Bin stored wheat temperature simulation under South Mediterranean climate

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Abstract: Cereal quality preservation is traditionally the accountability of grain store keepers who count on profound knowledge discovered through scientific research. The main purpose of this research study was to predict the evolution of wheat temperature in unaerated silo during storage period under Tunisia climate. First, a bidimensional mathematical combined model (silo wall model + heat transfer model in grain bulk), which describes the distribution of the unsteady temperature in a cylindrical grain storage system, was presented and simulated using the parabolic solver incorporated in the Matlab 2015a environment. Mesh refinement at the shortest boundaries, including triangular elements, was adopted to simulate storage temperatures. In this numerical model, the influence of Newman boundary conditions, which include solar irradiation and air convection, on the evolution and distribution of grain temperatures was considered. Second, the model was validated by conducting experiments in a weathered galvanized steel silo with conical bottom, preserving wheat during the period of autumn 2019 (from October 23rd, 2019 to October 29th, 2019). Utilizing the climatic data of the region of Medjez El Bab, located in Western North of Tunisia, the variations in stored grain temperatures were interpreted in detail. The obtained results when comparing the observed versus numerical data proved an excellent agreement according to the correlation coefficients r^2 for different measurement points (from 0.85 to 0.98), confirming that the developed model is an outstanding tool to monitoring and to predicting wheat conservation for regions with similar climate conditions as Tunisia.
Keywords: grain storage, grain temperature, numerical study, experimental study

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1 Introduction

Cereals are considered an essential harvest product for individual nourishment. Large amounts of cereal grains are designated for animal feed in order to produce nutritious foods that are necessary for human diets. The Tunisian population consumes considerable quantities of cereals throughout the whole year. Wheat, in Tunisia, is the most substantial arable crop covering approximately 725 000 hectares per year, mainly occupies the northern zones of the country (Bensassi et al., 2010; Sadok et al., 2019).

Although conserving grain systems have been used since prehistoric times in Tunisia, phenomena that occur during storage periods are not completely mastered in a hot climate, such as Tunisia climate, in order to satisfy the main purpose of storage. Systems for storing cereals have been described as agroecosystems that involve heat and

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material transfer in complex biological domain that can be damaged (Bala, 2016). It has been demonstrated that nutritional value changes during storage periods are the result of interactions between the components of storage ecosystems (Jayas et al., 1995; Moses et al., 2015).

Grain is commonly damaged by the development of insects, mites and fungi. In addition, grain contamination with the formation and growth of microorganisms rises the risk of dangerous health problems (Fleurat-Lessard, 2002, 2017; Lee and Ryu, 2017). In grain bulk, reduced storage temperature can block the development and reproduction of microorganisms (Kawamoto et al., 1989; Daglish et al., 2018). Therefore, insect and molds growth inside a grain ecosystem (spoilage risks) depends on storage temperature (Jian et al., 2005; Subrot et al., 2020). It has also been confirmed that grain temperature during storage periods is one of the most important factors affecting stored grain in bins (Chang et al., 1993; Thorpe, 1997; Hammami et al., 2016; Abdullah et al., 2019; Wang et al., 2020). The most important determinants that have significant impacts on the temperature of grain and its quality, especially in Tunisia, which has a warm climate in summer, are solar radiation and ambient air conditions (Wang and Zhang, 2015).

In order to prevent grain damage during conservation periods, ventilation with ambient air is frequently used in the world to cool stored grain (Iguaz et al., 2004a; Yang et al., 2017). The operation periods of the aeration process depend on seasonal and daily climatic fluctuations and commonly interspersed with prolonged non-aeration periods. Taking into account the hourly and daily variability of Tunisian climatic conditions, the aeration periods having the potential to cool and preserve cereals under safe conditions are limited.

Daily weather fluctuations and incident solar irradiation at different walls of the storage structure create temperature gradients within the grain bulk, and these gradients of temperature provoke the phenomenon of natural convection, which results in dampness circulation from high grain temperature to low grain temperature areas (Jia et al., 2000a; Quemada-Villagómez et al., 2020). When the temperature of ambient air declines in the winter season, the temperatures of stored grain bin peripheral layers become significantly cooler than the grain bulk inner temperatures. Therefore, ascending convective currents are created within the grain bulk and the moisture accumulates in the area centrally located in the upper part of the grain mass. However, the opposite of these phenomena occurs during the winter season, the convective currents within the grain bin are descending and the dampness increases in the region centrally located in the lower region of the grain bulk. Regular moisture circulation rises the probability of a wider allocation of insects and fungi and can then deteriorate the grain quality (Sun and Woods, 1997; Hammami et al., 2017). Tunisia climate is typified, in summer, by hot ambient temperature and prolonged ambient air moisture, being a convenient circumstance for the deterioration of grain quality. It is a hot summer Mediterranean weather, where ambient air temperatures in the months of July and August can surpass 40°C. The observed levels of wheat contamination by fungi can be justified by the fact of favorable effects of the Mediterranean climate of Tunisia for the development of fungi on produced grains. High ambient temperature and relative humidity are the most important causes rising fungi development (Beyer et al., 2007; Kammoun et al., 2010; Zaied et al., 2012; Ferrigo et al., 2016; Lee and Ryu, 2017).

Accurate predictions of grain temperature in storage bins can be used to improve and assess methods and scenarios of preserving grain quality and decreasing the use of chemical treatments in the control of insects and fungi development and growth. However, experimental works to analyze the temperatures distribution and evolution in grain silos are difficult, costly and time-consuming practices. Thus, the study of grain temperature variations based only on experiments is not practical. Numerical studies can simulate and predict the stored grain temperatures in storage bins of different dimensions, constructed by different types of materials and placed at different geographic regions (Alagusundaram et al., 1990; Jia et al., 2000b; Arias et al., 2013). Many researchers have solved the heat transfer problem in order to predict and investigate grain temperature in various form of storage bins, particularly round vertical bins (Dona and Stewart, 1988; Alagusundaram et al., 1990; Bala et al., 1990; Chang et al., 1993; Jia et al., 2001; Jian et al., 2005; Novoa-Muñoz, 2019). The investigators have resolved energy balance equation using one of the two numerical methods: finite difference method and finite element method (Subrot et al., 2020). It has been affirmed that the finite element method is advantageous due to its adaptability for the study of problems associated with complicated boundary conditions and the finite difference method is difficult to solve irregular shape of computational domain with mixed boundary conditions that incorporate air convection and solar irradiation (Jia et al., 2000a).

In this context, as a part of the whole project of optimizing thermal bin wall characteristics, the problematic of this research paper is to predict the evolution of storage conditions in non-aerated grain storage bin under the weather conditions of Tunisia.

To get the more accurate solution of the stored grain bulk temperature distribution, it's important to consider the heat transfer balance as well as the mixed boundary conditions that simulate the Mediterranean weather and to take account of heat of grain respiration and heat transfer through the storage bin's wall. The limitations in the past researches concerning storage grain systems are the following:

(1) Heat respiration of the stored grain was neglected;

(2) Storage bin's wall heat transfer was neglected and the computational domain of storage system was generally simplified as only grain domain. So, thermal insulation parameters of grain storage bins were not included in the mathematical model;

(3) Few experimental and numerical studies related to non-aerated grain storage bin that are appropriate to Tunisia climate.

The objective of the present work is to predict the temperature distribution of grain bulk stored in a galvanized steel bin during periods without aeration.

The main objective could be achieved through the following specific objectives:

(1) To develop tow-dimensional numerical unsteady combined model (bin wall heat transfer model + conduction in grain bulk) that describes heat transfer processes;

(2) To solve the heat transfer model with mixed boundary conditions that include Tunisian weather conditions (air convection + solar radiation) and the grain respiration heat;

(3) To validate the energy exchange model against experimental data;

(4) To describe and analyze the recorded temperatures of wheat during storage period.

2 Materials and methods

The mathematical equations predict and describe the evolution of wheat temperature in each control volume and the associated bin wall temperatures. The mixed boundary conditions, that include ambient air convection and solar radiation on the bin wall were included in the model.

At the external sides of the bin wall and roof, in contact with ambient air, the heat flux was calculated using the energy balance on these surfaces. The conductive heat transfer through the bin wall is the result of the convective heat exchanged with ambient air and the radiant heat. In fact, the net solar radiation heat flux is the summation of bin absorption from the heat flux accumulated from solar radiation and sky radiant heat flux. The emissivity and absorptivity of the galvanized steel material were 0.23 and 0.66, respectively (Jia et al., 2000a).

The two-dimensional partial differential equation describing the transient energy exchange through a homogeneous material was derived considering:

(1) The energy transfer rate across every boundary surface of an elementary control volume within the bin wall material would arise as a function of the gradient of temperature; and

(2) The change in internal heat of the bin wall material in the control volume is reflected by the change in the material temperature.

The resultant unsteady equation is given by Underwood and Yik (2008):

$$\rho_s c_s \frac{\partial T}{\partial t} - \nabla.\lambda\nabla T - q = 0 \tag{1}$$

Where ρ_s is the bin wall material density in (kg m^{-3});

c_s is the bin wall specific heat capacity in ($Jkg^{-1}K^{-1}$); λ is the thermal conductivity of the bin wall in ($Wm^{-1}K^{-1}$); T is the temperature of the bin wall in (K); q is the net rate of energy generated by the internal source within the material of the bin wall in (Wm^{-3}); and t is the time in (s).

For our research, to analyze the heat transfer through galvanized steel walls of the bin, Equation 1 can be simplified by adding the following hypotheses:

(1) Heat transfer through the bin wall is isotropic; and

(2) No heat created by internal source within the bin wall material (q=0).

Then, the Equation 1 is simplified to:

$$\rho_s c_s \frac{\partial T}{\partial t} - \nabla.\lambda \nabla T = 0 \quad (2)$$

The following hypotheses were considered to simplify heat transfer equation in grain bulk:

(1) The grain ecosystem is considered to be continuum where the intergranular air and the grain are in sorption and thermal equilibrium at every control volume in the grain bulk;

(2) The thermal transfer phenomenon is symmetrical around the central vertical axis of the grain bin; and

(3) The thermal transfer in the circumferential direction is negligible compared to the heat transfer in the axial and radial directions.

With the hypotheses above, the transient equation describing the conservation of the energy in a control volume in a cylindrical coordinate system is given by (Holman and White, 1992; Jia et al., 2000a; Novoa-Muñoz, 2019) :

$$\rho_g c_g \frac{\partial T_g}{\partial t} = k\left(\frac{\partial^2 T_g}{\partial r^2} + \frac{1}{r}\frac{\partial T_g}{\partial r} + \frac{\partial^2 T_g}{\partial z^2}\right) + q_{\text{int}} \quad (3)$$

Where ρ_g is the density of the grain bulk in ($kg\ m^{-3}$); c_g is the grain specific heat capacity in ($Jkg^{-1}K^{-1}$); k is the thermal conductivity of the grain bulk in ($Wm^{-1}K^{-1}$); T_g is the temperature of the cereal grains in (K); q_{int} is the internal produced heat in (Wm^{-3}); t is the time in (s); r and z are the radial and axial coordinates respectively in (m).

The chemical reaction involved in heat generation is an oxidation of carbohydrates such as starch. The energy is created by the following equation (Raudienė et al., 2017) (complete combustion of a typical carbohydrate):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + heat \quad (4)$$

$$180g + 192g \rightarrow 264g + 108g + 2835kJ \quad (5)$$

Based on this stoichiometric respiration equation, the generated heat, the ratio of oxygen consumed and the water vapor produced can be determined. The rate of carbon dioxide R_{co2} in mg[CO_2]kg-1[Dry matter] in 24 h is given by (White et el., 1982; Abalone et al., 2011; Arias and Bartosik et al., 2013).

The generated heat R_{resp} in Jkg^{-1}[Dry matter] in 24 h is (Gastón et al., 2009) :

$$R_{resp} = \frac{heat}{M_{CO_2}} R_{CO_2} = Q_H R_{CO_2} \quad (6)$$

Where heat is 2835 kJ; M_{CO2} is the molecular weight of CO_2; Q_H is 10.738 Jmg^{-1}[CO_2] and R_{CO2} is the rate of carbon dioxide in mg[CO2]kg^{-1}[Dry matter] in 24 hours.

The heat transfer equations (Equation 2 and Equation 3) need to be solved in conjunction with the energy balances that define the boundary conditions applied to the bin wall surfaces. Typical boundary conditions associated to the storage heat transfer problems include ambient air conditions and solar radiation corresponding to Tunisia climate.

Initial condition associated to Equation 2 is:

$$T\left(r,z,t=0\right) = T_0 \quad (7)$$

Initial condition associated to Equation 3 is:

$$T_g\left(r,z,t=0\right) = T_{g0} \quad (8)$$

Temperature variations on the surface layer of the grain bulk and on the bin wall surfaces depend mainly on fluctuations in both environmental temperature and incident solar irradiation. Thus, there are various boundary conditions for the heat transfer equations which are presented in detail.

The boundary condition on the bottom layer of the grain S_{inf} is given as

$$-k\frac{\partial T_g}{\partial z} = h_{S\inf}\left(T_g - T_{S\inf}\right)\left(t \succ 0\right) \quad (9)$$

Where h_{Sinf} is the convective heat transfer coefficient for the grain bulk bottom surface in ($Wm^{-2}K^{-1}$); and T_{Sinf} is the air temperature near the grain bulk bottom surface in (K).

Ambient air convection and solar radiation exist on the boundary S_{ext}, hence

$$-\lambda \frac{\partial T_g}{\partial r} = h_{Sext}\left(T_g - T_{Sext}\right) - q_{Sext} \qquad \left(t \succ 0\right) \tag{10}$$

Where h_{Sext} is the convective heat transfer coefficient for the circumference surface of the grain bulk in ($Wm^{-2}K^{-1}$); and T_{Sext} is the air temperature near the circumference surface of the bin in (K); q_{Sext} is the net solar radiation on the circumference bin wall in (Wm^{-2}).

The boundary condition on the grain bulk top surface S_{sup} is given as

$$-k \frac{\partial T_g}{\partial z} = h_{S\sup}\left(T_g - T_{S\sup}\right) - q_{S\sup} \qquad \left(t \succ 0\right) \tag{11}$$

Where h_{Ssup} is the convective heat transfer coefficient for the top surface layer of the grain bulk in ($Wm^{-2}K^{-1}$); and T_{Ssup} is the temperature of air near the grain top surface in (K); q_{Ssup} is the radiation from the bin roof to the grain bulk surface layer in (Wm^{-2}).

The net solar radiation on the bin wall in Equation 10 q_{Sext} can be determined as (Jia et al., 2001)

$$q_{Sext} = \alpha I_T + q_{w,rad} \tag{12}$$

Where α is the short-wave absorptivity of the storage structure wall; I_T is solar radiation on the storage structure wall in (Wm^{-2}); and $q_{w,rad}$ is the radiation from the storage structure wall to its surroundings in (Wm^{-2}).

$$q_{w,rad} = \sigma\varepsilon_{wl}\left(T_{aamb}^4 - T_{aw}^4\right) \tag{13}$$

Where σ (=5.6703×10^{-8} $Wm^{-2}K^{-4}$) is the constant of Stefan-Boltzmann; ε_{wl} is the long wave emissivity of the storage structure; T_{aamb} is the absolute ambient air temperature in (K); and T_{aw} is the absolute temperature of the storage structure wall in (K).

The radiation from the bin roof to the grain bulk surface layer q_{Ssup} can be calculated as follows

$$q_{S\sup} = \sigma\alpha_s F\left(T_{ar}^4 - T_{as}^4\right) \tag{14}$$

Where α_s is the grain mass surface layer absorptivity; F is the shape factor; T_{ar} is the absolute temperature of the storage structure roof in (K); and T_{as} is the absolute temperature of grain mass surface layer in the storage structure in (K).

Equation 15 was used to determine the convective heat transfer coefficient h_{Sext} corresponding to the external surface of the bin wall (Longstaff and Finnigan, 1983; Novoa-Muñoz, 2019).

$$Nu = 0.227\,\mathrm{Re}^{0.633} \tag{15}$$

$$Nu = \frac{h_{Sext} D}{k_{air}} \tag{16}$$

$$\mathrm{Re} = \frac{u_{air} D}{\upsilon_{air}} \tag{17}$$

Where Nu is the Nusselt number; Re is the Reynolds number; D is the bin diameter in (m); k_{air} is the air thermal conductivity in ($Wm^{-2}K^{-1}$); u_{air} is the local wind speed in (ms^{-1}); υ_{air} is the air kinematic viscosity in (m^2s^{-1}).

The kinematic viscosity and the thermal conductivity of the ambient air were calculated using the following mathematical equations (Jian et al., 2005):

$$\upsilon_{air} = \left(0.09T_{aamb} - 10.92\right)\times10^{-6} \tag{18}$$

$$k_{air} = \left(0.08T_{aamb} + 2.34\right)\times10^{-3} \tag{19}$$

The convective heat transfer coefficient for the grain bin bottom surface h_{Sinf} and the convective heat transfer coefficient for the grain bulk top surface h_{Ssup} were considered to be equal to half the convective heat transfer coefficient for the bin wall hSext (Iguaz et al., 2004b).

The mathematical unsteady model that describes the energy exchange in stored wheat of the control volume, composed of transient heat equations (Equation 2 and Equation 3) associated with boundary and initial conditions, was coded in Matlab 2015a programming language to predict the evolution of bulk stored wheat temperature. The 2-D partial differential equations were numerically solved by the finite element method for a cylindrical geometry using parabolic solver and 3600 seconds step for the time with 10^{-6} absolute tolerance in each discretization equation. It was hypothesized for the grain bulk temperature distributions in the storage bin to be symmetrical about the central vertical axis since the heat flux in the circumferential direction was assumed insignificant.

Figure 2 shows the discretization of the computational domain which was divided into two subdomains: the grain domain and the bin wall domain (Figure 1). The studied geometry was discretized into triangular meshes. Using mesh refinement at the edges was preferable for simulating grain temperatures in a grain bin by referring to literature (Jian et al., 2005). When developing the model, the numerical code generated 2947 elements in 2-D grid of the computational domain. A finer grid was created at the short edges where the highest thermal gradients are predicted to occur. The convergence of the model's equations was predicted to behave well because mesh nodes are concentrated in the short edges where there are large variations in the temperature profiles.

To validate the numerical code, wheat temperatures were simulated in Matlab 2015a programming language and the predicted results were compared to the experimental data. The numerical study covered the period from October 23rd, 2019 to October 29th, 2019. The duration of the field test was 154 hours. In this field test, the wheat was loaded in bin at an initial temperature of 302.15 °K. The physical configuration and size of the experimental galvanized steel bin are shown in Figure 1 and the sensors locations (measuring points) are showed in Figure 4. The thermal conductivity, the density and the specific heat of the bin wall material (corrugated galvanized steel) were 45.8 $Wm^{-1}K^{-1}$, 7790 kg m^{-3} and 470 $Jkg^{-1}K^{-1}$, respectively (Jia et al., 2001). The thermal conductivity, the density and the specific heat of stored wheat were 0.159 $Wm^{-1}K^{-1}$, 863 kg m^{-3} and 1757 $Jkg^{-1}K^{-1}$, respectively (Jia et al., 2001). The weather recording station of the National Institute of Meteorology supplied meteorological data.

The numerical calculation code was developed to find a solution for the problem of the wheat storage system under climatic fluctuations in Tunisia. The input data needed are the initial temperature of stored wheat, types of boundary conditions, the hourly climatic data such as wind velocity, solar radiation, ambient air temperatures, thermo-physical properties of stored grain, thermal properties of ambient air, thermal characteristics of storage structure material (thermal conductivity, emissivity and absorptivity of the bin wall (Table 1)), and the storage bin dimensions. By running this computer program, the distribution and the evolution of stored wheat temperature can be provided.

Table 1 Input thermal parameters of the heat model

Reference	Parameter
Short wave absorptivity of the bin wall (Jia et al., 2001)	α=0.66
Long wave emissivity of the bin wall (Jia et al., 2001)	ε_{wl}=0.23
Grain bulk surface layer absorptivity (Jia et al., 2001)	α_g=0.9

Conical form base bin, to make easy its emptying, is largely used. In Tunisia, cereals storekeepers use grain bins with conical form base to store their crops for a long period of time. To validate the numerical model, the model outputs have to be compared to experimental records on cereals storage structure under Tunisia weather conditions. The experimentation was carried out in a conical shaped base bin at the Higher School of Engineers of Medjez El Bab (Figure 3). The storage bin was constructed from corrugated galvanized steel. The fan and the perforated aeration ducts were mounted on the bottom of the bin. The aeration fan sucks air from the bottom of the bin and was switched off during the experiment. The circular bin has 1.5 m diameter and 2.9 m total height, such as 1.7 m for the cylindrical part and 0.6 m for the bottom and top conical parts respectively. The bin wall thickness was equal to 0.002 m (Figure 1).

The purpose was to analyze the influence of the storage structure conditions on the evolution of grain bulk temperatures during a storage period of 154 hours. Therefore, wheat bulk temperatures inside the bin were recorded every one hour at three positions during storage using temperature sensors (Figure 3-b). The type of these sensors is DS18B20 with a measurement accuracy of ±0.5 °K. The temperature sensors were mounted in perforated tubes, which were mounted horizontally across the cylindrical part of the storage bin (Figure 4). The perforated tubes were sealed at the bin wall to avoid communication with the ambient.

Three temperature sensors were inserted into the bin to measure wheat temperature at different positions. The coordinates (*r, z*) in meter for the three sensors were: sensor 1 (0.50, 0.98), sensor 2 (0.10, 0.53) and sensor 3 (0.68, 0.08). Figure 4 represents the locations of these temperature sensors (S1, S2 and S3). The sensor S3 was placed close to the bin wall in order to study the thermal behavior of the grain layers near the grain bin wall, the sensor S2 was inserted near the central axis of the grain bin to measure the stored grain temperature near the center of the bin and the sensor S1 was placed between locations of sensor S2 and sensor S3. The temperature sensors were connected to an Arduino board, then to a computer for recording the real time data.

A statistical analysis was used in order to quantify the accuracy of the heat transfer model for stored grain bulk without aeration. The correlation coefficients $\left(r^2\right)$ between the observed and simulated temperatures at the three locations were 0.91 (at S1), 0.98 (at S2) and 0.85 (at S3). The correlation coefficient is dimensionless. The standard error residuals (SE) and the average absolute difference (AAD) were used to compare the simulated and measured values.

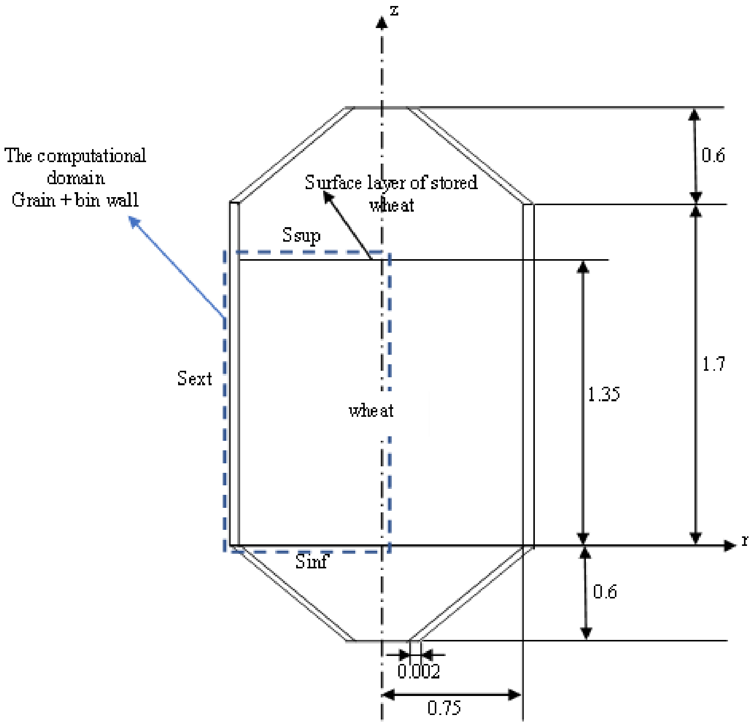

Figure 1 Physical configuration, boundaries and structure of the conical shaped base storage structure of wheat.
Note: The dimensions are in meters

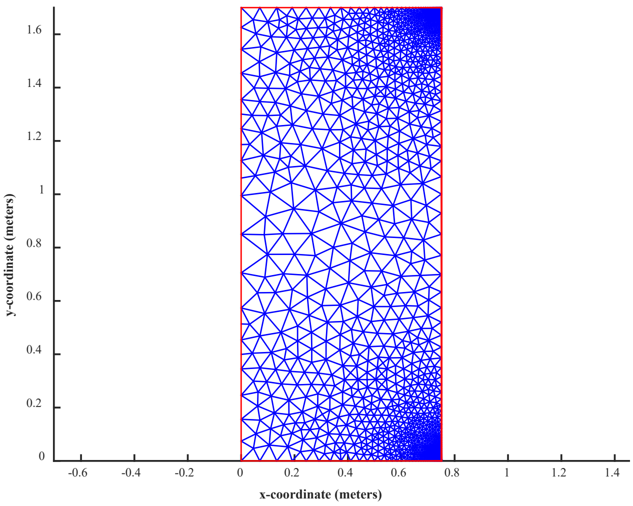

Figure 2 Bulk section with triangular element mesh

(a) the conical base storage bin

(b) The way of inserting the temperature sensors in the bin

Figure 3 The photos of conical base storage bin located at higher school of engineers of Medjez El Bab – Case of South Mediterranean climate: Tunisia

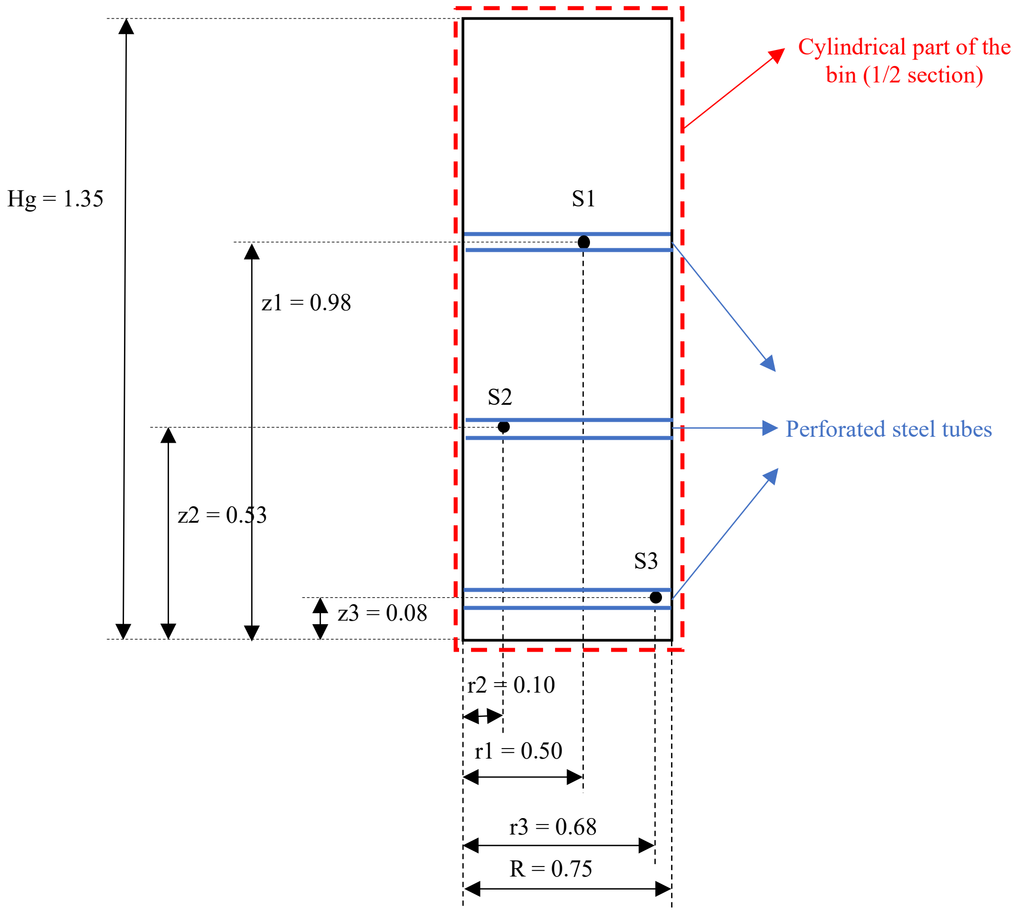

Figure 4 Locations of temperature sensors (S1, S2 and S3) in the grain bin (dimensions in meter)

Note: r1, r2 and r3 are the radial coordinates; z1, z2 and z3 are the axial coordinates and Hg is the height of stored grain in the bin.

3 Results and discussion

Figures 5, 6 and 7 show the measured and predicted grain temperatures at three positions in the bin wheat bulk during 154 hours without aeration. It can be observed that the grain predicted temperatures by the two-dimensional heat transfer model followed closely the measured grain temperatures at three locations throughout 154 hours of measurement.

The mathematical model generated small values of *SE* and *AAD* at each sensor location, with high correlation coefficient r^2 (Table 2) because the three calculated values of the correlation coefficient are very close to 1. The strong correlation coefficients demonstrate that the numerical simulation has predicted accurately the stored grain temperatures.

Table 2 Standard error (SE) and average absolute difference (AAD) between simulated and observed temperature for different sensors locations (S1, S2 and S3) in the grain bulk, denoted by radial and axial coordinates in meter

Measurement point (*r*, *z*)	*SE* °K	*AAD* °K
S1 (0.50, 0.98)	0.83	0.74
S2 (0.10, 0.53)	0.2	0.18
S3 (0.68, 0.08)	1.6	1.2

The statistical analysis through the calculation of the cited statistical parameters confirmed the close agreement between observed and simulated temperatures for bin-grain stored without aeration. This is to show that the bin-grain heat transfer model and used parameters are validated for predicting bin-grain temperatures without aeration. These results also showed that the choice of a fine mesh at the short edges of the domain improves the simulation of grain temperatures (Figure 2).

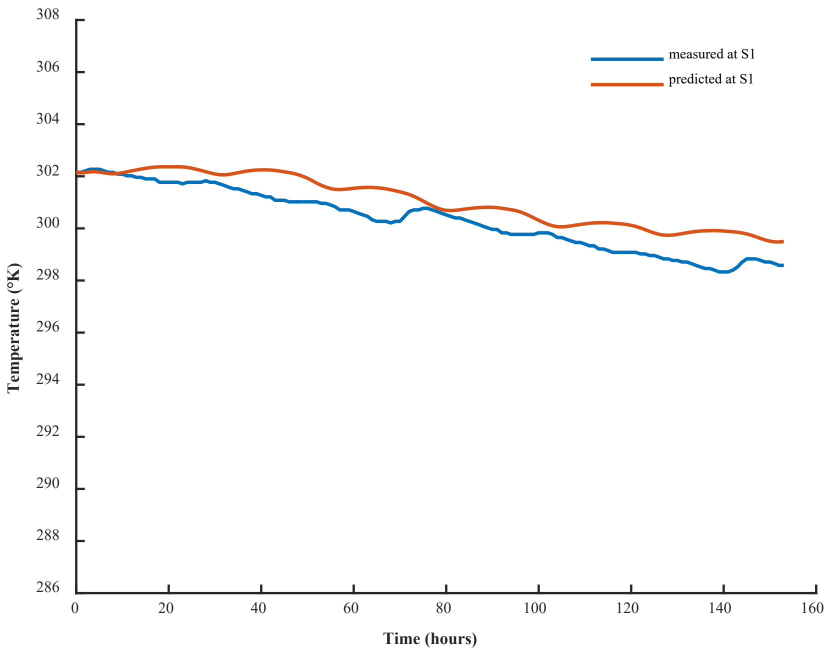

Figure 5 The evolution of predicted and measured grain temperature at the first location denoted by the radial and axial coordinates in meter: sensor S1 (0.50, 0.98)

The evolution of observed wheat temperatures at different positions and the fluctuation of ambient air temperature are given in Figure 8. It is observed that wheat temperatures measured by different sensors decrease during the experiment period, which suggested that the ambient air temperatures were evolving to lower values than the grain temperatures. It is important to announce that the present experiment of wheat storage without aeration was carried out after a storage period without aeration too. Therefore, the ambient air temperatures during the measurement period were lower than wheat temperatures.

Wheat temperatures at the inner positions (sensors S1 and S2) are higher than the one near the bin wall surface (sensor S3). Throughout the storage period of the non-aerated stored grain bulk, it can be observed that the temperatures of grain on the southern side (sensor S1) slightly toward the bin center have recorded a slow decrease. However, the sensor, S2, close to the bin center has recorded more stable temperatures. The behavior of temperatures in those 2 locations is due to the low thermal conductivity of wheat. Temperatures of wheat near the bin wall surface, sensor S3, follow the trend of the ambient air variations as the heat was transferred between the ambient and wheat bulk through the bin wall. It can be seen from Figure 8 that fluctuations between diurnal and nocturnal temperatures are significant only for wheat temperatures recorded by the sensor S3 close to bin wall. This is to confirm the influence of the ambient air temperature on the ecosystem of a stored wheat bulk.

Predicted and measured wheat temperatures for the three location of storage bin are shown in Figure 5, 6 and 7. As it was shown, the predicted stored grain temperatures agreed well with the measured ones during the study period for the three locations in storage bin.

Statistical study quantified the discrepancy between measured and predicted grain temperatures. Even though the statistical parameters are very acceptable for the heat transfer model. A higher discrepancy is observed for the sensor S3, close to the bin wall, and could be explained by the used values of hS_{inf}, h_{Sext} and h_{Ssup}. These values must be calculated using the hourly wind velocity, but in this study the grain temperatures were predicted using the available daily average ambient wind velocity.

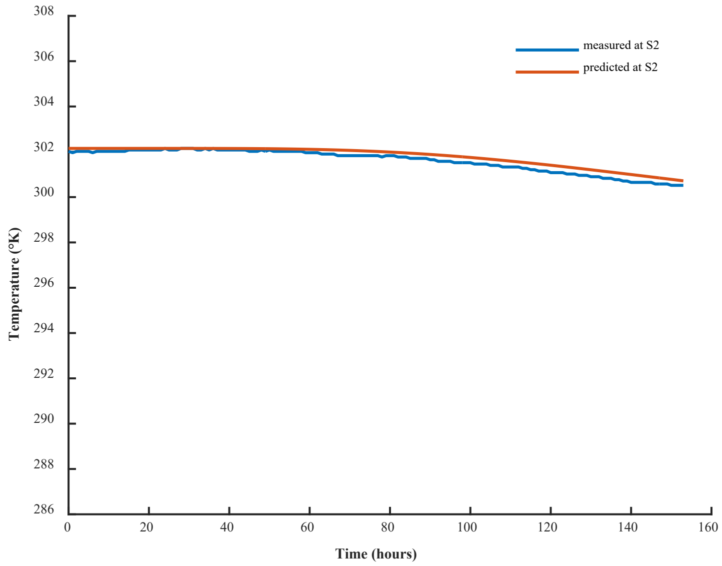

Figure 6 Evolution of predicted and measured grain temperature at the first location denoted by the radial and axial coordinates in meter: sensor S2 (0.10, 0.53)

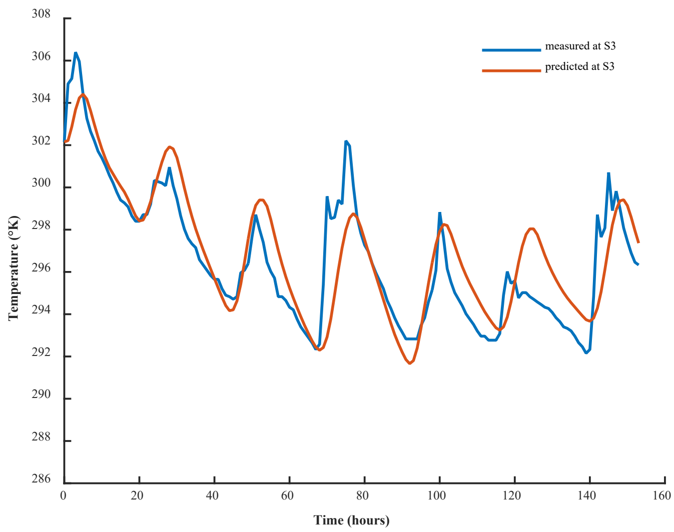

Figure 7 Evolution of predicted and measured grain temperature at the first location denoted by the radial and axial coordinates in meter: sensor S3 (0.68, 0.08)

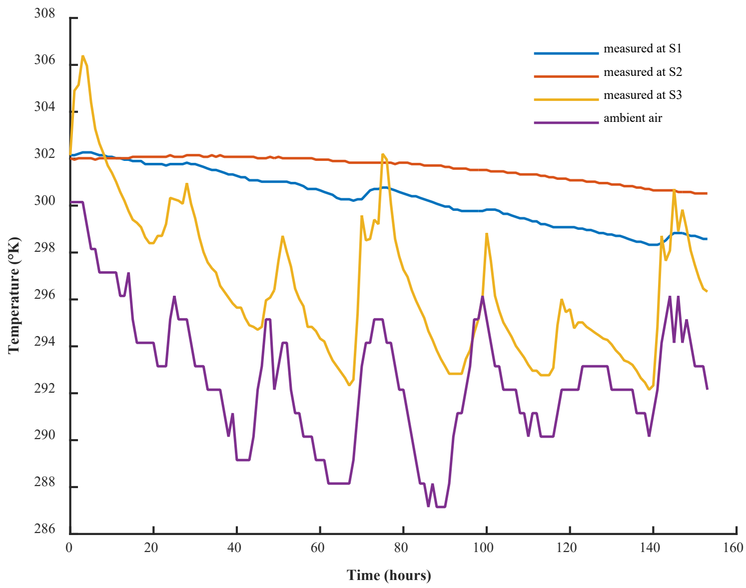

Figure 8 Measured grain temperatures at different measured points (sensors, S1-S3) and ambient air temperature during storage period without aeration

4 Conclusion

The mathematical model with 2947 triangular meshes was able to simulate stored grain temperature in 1.5-meter bin diameter containing wheat. The provided results indicated that the choice of a fine mesh at the shortest edges of the computational domain enhances the prediction of grain temperatures. In fact, temperatures of grain near bin wall surface follow the trend of the ambient air fluctuations as the heat was exchanged between the ambient and the ecosystem of stored grain. The average absolute differences of 0.18 °K to 1.2 °K and the standard errors of 0.2 °K to 1.6 °K were calculated at different measurement location inside the storage bin. The value of these statistical parameters confirmed the validation of the combined bidimensional heat transfer model used to predict grain temperatures throughout a simulation corresponding to 154 hours of bin wheat storage without aeration.

This research work demonstrated the potential of the parabolic solver incorporated in Matlab 2015a environment for simulating complex boundary conditions of bin stored grain under the varying Tunisian weather conditions. This solver can be used to study and analyze thermal insulation parameters, in a design purpose, of the storage structure under South Mediterranean climate conditions. The improve of design method can diminish the use of chemical treatments during the grain storage period.

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Nomenclature

symbol	
c_g	specific heat of grain ($Jkg^{-1}K^{-1}$)
c_s	specific heat of the bin wall ($Jkg^{-1}K^{-1}$)
D	diameter of the bin (m)
F	shape factor, 0.3 for bin roof and grain surface layer
h_{Sext}	convective heat transfer coefficient for the bin wall ($Wm^{-2}K^{-1}$)
h_{Sinf}	convective heat transfer coefficient for the grain bottom surface ($Wm^{-2}K^{-1}$)
h_{Ssup}	convective heat transfer coefficient for the top surface layer of the grain bulk ($Wm^{-2}K^{-1}$)
I_T	solar radiation on the bin wall (Wm^{-2})
k_{air}	thermal conductivity of the air ($Wm^{-1}K^{-1}$)
k	thermal conductivity of grain ($Wm^{-1}K^{-1}$)
M_{CO2}	molecular weight of carbon dioxide
Nu	Nusselt number
q	net rate of energy created from the internal source within the bin wall material (Wm^{-3})
Q_H	heat released in respiration, 10.738 $Jmg^{-1}[CO_2]$
q_{int}	internal heat in grain bulk (Wm^{-3})
q_{Sext}	net radiation on the bin wall (Wm^{-2})
q_{Ssup}	radiation from the bin roof to the grain surface layer (Wm^{-2})
$q_{w,rad}$	radiation from the bin wall to surrounding (Wm^{-2})
r	radial coordinate (m)
Re	Reynold number
R_{CO2}	rate of carbon dioxide $mg[CO_2]kg^{-1}$[Dry matter] in 24 h
Rresp	generated heat by wheat respiration Jkg^{-1}[Dry matter] in 24 h
T	bin wall temperature (K)
T_0	initial temperature associated to the heat transfer through the bin wall (K)
t	time (s)
T_{aamb}	absolute temperature of ambient air (K)
T_{ar}	absolute temperature of the bin roof (K)
T_{as}	absolute temperature of grain bulk surface layer in the bin (K)
T_{aw}	absolute temperature of the bin wall (K)

T_g	grain temperature (K)
T_{g0}	initial temperature associated to heat transfer in grain bulk (K)
T_{Sext}	temperature of the air near the circumference surface of the bin (K)
T_{Sinf}	temperature of air near the grain bottom surface (K)
T_{Ssup}	temperature of air near the grain top surface (K)
u_{air}	local wind velocity (ms^{-1})
z	Axial coordinate (m)

Subscripts

0	initial
Sinf, Ssup, Sext	bin boundaries (indicated in Figure 1)

Greek symbols

α	short-wave absorptivity of the bin wall
α_s	grain bulk surface layer absorptivity
ρ_g	grain density (kg m^{-3})
ρ_s	material density of the bin wall (kg m^{-3})
σ	Stefan-Boltzmann constant ($=5.6703\times10^{-8}$ $Wm^{-2}K^{-4}$)
υ_{air}	kinematic viscosity of the air (m^2s^{-1})
ε_{wl}	long wave emissivity of bin wall
λ	bin wall thermal conductivity in ($Wm^{-1}K^{-1}$)