Journal of Agricultural Sciences (Tarim Bilimleri Dergisi) 2022, 28 (1) : 145 – 158 DOI: 10.15832/ankutbd.715508

Journal of Agricultural Sciences
(TarimBilimleriDergisi)

J Agr Sci-Tarim Bili
e-ISSN: 2148-9297
jas.ankara.edu.tr

JAS

Cooling Potential of Bin Stored Wheat by Summer and Autumn Aeration

Mohamed Nejib EL MELKI[a*], **Khaled ELMOUEDDEB**[a], **AbdullahBEYAZ**[b]

[a]*Department of Mechanical and Agro-Industrial Engineering, Higher School of Engineers of Medjezel Bab, University of Jandouba, Research Unit: Renewable Energies in Agriculture and Agro-IndustryP5, 9070*

[b]*Ankara University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, 06130, Diskapi, Ankara, TURKEY*

ARTICLE INFO
Research Article
Corresponding Author: Mohamed Nejib EL MELKI, E-mail:mohamed.najib.melki@gmail.com
Received: 7 April 2020 / Revised: 27 March 2021 / Accepted: 28 March 2021 / Online: 20 January 2022

ABSTRACT

A one-dimensional mathematical model based on the formulation of mass and energy balance in stored grain was used to simulate grains storage conditions. The objective of such simulations was to produce grain ventilation strategies. The model was validated using data obtained from the monitoring of wheat stored in a galvanized steel cylindrical tank with corrugated conical bottom ventilated by perforated distribution pipes. A control strategy based on night time aeration from July to November followed by day time aeration for December to January was applied. Good agreement between the predicted and measured storage conditions has been observed (R^2= 0.9698, S.E.= 1.479 °C in average temperature and R^2= 0.99, S.E.= 0.00079 kg $kg^{-1}$for moisture content). Night time grain aeration provided sufficient cooling (temperature near 10 °C in November). However, an 18% grain humidification process was induced. Day time aeration started at the end of November corrected this humidification effect for a grain temperature of 15 °C and a grain moisture content of 15% on dry basis.

Keywords: Heat and mass transfer, Computer simulation, Grain storage, Mathematical modelling, Warm climate, Tunisia

1. Introduction

Cereal harvesting in Tunisia usually begins by mid-June, when grain temperature exceeds 25 °C. Bin storage exposes cereals to a range of complex ecological factors which, if improperly managed, can lead to important economic losses for the Tunisian grain industry. The main management factors are storage temperature and moisture content. Storage temperature is important because it directly affects grain storage quality through pest development and matter losses (Muir 1970; Sun & Woods 1994; Maier et al. 1996). The moisture content controls the development of fungi, and the growth of insects and mites populations (Longstaff 1994). Proper grain storage requires preventive management strategies rather than the application of solutions as problems occur. Since aeration is capable of controlling grain temperature and moisture, it is the most common preventive technique against grain deterioration agents. Aeration consists in forcing ambient air through the grain mass to remove respiration heat and moisture, when the ambient air enthalpy and moisture content is appropriate. Aeration is challenging in tropical and subtropical climates, where ambient air temperature and/or relative humidity is too high to achieve proper grain curing, especially during the critical storage period such as from July to December in Tunisia. Actually, aeration is not a common management practice for grain storage in Tunisia, simply because of generally high ambient temperatures during the early storage grain period. The main method for grain preservation relies on pesticide applications to control insect growth and bin-to-bin transfer to reduce grain temperature. The potential use of aeration to cool stored grains for their preservation has not been thoroughly evaluated in Tunisia. Usually, during the Tunisian summer and fall, the ambient air is characterized by a high daytime temperature and low relative humidity, and a lower night temperature with a higher relative humidity. The potential use of ambient air aeration to protect stored grain masses against deterioration warrants investigation.

Accurate prediction of stored grain ecosystem helps to develop and evaluate ventilation strategies adapted to the climatic characteristics of the storage region. Methods of predicting temperature and grain moisture content can be used to evaluate the effectiveness of aeration and estimate if chemical treatments are required to fight insects, mites and fungi. However, the testing of various aeration strategies to establish best practices to preserve stored grain masses is expensive since it requires the monitoring of temperature and humidity at several points in a large number of grain bins, and for several seasons.

Simulation models can economically be used to predict the temperature and moisture of stored grain, under different climatic conditions and aeration strategies. Generally, these models are used to evaluate the efficacy of ambient air aeration, to estimate the maximum safe storage period for grain and to predict the required aeration time. The outputs of simulation models allow for the analysis of stored grain aeration viability for a specific region. Many mathematical models are available to simulate the heat and the mass transfers in aerated bulk stored grains. (Jia et al. 2001; Thorpe 2001; Andrade et al. 2002 ; Iguaz et al. 2004)

Generally, these models are based on energy and mass balances. In some cases, it is also possible to estimate the temperature distribution, the moisture content and the time required to cool a grain mass.

Some authors have developed control strategies for grain aeration systems. Using a software package called AERO (de Carvalho Lopes et al. 2008). de Carvalho Lopes et al. (2008) implemented a control strategy that relates four conditions (C1, C2, C3 and C4): C1 pertains to the dew point; C2 is evaluated by AERO 1 and AERO 2 to maintain a safe grain moisture content (de Carvalho Lopes et al. 2008), and on recommendations presented by Navarro and Noyes (Navarro & Noyes 2001). The control strategy aimed at providing low and uniform grain mass temperatures and to maintain a safe grain moisture content. The simulation process based on the ambient data (temperature and humidity) and the measured storage conditions of the grain predict the aerated grain temperature and moisture content. By comparing the simulated and measured stored grain conditions, the fan air flow rate was either turned on, turned off or maintained in its previous state.

The four conditions set by the AERO control strategy (de Carvalho Lopes et al. 2008) to limit the fan operation time could be applied to Tunisian climatic conditions. In fact, during night time, the aeration will usually be limited by condition C2 because of the high air relative humidity and during daytime, the 4 conditions (C3 or C4 and C1 and C2) could be met to turn on the aeration then a grain heating effect can be observed.

Other authors have developed control strategies based on historical weather data to determine the number of hours during which ambient air temperatures are below a reference level. Based on initial grain mass storage conditions, this temperature is closely related to the storage period and to the lower limits for insect development (Frank & Arthur et al. 2003; Arthur & Casada 2005) . In Tunisia, this control strategy is challenged by the low cooling potential of daytime air temperatures and its negative effect on grain humidity because of higher night time relative humidity.

Most of the modelling work was specifically developed to predict the temperature evolution of grain masses. Subtropical climates as that of Tunisia provide a limited time for the cooling of grain masses by aeration, which directs the investigation toward night time ventilation performance. In Tunisia, aeration can cool the grain mass during lower night temperatures and limit microorganism growth, but under close monitoring of grain moisture content. Aeration with air with high relative humidity can lead to a gain in grain moisture promoting microorganism growth. Usually, microorganism development is strongly linked to both grain temperature and moisture content.

Accordingly, this general study aims at developing strategies for the aeration of grains in storage under Tunisian climatic conditions, mainly cooling under grain humidification control. The objective of this study was to evaluate the effectiveness of aeration during summer and fall, to cool bin stored wheat under the typical Tunisian conditions. This objective was achieved by 1) Using a model, predicting grain temperature and moisture under bin storage; 2) Validating the simulation results with experimental data; 3) Identifying aeration conditions which can preserve wheat in storage from July to December.

2. Material and Methods

2.1. Heat and mass transfer model

To describe the evolution of wheat temperature and moisture, aerated with ambient air, a model was developed based on the mathematical formulation of heat and mass balance transfer for a control cylindrical volume.

To develop balance equations, the following assumptions were adopted to simplify the simulation:

1. Heat and mass transfer through the walls of the storage bin are neglected;
2. The heat flux produced by the storage insects and microorganisms is neglected;
3. The ventilation air flow is assumed unidirectional and parallel to the vertical wall of the bin;
4. The air distribution is assumed uniform and isotropic, and;
5. Heat and mass transfer are assumed to occur between the grain and the interstitial air.

The control volume (Figure 1) has a height of Δz and a circular cross section area A.

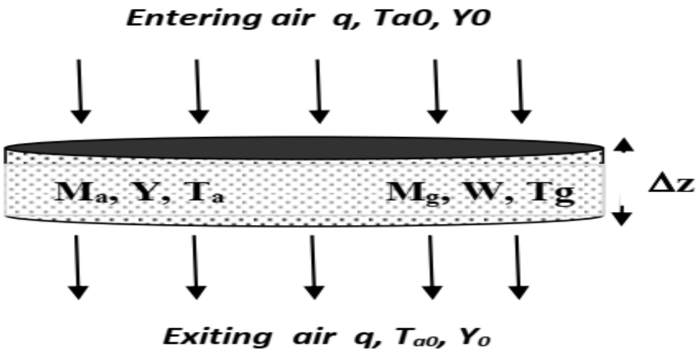

Figure 1- Modelled aeration air flow through the control volume

The mass balance for the moisture of the grain in each control volume (Figure 1) on a dry basis is described by Equation (1).

$$\frac{\partial Y}{\partial t} = \frac{v}{\varepsilon \Delta z}(Y_0 - Y) - \frac{(1-\varepsilon)\rho_g}{\varepsilon \rho_a}\frac{\partial W}{\partial t} \quad (1)$$

Where; Y, is the moisture content of the air leaving the control volume (kg kg^{-1})on a dry basis; Y_0, is the moisture content of the ambient air entering the control volume(kg kg^{-1}) on a dry basis;v , the aeration air velocity (m s^{-1}); ε , the grain porosity (decimal); Δz is the section height (m);ρ_a, the density of interstitial air (kg m^{-3});ρ_g,the bulk density of the grain (kg m^{-3}) and w is the grain moisture content (%) on a dry basis.

The heat balance in the grain mass control volume is described by Equation (2).

$$\frac{\partial [M_g c_g T_g]}{\partial t} = h_V V(T_a - T_g) + \frac{\partial w}{\partial t} M_g h_{vap} - \frac{\partial w}{\partial t} M_g c_v (T_a - T_g) \quad (2)$$

Where;T_g is the grain temperature (°C);M_g, is the grain mass in the control volume (kg) on a dry basis; Ta, is the temperature of the aeration air in the control volume (°C); c_g, the specific heat of dry grain (J $kg^{-1}K^{-1}$); c_v, is the specific heat of water (J $kg^{-1}K^{-1}$);h_v, is the grain volume convective heat transfer coefficient (W $m^{-3}K^{-1}$) and h_{vap} is the latent heat of water vaporization (J kg^{-1}).

The left-hand side of Equation (2) was determined as a numerical derivation over time as described by Equation (3).

$$\frac{\partial [M_g c_g T_g]}{\partial t} = M_g \left[c_g \frac{\partial T_g}{\partial t} + T_g \frac{\partial c_g}{\partial t} + c_g \frac{\partial T_g}{\partial t} + c_g T_g \frac{\partial w}{\partial t}\right] \quad (3)$$

The grain mass in the control volume is described by Equation (4).

$$M_g = (1-\varepsilon)\rho_g A \Delta z \quad (4)$$

Combining Equations (2), (3) and (4), the following Equation (5) represents the time partial derivative expression of grain temperature as described by Equation (5).

$$\frac{\partial T_g}{\partial t} = \frac{h_v(T_a - T_g)}{(1-\varepsilon)\rho_g C_g} + \frac{1}{C_g}\frac{\partial W}{\partial t} h_{vap} - \frac{C_v}{C_g}(T_a - T_g)\frac{\partial W}{\partial t} - \frac{T_g}{C_g}\frac{\partial C_g}{\partial t} - T_g \frac{\partial W}{\partial t} \quad (5)$$

The heat balance in the interstitial air of the control volume is described byEquation (6).

$$\frac{\partial [M_a c_a T_a]}{\partial t} = G_a(T_{a0} c_{a0} - T_a c_a) + M_g \frac{\partial W}{\partial t} h_{vap} - h_V V(T_a - T_g) + c_v (T_a - T_g) M_g \frac{\partial W}{\partial t} \quad (6)$$

Where; T_{a0}, is the temperature of the aeration air entering the control volume (°C); M_a, is the air mass in the control volume; c_a, is the specific heat of air in the control volume (J $kg^{-1}K^{-1}$);c_{a0}, is the specific heat of air entering the control volume (J $kg^{-1}K^{-1}$) and G_a is the air mass flow rate (kg s^{-1}).

The left-hand side of Equation (6) was determined as a numerical derivation over time in the form of Equation (7).

$$\frac{\partial [M_a c_a T_a]}{\partial t} = M_a \left(c_a \frac{\partial T_a}{\partial t} + T_a \frac{\partial C_a}{\partial t} + c_a T_a \frac{\partial y}{\partial t}\right) \quad (7)$$

The air mass in the control volume is described by Equation (8).

$$M_a = \varepsilon \rho_a A \Delta z \tag{8}$$

The air mass flow rate, Ga, through the interstitial space of the control volume is described by Equation (9).

$$G_a = \rho_a A\, v \tag{9}$$

Combining Equations (7), (8) and (9), the time partial derivative expression of grain temperature is described by Equation (10).

$$\left(\frac{\partial T_a}{\partial t}\right) = \frac{1}{\varepsilon \rho_a \Delta z C_a}\left[\rho_a\, v\left(T_{a0} C_{a\,0} - C_a\; T_a\right) + (1-\varepsilon)\rho_g\, \Delta z\left[\frac{\partial W}{\partial t} h_{vap} + C_v\left(T_a\; - T_g\right)\frac{\partial W}{\partial t}\right] - h_v A \Delta z\left(T_a\; - T_g\right)\right] - T_a\left(\frac{1}{C_a}\frac{\partial C_a}{\partial t} + \frac{\partial Y}{\partial t}\right) \tag{10}$$

The heat transfer between the aeration air and grain is calculated based on the volume or surface heat transfer coefficient. Bala& Woods (1984)proposed the following expression for the global volumetric heat transfer coefficient estimated by Equation(11).

$$h_v = \; 49{,}32\; q^{\mathbf{0.6}} \tag{11}$$

Where; q, is the surface air mass flow rate ($kgm^{-2}\ s^{-1}$).

With a maximum error of 0.02% in the temperature range from 0 to 50 °C, the latent heat of vaporization of water is presented by Cengel and Boles, according to Thorpe (2001):

$$h_{vap} = 2501330 - 2363Ta \tag{12}$$

Brookeret al. (1992) reported that the specific heat of grain changes according to the grain moisture content variation:

$$C_g = 1000(a + b\, w) \tag{13}$$

The density of intergranular air was calculated by using Equation (14), presented by (Chung & Pfost, 1967), in order to consider the altitude effects on this parameter.

$$\rho_a = \frac{325.8 P_a}{101.325(T_a + 273.15)} \tag{14}$$

Where; Ta, is the aeration air temperature (°C) and Pa is the barometric pressure (kPa).

The grain drying rate, $\frac{\partial W}{\partial t}$, described by Equation (15) (Iguaz et al. 2003) represents the time variation of grain moisture content and was found to satisfactory predict the drying kinetic of grain.

$$\frac{\partial W}{\partial t} = \; -K(w - W_e) \tag{15}$$

Related to air temperature by Equation(16), K is the drying constant in s^{-1} (Menzies & O'Callaghan, 1971).

$$K = \; 2000 e^{-\frac{5094}{273.15 + T_a}} \tag{16}$$

W_e, is the grain equilibrium moisture content in kg kg^{-1} [dry basis] calculated using the Chung&Pfost (1967) equation (Equation17), which was approved by the ASAE (Brooker et al. 1992).

$$W_e \; = -\frac{1}{B}\ln\left(-\frac{T_a + C}{A}\log r\right) \tag{17}$$

Where; A, B and C are constant values that depend on the stored product (Table 1) and r is the relative humidity of the aeration air, %.

The partial differential equations (1), (5) and (10) that describe the heat and mass transfer in the bulk stored grains of the control volume were programmed using MATLAB (R2013b). The ODE solver 15 s was used to solve the differential equations with an absolute tolerance of 10^{-6} because the temperature and the relative humidity of the aeration air vary arbitrarily with time.

2.2.Experimental device

To validate the simulation model, an aeration experiment was conducted on wheat stored in a bin at the Medjezel Bab station in central Tunisia (Ecole Supérieure des Ingénieurs de l'Equipement Rural at the University of Jendouba, Tunisia). The circular storage bin was of corrugated galvanized steel with a conical bottom, equipped with perforate air distribution ducts. The bin dimensions and the location of the grain temperature sensors are shown in Figure 2. Three temperature sensors were connected to a Duoline Manager Data acquisition system.

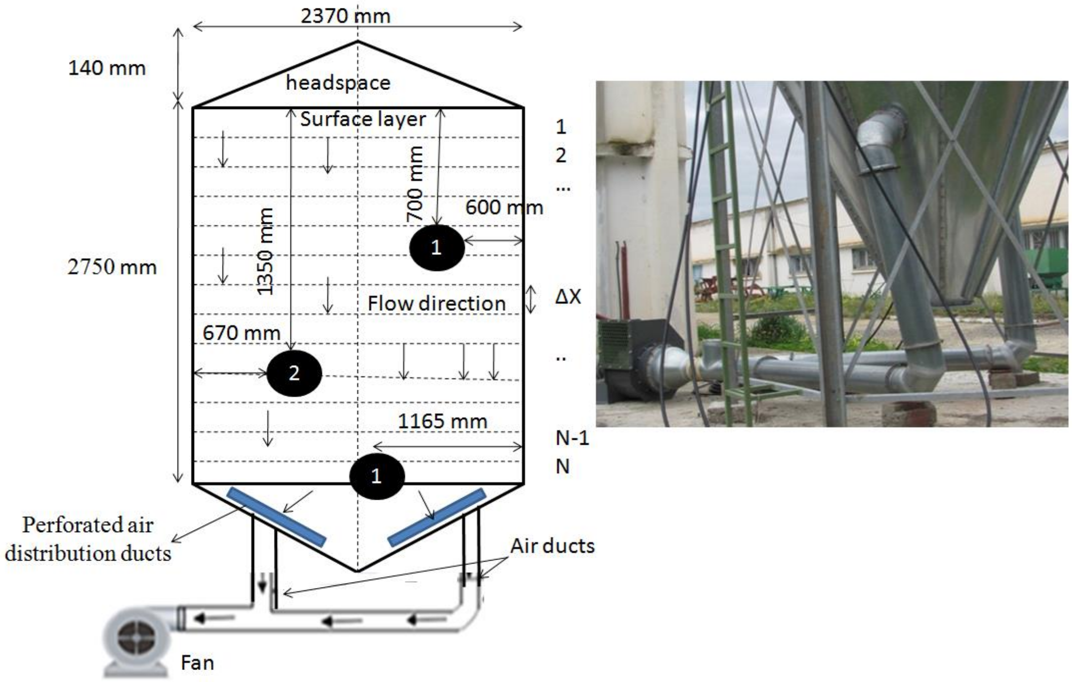

Figure 2- Pictures and diagram of the experimental bin

Bin temperatures data were recorded every 60 min using probes with an accuracy of ± 0.1 °C. Aeration was achieved by mechanically sucking ambient air through the grain mass (downward airflow) when the cooling process was possible.

The main objective of this study was to verify the cooling effectiveness of summer and fall aeration for stored wheat under typical Tunisian climatic conditions. Thus, the weather data was obtained from the closest weather recording station, located in Beja. The daily favourable aeration period was selected from a monthly calculation of hourly averages of air psychometrics parameters (temperature and relative humidity). The selection was based on the analysis of historical available data for period with no missing values of hourly temperature and relative humidity for 2010, 2011 and 2012 years, from August 1 to January 10.A monthly hourly average of psychometric parameters of the air (temperature and relative humidity) was calculated using equation (18).

$$.X_{ij} = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \quad 0 \leq i \leq 23 \tag{18}$$

Where;X_{ij} , is the monthly hourly average of psychometrics parameters for ambient air;x_{ij}, is the hourly parameters of the air (temperature and relative humidity); n, is the number of days of the month and i is the hour time indicator of the day.

Figure 3-4 shows the evolution of hourly monthly average air temperature and relative humidity. For 2010 to 2012, air temperature and air relative humidity evolve in a sinusoidal wave but in opposite phase.

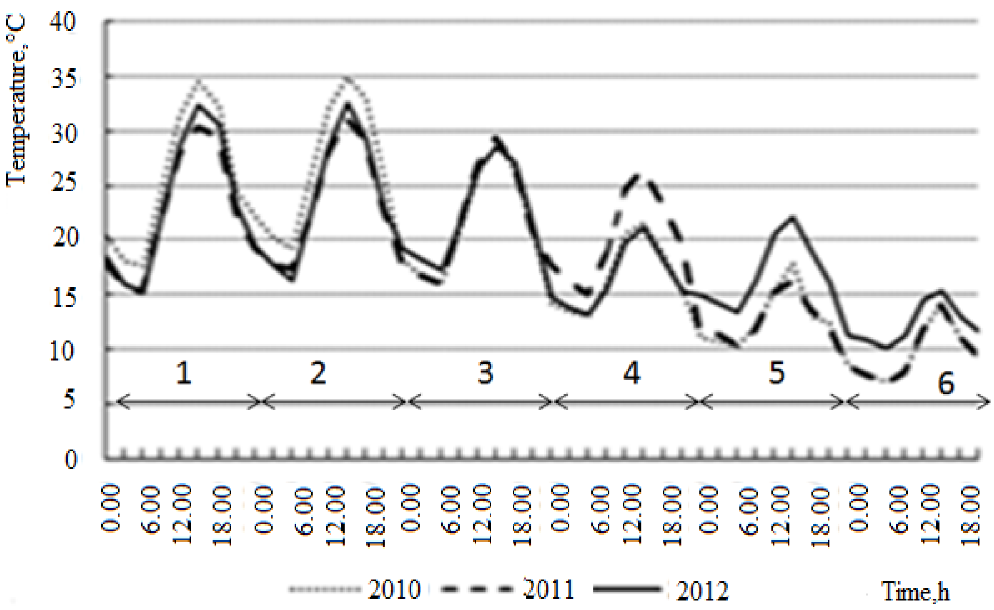

Figure 3-Average monthly hours of ambient temperature at the Beja weather station during the period of 1st August to 10th January (1: August, 2: September, 3: October, 4: November, 5: December, 6: December 31 to January 10)

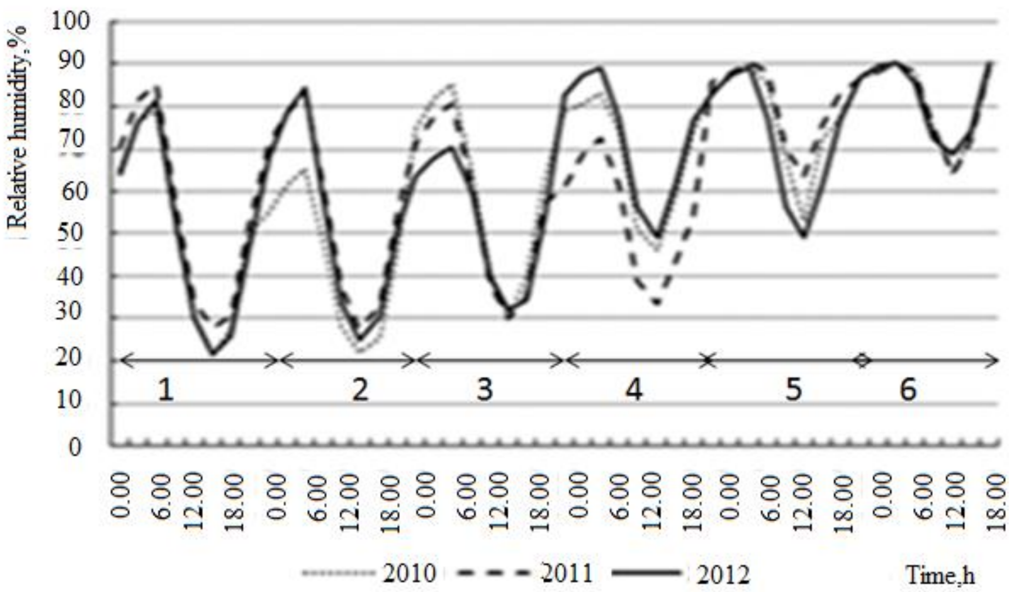

Figure 4 -Average monthly hours of ambient relative humidity of the Beja station during the period of 1st August to 10th January (1: August, 2: September, 3:October, 4: November, 5: December, 6:December 31 to January 10)

During the summer period the hours available for cooling aeration are usually between midnight and 6:00 am where air temperature and humidity are below 20 °C and 80% respectively. Nocturnal aeration especially during the fall still offers air temperatures under the upper limit for insect development of < 15 °C (Figure 4). However, towards the end of November, the air relative humidity exceeds 85% at night time, which can induce grain humidification.

To achieve the main objective, the experiment and the analysis were done for the period of July 9th, 2018 to January 10th, 2019. A such period corresponds to the storage beginning until the hypothetical cooling achievement.

For the experiment, the fan was operated from 12:00 am until 6:00 from July 9th to November 29th2018 and from 10:00 am to16:00 pm from November 30th2018 to January 10th2019. During the period of July 9th to November 29th2018, the night aeration was activated for 144 days at a rate of 6 hours per day (from 12 p.m. to 6 a.m.) or 864 hours of night aeration. However, during the period of November 30th2018 to January 10th2019, daytime aeration was activated for 42 days corresponding to252 hours of aeration. The initial moisture content of the stored wheat was 13.7% (dry basis). Initially, the temperature recorded by sensors 1, 2 and 3 (Figure 2) was 26.1, 27.2 and 26.5 °C, respectively. Table 1 shows the ambient aeration air and stored wheat thermo physical properties, where the grain bulk density and porosity were determined experimentally (Table1). The temperature and relative humidity of the ambient air were measured continuously by two sensors (Pt-100, Testo, Germany with a measuring accuracy Δ1.55% for relative humidity and Δ0.58 °C for temperature), installed in a shaded area close to the experimental bin.

Table 1 - Aeration air and stored wheat thermo physical properties

Term	*Value or equation*	*Reference*
Grain porosity (decimal)	0.49	measured
Bulk density of the grain (kg m^{-3})	863	measured
Specific heat of water (J kg^{-1} K^{-1})	4186	(Navarro and Noyes 2001)
Specific heat of humid air (J kg^{-1} K^{-1})	Ca = 1 + 1.805Y	(Ojer 1995)
Chung- Pfost constants	A=921.65	(ASAE D245.4.1994b.)

To evaluate the moisture content of the grain (dry basis), samples were taken every 15 days till the end of October 2018and twice a week for the remainder of the experimental period (from October 31st2018 to January 10th2019) under higher risk of stored grain humidification. During aeration, the hourly ambient air temperature and relative humidity were taken as model inputs to predict the evolution of the moisture content and temperatures of grain at the level of the three sensors (Figure 2).

Typical airflow rates recommended for stored wheat are 0.08 $m^3 min^{-1} m^{-3}$. Because the grain cooling rate can't be improved with higher air velocity after a specific relative short time of aeration, the influence of airflow velocity was low on cooling rate even for aerated stored fruits with higher moisture content (Behaeen et al.2018). Thus, the consumption of energy could be reduced by selecting an acceptable low airflow velocity in aerated grain storage. Furthermore, to minimize the grain moistening effects during night time aerations, the airflow rate used in the experiment is 0.49 $m^3 h^{-1} m^{-3}$ (0.008 $m^3 min^{-1} m^{-3}$).

The standard error of residuals (S.E.), average of absolute values of the residuals (AAVR), the correlation coefficient (R^2) and index of agreement (d) were used to evaluate the accuracy of the model. The parameters: AAVR, S.E. and d are described by Equations (19), (20) and (21) respectively (Mayer & Butler 1993; Willmott 1981; Yang and Huffman 2004).

$$\mathrm{AAVR} = \frac{\sum_{i=1}^{n} |P_i - P_i^*|}{n} \tag{19}$$

$$\mathrm{S.E.} = \sqrt{\frac{\sum_{i=1}^{n} \left(P_i - P_i^*\right)^2}{\mathbf{n-1}}} \tag{20}$$

$$d = 1 - \frac{\sum_{i=1}^{n} \left(P_i - P_i^*\right)^2}{\sum_{i=1}^{n} \left(|P_i - \overline{P^*}| + |P_i^* - \overline{P^*}|\right)^2} \tag{21}$$

Where;P_i, is the experimental parameter of the model (moisture content, grain temperature);P_i^*, is the predicted parameter of the model and n is the number of testing data. The index of agreement is dimensionless. The units of AAVR and S.E. depend on the evaluated parameter of the model. Thus, in this study, to assess the temperature parameter P_i and P_i^* represent hourly experimental and predicted temperatures. However, to assess the moisture content P_i and P_i^* represent experimental and predicted moisture contents at the moment of sampling.

3. Results and Discussion

3.1 Evolution of the grain moisture contents

3.1.1 Measured grain moisture content

During the first 510 hours of night aeration of the grain from July 9th to October 1st, 2018 (period A1 in Figure 5), the grain moisture content did not change significantly. After this period, the stored grain started to pick up humidity increasing risks of losses (Figure 5).

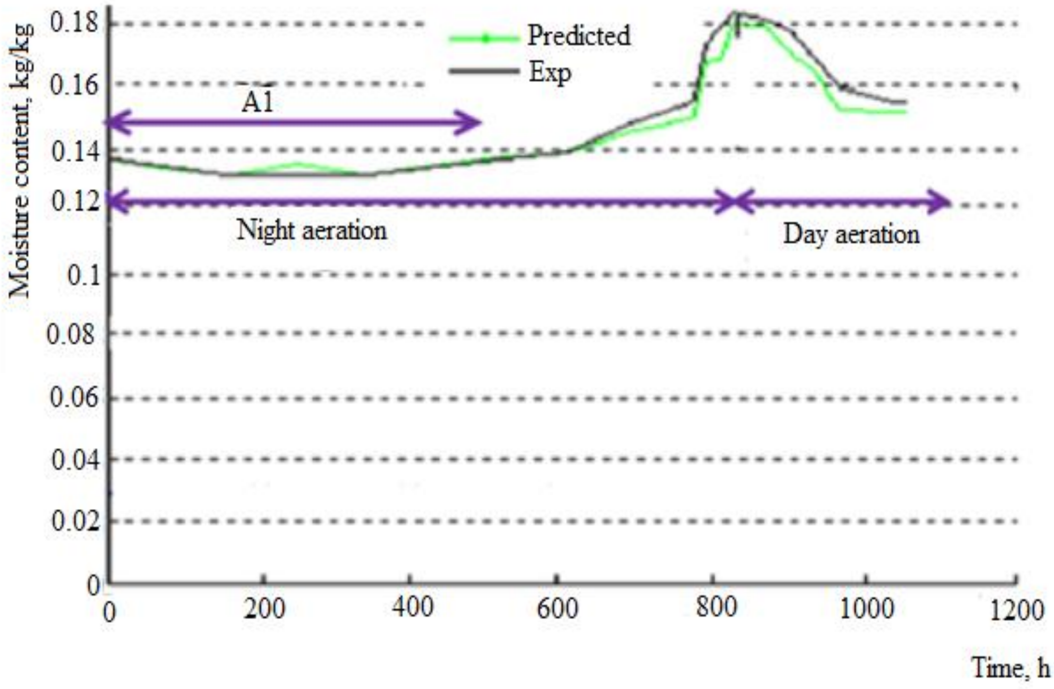

Figure 5 - Predicted and measured grain moisture content during the period of July 09th2018 to January 10th, 2019

In fact, night time ambient air in Northern Tunisia usually offers a higher relative humidity than the day time ambient air, often reaching saturation. During the 864 hours of night aeration from July 9th to November 29th, the stored grain gained from 13.7 to 18.36% (dry weight basis) in humidity (Figure 5). To avoid grain deterioration from such a high grain moisture content, aeration was switched to a daytime schedule from November 30th to January 10th for a period of 252 hours of daytime aeration (daily from 10:00 am to16:00 pm) to take advantage from the lower day time air temperature and relative humidity. The low grain temperature and moisture could thus be maintained.

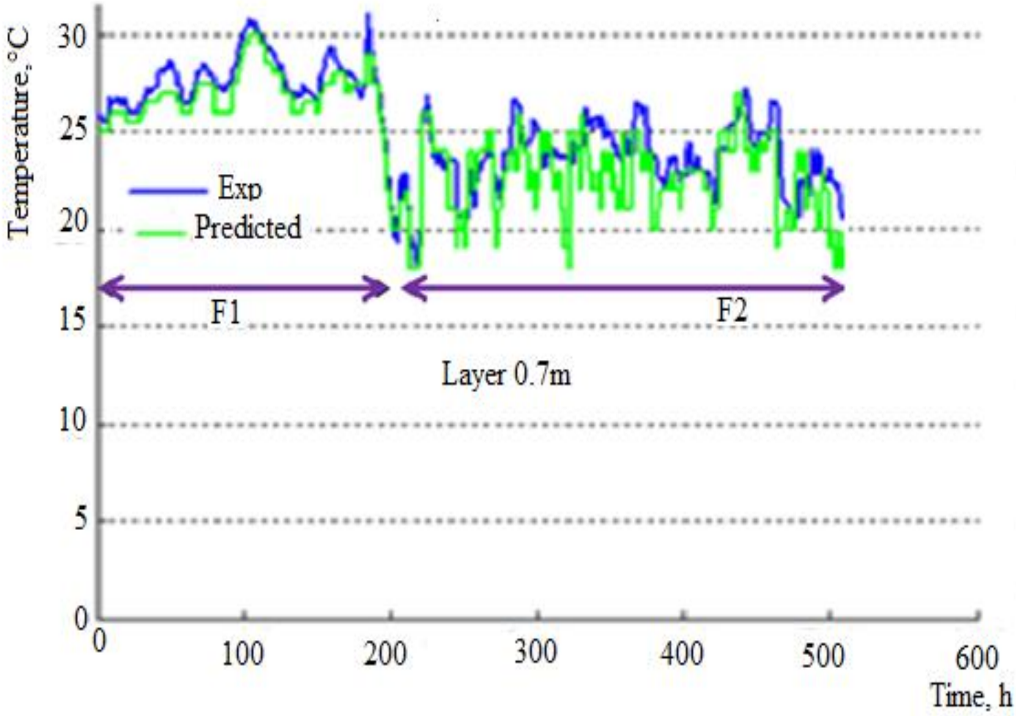

Figure 6 - Predicted and measured grain temperature from July 09th to September 30th 2018 for a grain layer height of 0.7 m

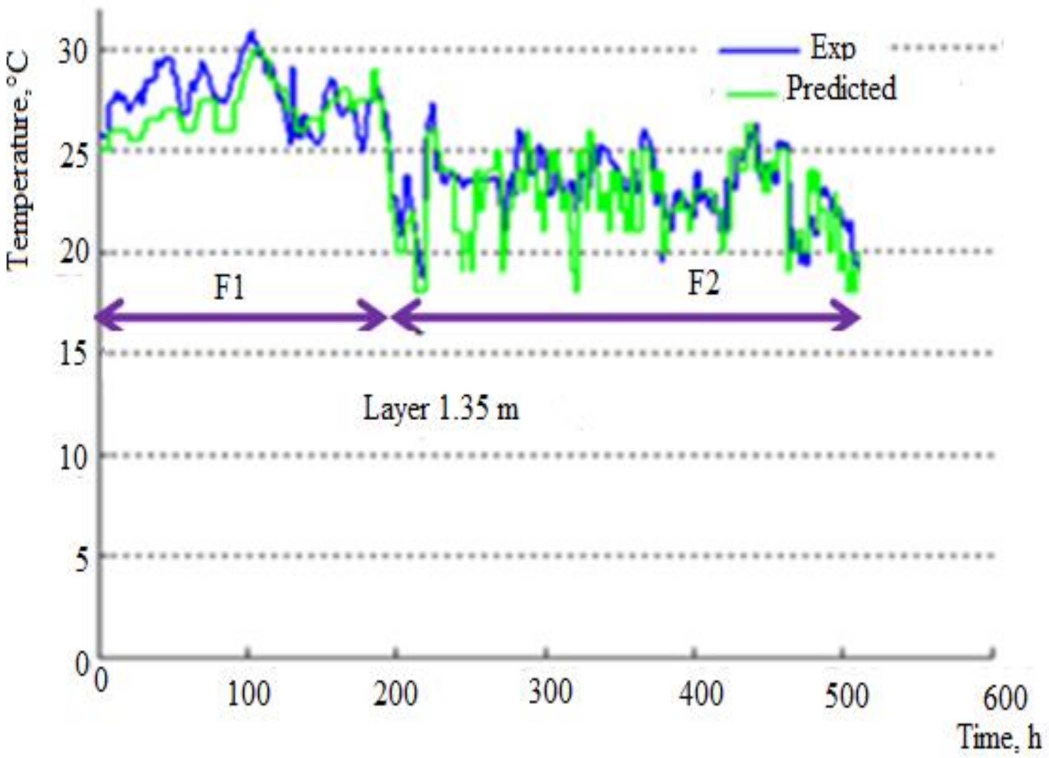

Figure 7- Predicted and measured grain temperature from July 09th to September 30th 2018 for a grain layer height of 1.35 m

The adjustment in aeration program as off November 29th2018 produced the required drying effect predicted by simulation (Day aeration Figure 5). Furthermore, no microorganism activity was observed during the whole experimental period which is an improvement as compared to the usual insect's infestation, generally observed by the end of September for bulk grain with no chemical treatments. When harvested at the end of June, the grain is relatively free of insects. But, insects will there of migrate into the stored grain mass and multiply (Hagstrum, 2000). Generally, insects appear in the upper layers of the grain mass (0 to 1.2 m) because of its aeration, and theirs growths begins in September (Flinn et al. 2010). Insect growth in surface layers is also encouraged by the thermal front of September where the night temperatures are below 20 °C (Figure 5 to 7).

3.1.2 Simulated grain moisture content

Figure 5 shows the evolution of measured and simulated moisture content (dry basis) of the stored grain in response to the aeration scheme. It is observed that the simulated and measured moisture contents are very similar, representing a good fit between simulated and measured values (Table 2).

Table 2 - Aeration air and stored wheat thermo physical properties

Parameter	*Layer*	R^2	*AAVR*	*S.E*	*d (%)*
	1	0.9545	1.1032°C	1.6160°C	97.43
Temperature	2	0.9765	1.1447°C	1.5923°C	97.54
	3	0.9784	0.7967°C	1.2289°C	82.96
Moisture content		0.99	0.0032 kg kg^{-1}	0.0007 kg kg^{-1}	99.9

AAVR and S.E provide a term-by-term comparison of the predicted and observed values. The model also produced small AAVR and SE (AAVR=0,00326 kg kg^{-1}and S.E.= 0,00079 kg kg^{-1}), with a strong correlation R^2=0.99.The high index of agreement (99.9%) indicates the simulation accurately estimated the observed variations. This index varies from 0 to 100% where the 100% reflects perfect agreement between observed and predicted data. According to Willmott (1981), this important index measures the degree of error free model predictions.

The validation of the model allowed for its use in predicting the moisture content of aerated stored grain for various aeration schemes to avoid or delay its deterioration.

3.2. Temperature evolution of the aerated bin stored grain

3.2.1 Measured temperature

Measured wheat temperatures at different levels of the grain mass surface are shown in Figures. 6 - 11. Figures 6, 7 and 8 show the evolution of grain temperature for the period of July 09th to September 30th with a cumulative of 504 hours of night aeration. However, Figures 9, 10 and 11 show the evolution of grain temperature during the period of October 01st 2018 to January 10th 2019, with a cumulative of 612 hours of aeration. The measured temperatures at the end of the summer aeration period were around 24 °C for the three sensors (Figures 6, 7 and 8). During this period of summer aeration, the grain bulk was protected from self and solar radiation heating. Indeed, the first 200 hours of night aeration were used to attenuate and cushion the impact of heat exchanges through the roof and walls of silo during off-peak hours of days when the ambient air temperature generally exceeds 35°C (Figures 6, 7 and 8, phase F1).

The continuation of night aeration during the 304 hours of the phase F2 was marked by an oscillation of the temperature of the grain layers around 24 °C with a cooling effect at the end of this aeration phase, F2 (September 30th) (Figures 6-8).

A significant grain cooling was achieved by the night aeration program during the months of October and November (phase F3). The reached measured temperatures after 360 hours (phase F3, October 01st 2018 to November 29th 2018) of aeration was 10 °C for the three grain layers (Figures 9-11). By the end of October, the measured temperatures for the three sensors were close to 17 °C and no insect's development was observed. Field research confirms the benefits of an initial cooling cycle from the mid 30 °C to about 24 °C, followed by further cooling to 17 °C when outside ambient temperatures are consistently below this threshold (Arthur & Casada 2005).

Figures 6 to 10 illustrate the obvious cooling trend measured by the three bin temperature sensors located in Figure 2 during the night aeration scheme. By the end of October, the grain temperature reached 17 °C for the three sensors. Applied as off the end of November, (phase F4 in Figures 9, 10 and 11), the daytime aeration scheme maintained acceptable low grain temperatures recorded by the three sensors, and dried the grain to a safe level (Figure 3).

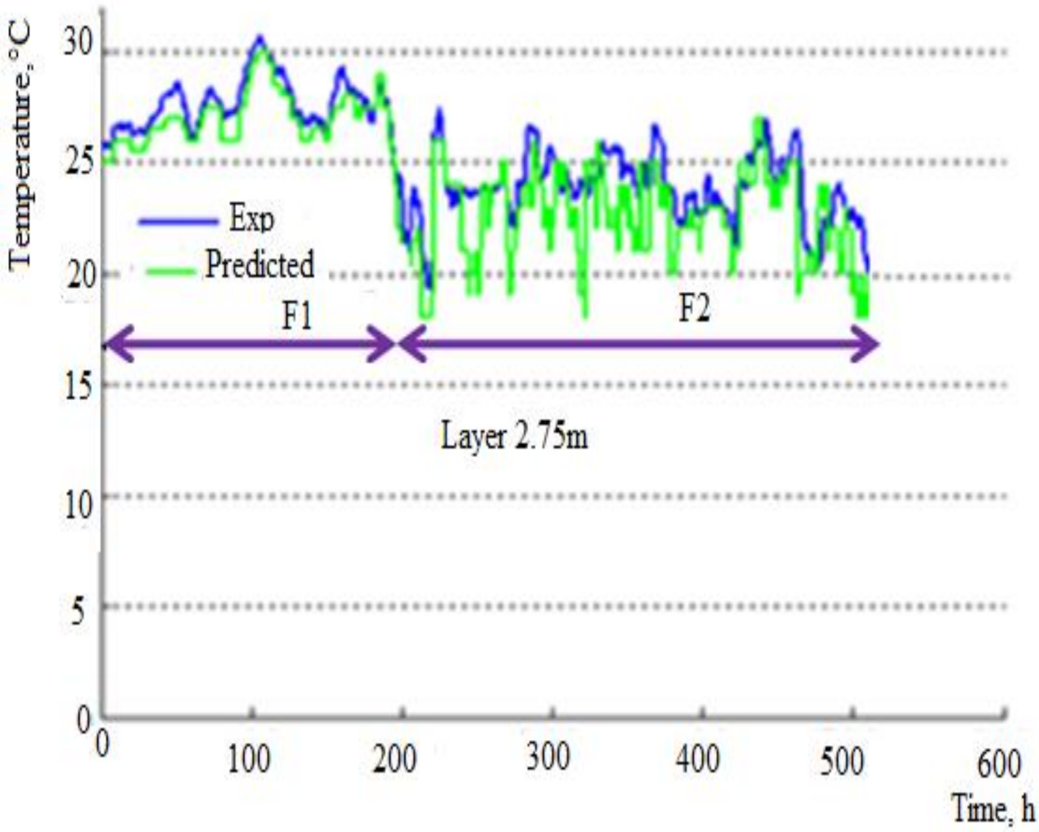

Figure 8- Predicted and measured grain temperature from July 09th to September 30th 2018 for a grain layer height of 2.75m

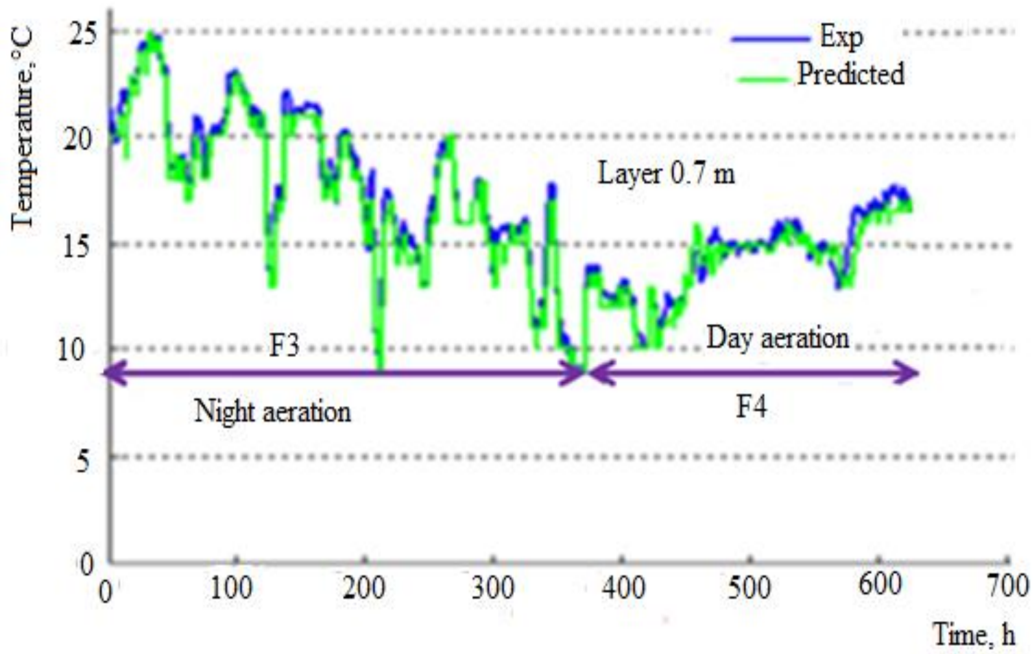

Figure 9- Predicted and measured grain temperature from October 01st, 2018 to January 10th, 2019 for a grain layer height of 0.7 m

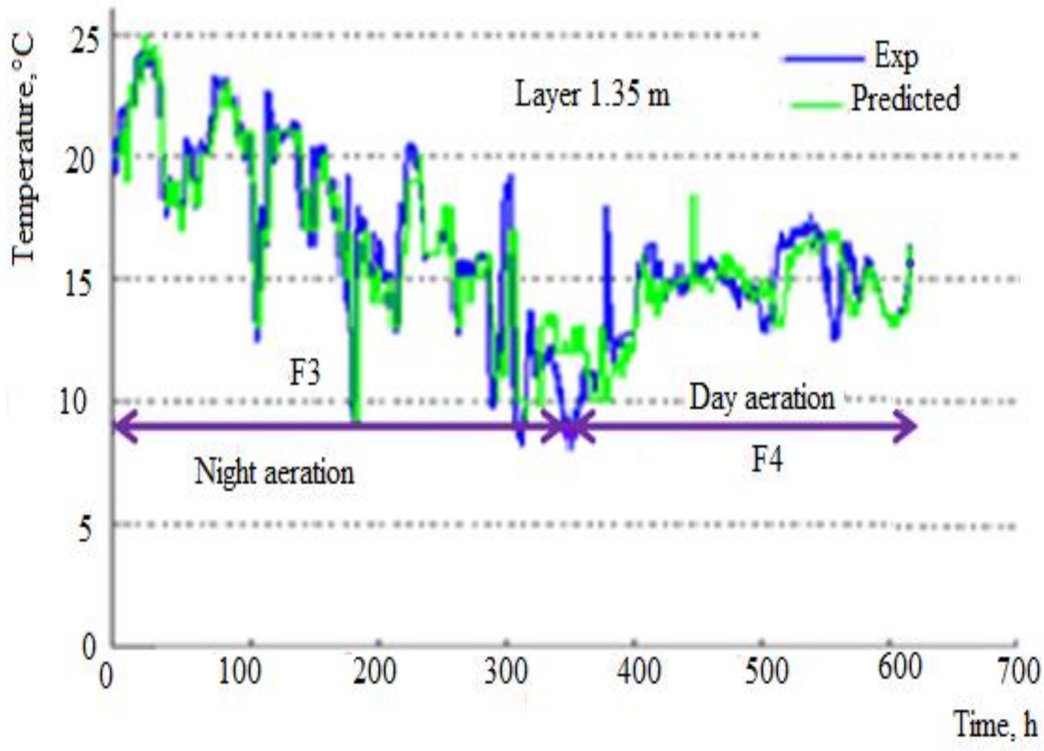

Figure10- Predicted and measured grain temperature from October 01st, 2018 to January 10th, 2019 for a grain layer height of 1.35 m

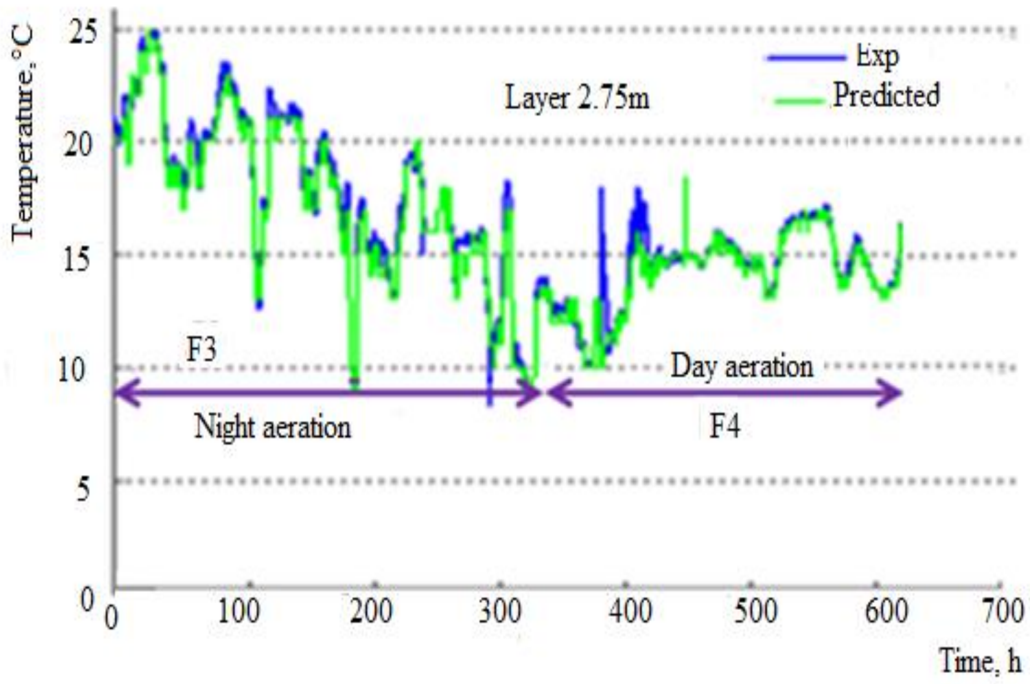

Figure 11- Predicted and measured grain temperature from October 01st, 2018 to January 10th, 2019 for a grain layer height of 2.75 m

3.2.2 Simulated temperature

The model simulation produced results similar to those observed. Figures 6 to 11 illustrate the similar predicted and measured temperatures for the three layers of grains (S.E. below 1.7 °C, AAVR below 1.2 °C and a correlation exceeding 0.95) (Table 1). However, the predicted values were always lower than these measured mainly during the summer aeration scheme because:

- The predicted temperatures of the upper layer (Sensor N° 1) at the beginning of the period were significantly lower than that observed. The model did not take into account the silo head space warming effect of about 8 °C (depending on temperature sensor in the headspace). The discrepancy was higher early in the aeration scheme because of radiation effects. Differences for sensor 2 were explained by a longer sunlight exposure of the bin left side, quantified by AAVR (1.10 °C for Sensor N°1and 1.14 °C for Sensor N° 2). During the rest of the cooling period, the predicted temperature values follow those measured.

- The predicted temperature was the average of the simulated layers. Because of delays in layer cooling, a logic discrepancy occurred. The discrepancy tended towards a minimum after the entire layer cooling. A larger discrepancy was observed for thicker simulated layers. The discrepancy is explained in Table 2 by the index of agreement (d); indeed, the delay importance for layer 3 provides an agreement between observed and predicted value of 82.96%; however, the agreement increases as the thickness decreases, being greater than 97% for thicknesses of 0.7 m and 1.35 m.

4. Conclusions

The objective of the project was to validate a simulation model to recommend aeration schemes for grain stored under Tunisian climatic conditions.

According to the measured and simulated stored grain mass temperature and moisture content, it can be concluded that:

- Simulation using the appropriate mathematical model gives a good prediction of the aerated stored grain system (R^2=0.99 for moisture content with a range of 0.95 to 0.98 for the 3 layers). The reliable simulation outputs can be used to provide the appropriate aeration scheme to safely store grain masses.

- Night aeration seems to be a good alternative to avoid overheating of the stored wheat from July to August, in Tunisia and subsequently cool the grain to safe temperatures preventing the development of insects.

- Night aeration has a moistening effect of the grains which was simulated and observed. However, critical values were reached in late November when daytime ventilation can be used to maintain low temperatures while maintaining safe grain moisture levels. Lower winter daytime air relative humidity allowed for the observed and simulated grain drying effect.

For continental climatic conditions such as those of Northern Tunisia, night and day time grain aeration schemes can be combined to prevent the development of insects and microorganisms in stored grain masses. In fact, no microorganism activity was observed during the whole experimental period where stored wheat was properly aerated. This is a major advantage for grain storage facilities in Tunisia, where a general lack of proper storage schemes produces insect and mold infestations by September, yearly.

The mathematical model validated for grain bin storage conditions can be further used to develop appropriate aeration schemes for subtropical climatic conditions such as those of Tunisia where the differences between the ambient aeration air and the grain mass temperatures are small.

Acknowledgements

The author acknowledges the financial contribution of Institution de la Recherche et de l'EnseignementSupérieur Agricole and the research unit entitled: Renewable Energies in Agriculture and Ag-Industry of the École Supérieure des Ingénieurs de Medjez El Bab.

References

Andrade SM, Couto D, Queiroz y L and Faroni. 2002. "Three Dimensional Simulation of the Temperature Variation in Corn Stored in Metallic Bin." *ASAE Annual Meeting*: Paper Nº02-3150. https://doi.org/10.13031/2013.9175

Arthur F H and Mark Casada 2005. "Feasibility of Summer Aeration for Management of Wheat Stored in Kansas." *Applied Engineering in Agriculture* 21(6): 1027-38. https://doi.org/10.13031/2013.20019

Arthur Frank H, Keiichi Takahashi Courtenay K Hoernemann and Nahoko Soto 2003. "Potential for Autumn Aeration of Stored Rough Rice and the Potential Number of Generations of Sitophilus Zeamais Motschulsky in Milled Rice in Japan." *Journal of Stored Products Research* 39(5): 471-87. https://doi.org/10.1016/s0022-474x(02)00038-3

"ASAE Standards. 41st Ed. 1994b. D245.4 DEC93. Moisture Relationships of Grains. 432-436. St. Joseph."

Bala BK and JL Woods 1984. "Simulation of Deep Bed Malt Drying." *Journal of Agricultural Engineering Research* 30: 235-44. https://doi.org/10.1016/s0021-8634(84)80024-4

Behaeen, Mohammad-Ali, Asgar Mahmoudi and Seyed-Faramarz Ranjbar 2018. "An Evaluation of the Performance of Forced Air Cooling on Cooling Parameters in Transient Heat Transfer at Different Layers of Pomegranate." *Journal of Agricultural Sciences* 24(1): 12-21. https://doi.org/10.15832/ankutbd.446362

Brooker DB, Bakker-Arkema FW& Hall CW 1992. *Drying and Storage of Grains and Oilseeds. AVI Book*. USA.

de Carvalho Lopes, Daniela et al. 2008. "Aeration Strategy for Controlling Grain Storage Based on Simulation and on Real Data Acquisition." *computers and electronics in agriculture* 63(2): 140-46. https://doi.org/10.1016/j.compag.2008.02.002

Chung, Do Sup and Harry B Pfost 1967. "Adsorption and Desorption of Water Vapor by Cereal Grains and Their Products Part II: Development of the General Isotherm Equation." *Transactions of the ASAE* 10(4): 552-55. https://doi.org/10.13031/2013.39727

Flinn PW, DW Hagstrum, C Reed and TW Phillips. 2010. "Insect Population Dynamics in Commercial Grain Elevators." *Journal of Stored Products Research* 46(1): 43-47. https://doi.org/10.1016/j.jspr.2009.09.001

Hagstrum, David W 2000. "Using Five Sampling Methods to Measure Insect Distribution and Abundance in Bins Storing Wheat." *Journal of Stored Products Research* 36(3): 253-62. https://doi.org/10.1016/s0022-474x(99)00047-8

Iguaz a et al. 2003. "Modelling Effective Moisture Difusivity of Rough Rice (Lido Cultivar) at Low Drying Temperatures." *Journal of Food Engineering* 59(2–3): 253-58. https://doi.org/10.1016/s0260-8774(02)00465-x

Iguaz A, C Arroqui, A Esnoz and P Vírseda. 2004. "Modelling and Simulation of Heat Transfer in Stored Rough Rice with Aeration." *Biosystems Engineering* 89(1): 69-77. https://doi.org/10.1016/j.biosystemseng.2004.05.001

Jia, Canchun, Da-Wen Sun and Chongwen Cao. 2001. "Computer Simulation of Temperature Changes in a Wheat Storage Bin." *Journal of Stored Products Research* 37(2): 165-77. https://doi.org/10.1016/s0022-474x(00)00017-5

Longstaff B C 1994. "The Management of Stored Product Pests by Non-Chemical Means: An Australian Perspective." *Journal of Stored Products Research* 30(3): 179-85. https://doi.org/10.1016/0022-474x(94)90046-k

Maier DE, WH Adams, JE Throne and LJ Mason. 1996. "Temperature Management of the Maize Weevil, Sitophilus Zeamais Motsch. (Coleoptera: Curculionidae), in Three Locations in the United States." *Journal of Stored Products Research* 32(3): 255-73. https://doi.org/10.1016/s0022-474x(96)00014-8

Mayer DG, and DG Butler. 1993. "Statistical Validation." *Ecological Modelling* 68(1-2): 21-32

Menzies DJ, and JR O'Callaghan. 1971. "The Effect of Temperature on the Drying Rate of Grass." *Journal of Agricultural Engineering Research* 16(3): 213–22 https://doi.org/10.1016/s0021-8634(71)80015-x

Muir WE. 1970. "Temperature in Grain Bins." *canadian Agricultural Engineering* 12: 21-24

Navarro S, Noyes RT. 2001. "The Mechanics and Physics of Modern Grain Aeration Management." In *The Mechanics and Physics of Modern Grain Aeration Management*, CRC Press, Boca Raton, 647. https://doi.org/10.1201/9781420040333.ch7

Sun DW, Woods J L. 1994. "Low Temperature Moisture Transfer Characteristics of Barley: Thin-Layer Models and Equilibrium Isotherms." *Journal of Agricultural Engineering Research* 59: 273-83. https://doi.org/10.1006/jaer.1994.1086

Thorpe GR. 2001. "Physical Basis of Aeration. In: Navarro, S., Noyes, R.T. (Eds.)." In *The Mechanics and Physics of Modern Grain Aeration Management*, CRC Press, Boca Raton, 125-194. https://doi.org/10.1201/9781420040333.ch4

Willmott CJ. 1981. "On the Validation of Models." *Physical Geography* 2(2): 184-94

Yang JY and EC (Ted) Huffman. 2004. "EasyGrapher: Software for Graphical and Statistical Validation of DSSAT Outputs." *Computers and Electronics in Agriculture* 45(1–3): 125-32. https://doi.org/10.1016/j.compag.2004.06.006