BACKGROUND

2.1. The Aeration Process

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.

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 Control and Monitoring

The control of an aeration system on a bin 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 turns the fan on 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 System Definition

An experimental prototype, specially designed for the purposes of this work, was used to test the control hardware and software. Basically, the prototype consists of a PVC column with, approximately, a height of 200 cm and internal diameter of 25 cm. A fan driven by a 368 W single phase motor attached to a PVC duct with an internal diameter of 7.5 cm is used to supply the desired airflow rate to the grain mass (Figure 2).

A grain column with, approximately, a height of 100 cm was used in the tests. The grain column was divided into four layers with a thickness of 25 cm each. Due to the reduced dimensions of the prototype and possibility of developing a model with greater dimensions, it was chosen to use temperature sensors with 1-*Wire*^{TM} interface, from Dallas Semiconductor. This approach allowed for a digital output and the interface to a computer through a serial field bus, and also permitted the control of the ventilation system by a digital output device with 1-*Wire*^{TM} interface actuated by a power relay. Temperature sensors were placed inside the grain column at the top of each layer, respectively at 25 cm, 50 cm, 75 cm, and 100 cm from the bottom. Three temperature sensors were used to measure the air temperature and relative humidity: One sensor was placed at the inlet air stream, and two sensors were placed outside in the ambient to measure both the dry bulb and wet bulb temperatures. First calculating the ambient air relative humidity, and then considering the heating process from the ambient to the inlet air temperature using the psychrometric equations it is possible determine the inlet air relative humidity.

3.2. The Computer Program

A computer program (Figure 3) was specially developed for this project. The program executes the real time data acquisition task, performs all the necessary calculations and, based on the psychrometric conditions of the air and the grain mass conditions, along with the managing strategy implemented, decides to turn the ventilation system on or off.

The computer program was developed using MATLAB language (Chen et al., 1999; MATLAB, 1996) to perform the data acquisition task and make all the calculations to periodically determine the cooling temperature for the aeration process in a grain storage unit. The relationships between the equilibrium moisture content (EMC) of the grain and air conditions are used to decide what strategy should be taken in account.

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):

$$H = 1.00 - \exp\left[-k\left(T + c\right)M_e^n\right] \tag{1}$$

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. Although this will dry the grain a little, its moisture content will not be decreased more than a 0.5 point percent, if the process is conducted under normal conditions. 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 a numerical method to find the root of the following equation:

$$w = \frac{h - 1.006\,T_e}{2501 + 1.775\,T_e} \tag{2}$$

To calculate T_e in Equation (2) the following auxiliary equations are necessary:

$$P_{vs} = 0.61078\left[10^{\left(\frac{7.5\,T}{237.3+T}\right)}\right] \tag{3}$$

for T > 0

$$P_{vs} = 0.61078\left[10^{\left(\frac{9.5\,T}{265.5+T}\right)}\right] \tag{4}$$

for T < 0

$$P_v = H \cdot P_{vs} \tag{5}$$

$$w = \frac{0.62198\,Pv}{P_{atm} - P_v} \tag{6}$$

$$h = 1.006\,T + w\left(2501 + 1.775\,T\right) \tag{7}$$

Assuming that the grain moisture content is kept approximately constant, and the dry bulb temperature and relative humidity of the inlet air are available at any time, the equilibrium relative humidity (H_e) of intergranular air can be calculated by Equation (1). Using the Equations (3) to (7) the enthalpy of the air can be calculated. Another way of doing this is to place reliable moisture content sensors inside the grain mass to measure its value in real time.

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 = $H_{e.}$ This can be performed using a numerical method, by calculating and recalculating H as a function of absolute humidity (w) and equilibrium temperature (T_e), 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 to the air temperature decremented by one step value. This temperature is assumed to be the calculated aeration temperature, and is supposed to be the possible value that can be reached by the grain mass under a given inlet air condition. The time that it takes to cool the grain mass to this value depends, besides the inlet air temperature, on both the airflow rate and the grain conditions.

3.3. Experimental Tests

The experimental tests consisted of automatically measuring the inlet air temperature and relative humidity, and the temperature in the centre of the grain column at four positions equally spaced from each other (Figure 2). The maximum temperature inside the grain mass was used to determine the progress of the cooling front.

The experiments were carried on using approximately 40 kg of maize with initial moisture content of approximately 12% w.b.. This maize filled the experimental bin up to 100 cm high. An airflow rate of approximately 1 m^3/min.t was used to cool the grain mass. This airflow rate is higher than that normally used for grain aeration. However, the purpose of this work was to develop and test the proposed monitoring and control system by real time data acquisition based on some strategy. Therefore, neither the grain quality nor the airflow rate were under concern, although the grain quality was apparently preserved by aeration.

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 calculated aeration temperature (Equation 2) and the inlet air temperature, and turn it off whenever the lower temperature limit is reached. In order to keep the maximum grain temperature within adequate limits it may be added a hysteresis value to both the high and low temperature limits. The computer program executes an infinite loop, and acts on the aeration system control, according to the strategy adopted, to keep the maximum grain temperature between the minimum and the maximum pre-established limits.

4. RESULTS AND DISCUSSION

To test the control system, an experimental run was executed during 35.5 hours. The data were collected at interval of 3 minutes. The results are shown in Figures 4, 5 and 6.

It can be observed in Figure 4 that the maximum grain mass temperature was all the time between the upper and lower pre-established limits, which vary according to the ambient air conditions (Figure 5). In the present case these conditions did not vary too much because the experiments were run inside a closed room. However, this fact does not influence the control system since the data are collected in real time.

The progress of the cooling front is shown in Figure 6. It can be observed that the cooling front of all the four layers followed the same pattern. It shall be noted that it is sufficient that the maximum temperature is in the desired range to maintain all grain mass sufficiently cool.

The strategy proposed in this work was based on the equilibrium condition (Equation 2) between the inlet air and the grain mass, assuming a constant and uniform grain moisture content. Based on the local weather characteristics the upper temperature limit was chosen to be approximately 5ºC above the inlet air temperature, and the lower limit the calculated equilibrium temperature increased by an empirical hysteresis value (1ºC in this case) to avoid any stacking of the process. Although the proposed strategy seems to be working very well, when compared with some simulation studies (Ferreira et al., 1993; Sinício & Muir, 1998), research should continue to test several other strategies in long term run to optimise the process.

5. CONCLUSIONS

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

The proposed monitoring and control system was able to monitor and control the aeration process by keeping the maximum grain mass temperature between the upper and lower pre-established limits (Figure 5).

The results obtained in this work were, according to the strategy used, sufficient to test both, the software and hardware for the monitoring and control systems.

The **MATLAB** programming language, in conjunction with **M** and **C-MEX** functions, may be used as a powerful programming tool for monitoring and control the aeration process of a stored grain mass (Mota et al., 1998).

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

Long-term experiments should be run, to test the reliability of both, software and hardware, and allowing for different strategies testing.

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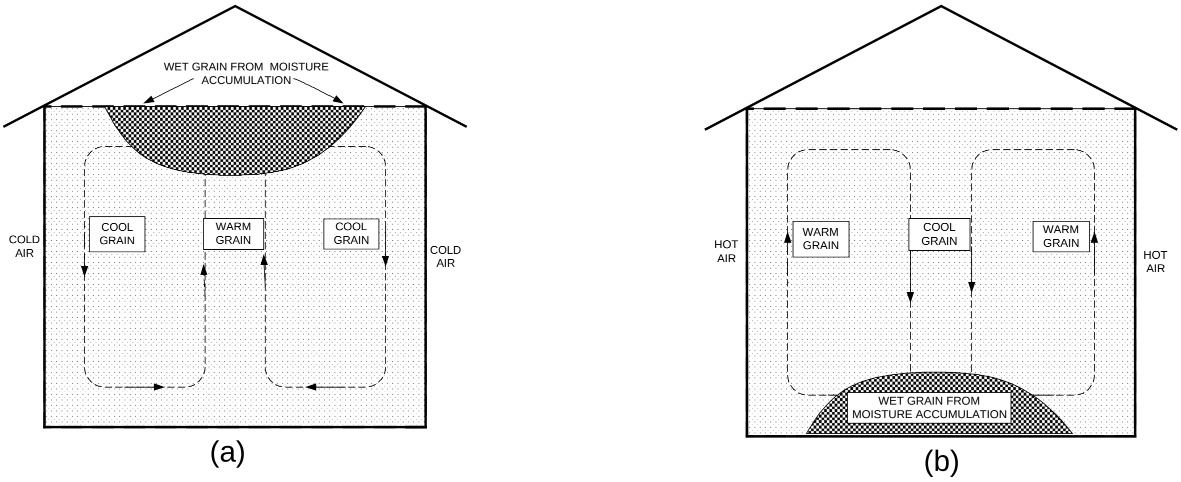

(a)

(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.

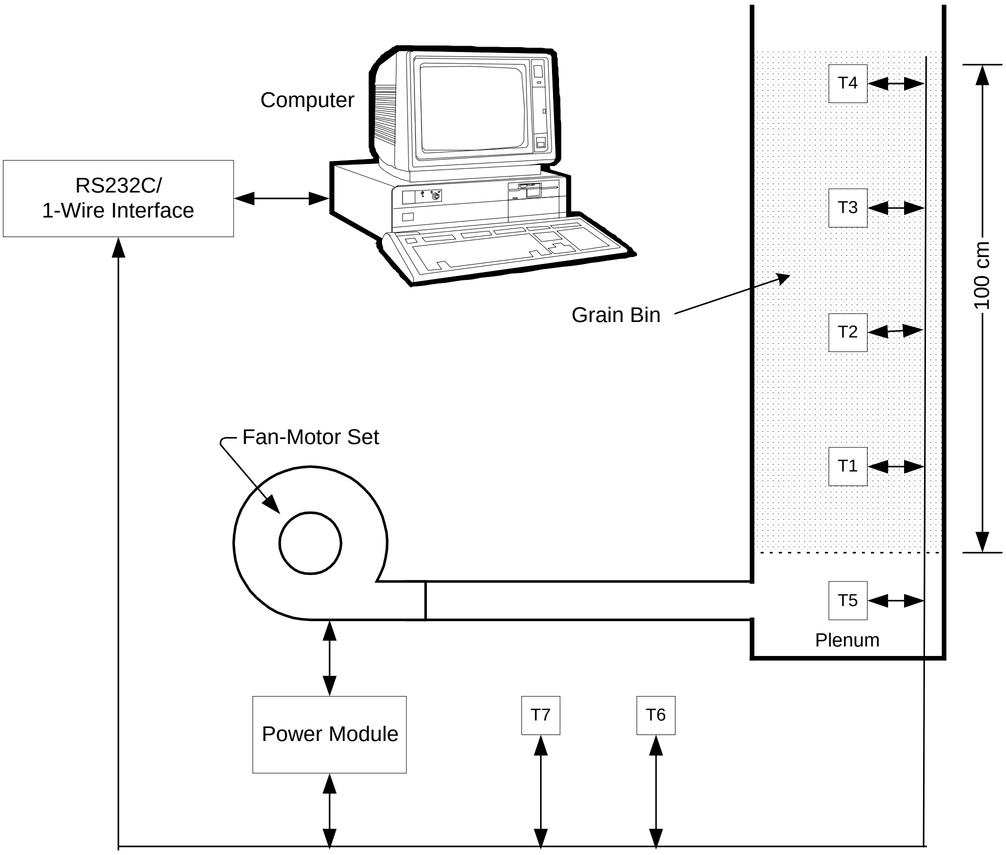

Figure 2. Simplified schematic of the experimental prototype.

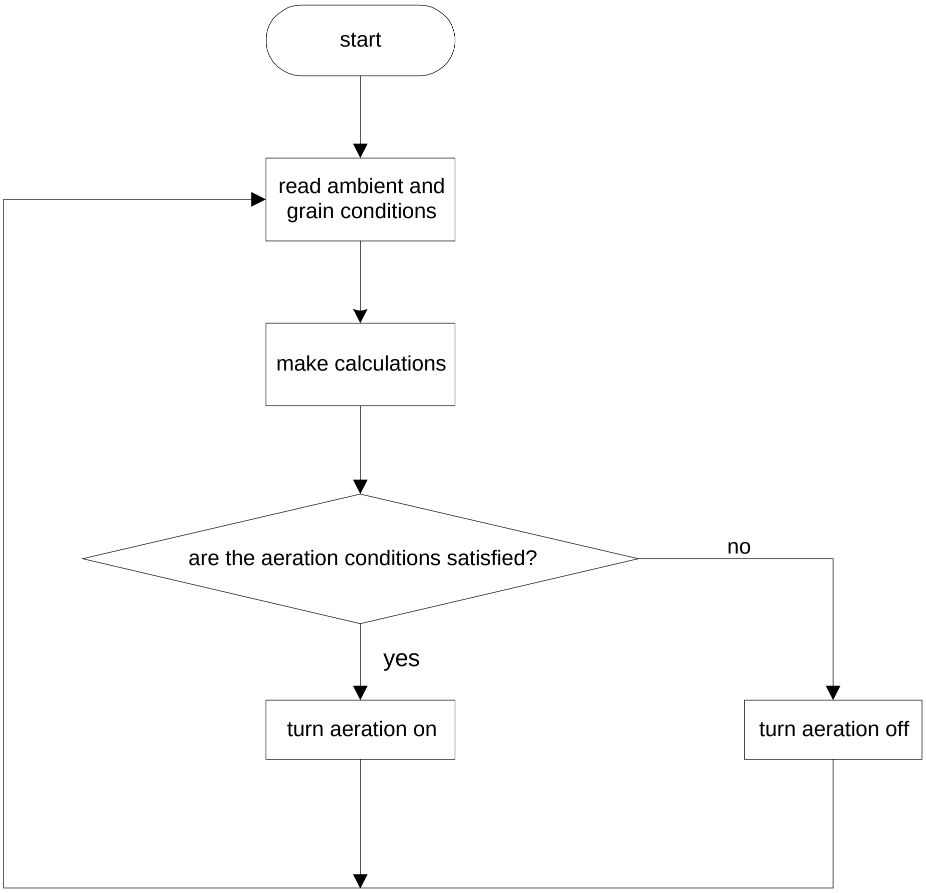

Figure 3. Simplified flowchart of the computer program.

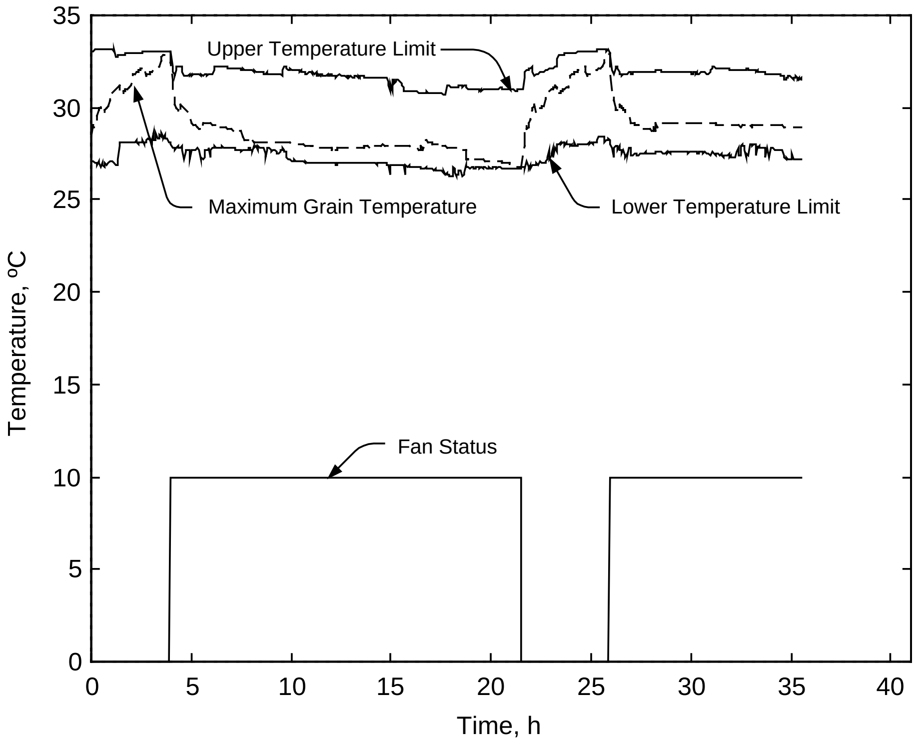

Figure 4 – Variation of maximum grain temperature during 35.5 hours of aeration. Test date: 22/June/2000; Starting time: 10h:52m:16s; Product: Maize; Initial moisture content: 12% w.b.; Airflow rate: 1 $m^3.min^{-1}.t^{-1}$.

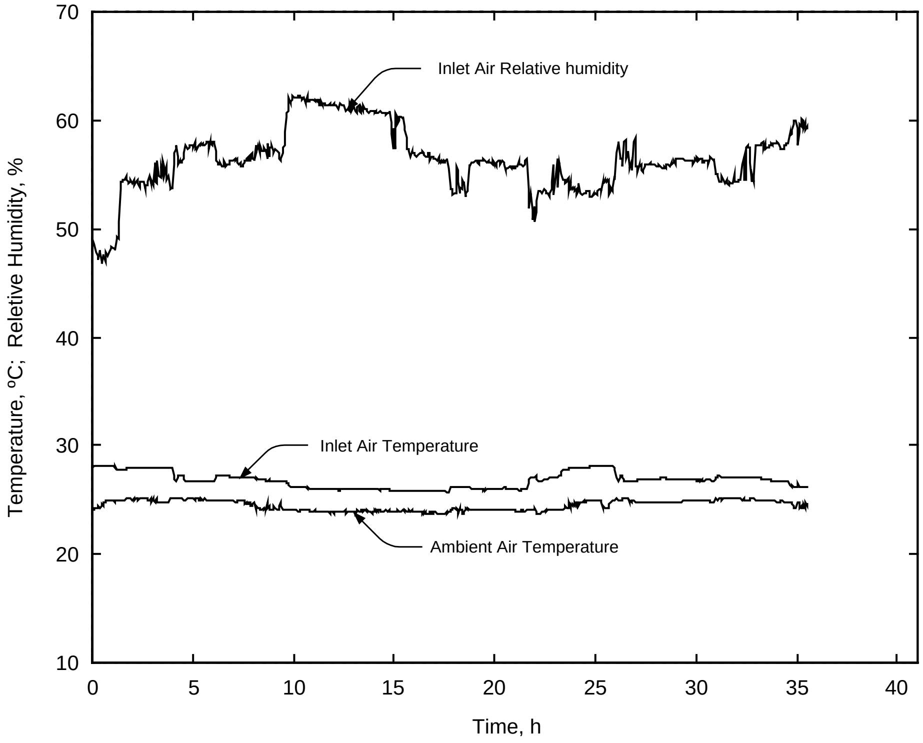

Figure 5 – Variation of inlet air temperature and relative humidity during 35.5 hours of aeration. Test date: 22/June/2000; Starting time: 10h:52m:16s; Product: Maize; Initial moisture content: 12% w.b.; Airflow rate: 1 $m^3.min^{-1}.t^{-1}$.

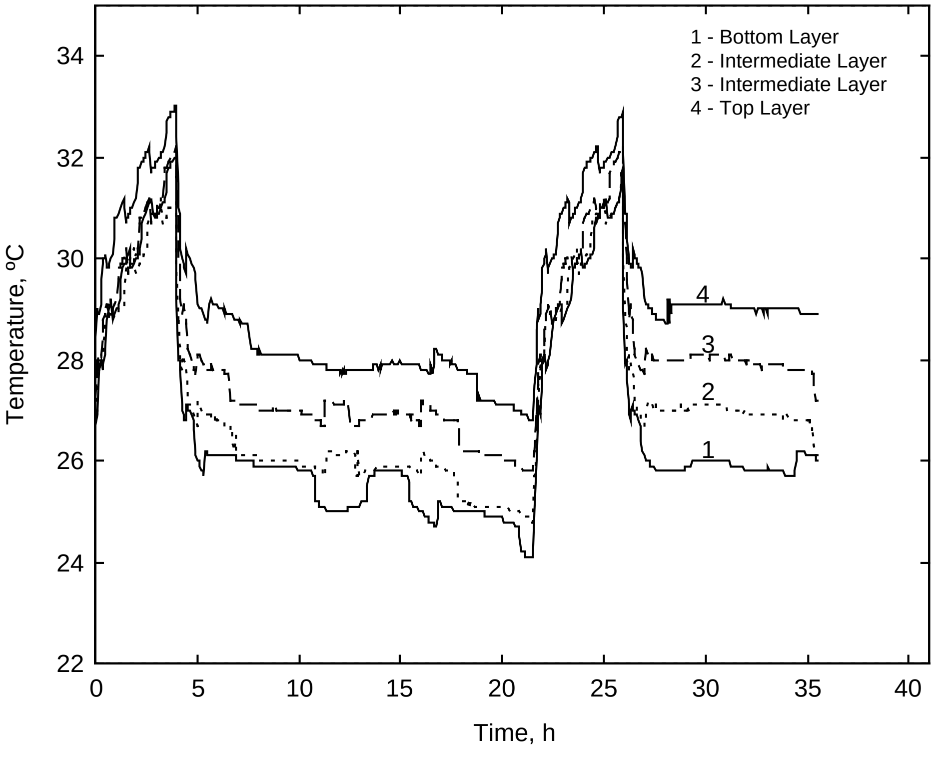

Figure 6 – Progress of the cooling front inside the grain mass during 35.5 hours of aeration. Test date: 22/June/2000; Starting time: 10h:52m:16s; Product: Maize; Initial moisture content: 12% w.b.; Airflow rate: 1 $m^3.min^{-1}.t^{-1}$.