BIOSYSTEMS ENGINEERING 118 (2014) 105–114

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Comparison of equilibrium and logarithmic models for grain drying

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ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form
6 November 2013
Accepted 27 November 2013
Published online 25 December 2013

ABSTRACT

Mathematical simulation is an important tool for optimising agricultural processes to reduce costs. Many models have been proposed and adapted to simulate grain drying. Among them, are the logarithmic or Hukill model and the equilibrium or Thorpe model, which do not require expensive solution techniques and can be used to evaluate the grain-drying behaviour regarding process time, grain temperature and variations in grain moisture content. These models were compared with experimental data found in the literature. The two models were also compared regarding predicted grain temperatures, grain moisture contents and drying times. Results showed that both models gave good prediction performance, but the Thorpe model was slightly better than the Hukill. The Thorpe model is applicable over a wider range of drying situations, including processes with variable inlet air conditions. It also provides a more fundamental understanding of the drying process. However, the logarithmic model has advantages with respect to simplicity and speed of solution.

1. Introduction

Considerable amount of grain is dried artificially either using near-ambient or high temperature air in various grain-drying systems (Aregba & Nadeau, 2007). Mathematical modelling of grain drying has been widely used to provide a better understanding of this process, to evaluate the performance of dryers, to make decisions about drying conditions or to aid in the design process of innovative systems (Bunyawanichakul, Walker, Sargison, & Doe, 2007; Jumah, 2005; Martinello, Munoz, & Giner, 2013; Martinello & Giner, 2010; Zare & Chen, 2009).

Grain-drying models can be classified as equilibrium, non-equilibrium or logarithmic types. Equilibrium models assume that equilibrium conditions exist between the grain and the drying air in each layer during a discrete period of time (Brooker, Bakker-Arkema, & Hall, 1992). Non-equilibrium models are based on the assumption that, in a deep-bed, there is no equilibrium between the drying air and grain. Thus, a set of partial differential equations is derived from the laws of heat and mass transfer and the mathematical theory of drying single solid bodies (Srivastava & John, 2002). Finally, the logarithmic models describe deep-bed drying under uniform initial and constant boundary conditions, providing an explicit analytical solution to the drying kinetics and efficiency of the drying process against time, drying air parameters and grain properties (Aregba, Sebastian, & Nadeau, 2006).

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1537-5110/$ – see front matter
http://dx.doi.org/10.1016/j.biosystemseng.2013.11.011

Nomenclature

C, D, E	constant values that depend on the stored product
c_a	specific heat of air (J kg^{-1} °C^{-1})
c_g	specific heat of grain (J kg^{-1} °C^{-1})
c_w	specific heat of water (J kg^{-1} °C^{-1})
d	index of agreement (dimensionless)
D_v	differential of latent heat of vapourisation with relation to temperature (J kg^{-1} °C^{-1})
H	half-response time of grain moisture ratio (from 1.0 to 0.5 at T_a)
h_s	differential heat of sorption (J kg^{-1})
h_v	latent heat of vapourisation of water (J kg^{-1})
i	denotes the nodes
m	denotes the temporal step
MAE	mean absolute error (h)
MBE	mean bias error (h)
M_m, M_t	grain conditions modifiers (dimensionless)
m_s	grain's dry matter loss (decimal)
M_s	rate at which dry matter is lost (s^{-1}).
N	grain depth calculated from the bulk base to the middle of the considered layer (m)
n	number of testing data (dimensionless)
O	experimental drying time (h)
P	predicted drying time (h)
q	total airflow rate (m^3 s^{-1})
Q_r	heat of oxidation of grain (J s^{-1} m^{-3})
R	humidity ratio of air (kg kg^{-1})
RMSE	root mean square error (h)
S	dryer or bin area (m^2)
T	air temperature (°C)
t	time (s)
T_a	drying air temperature (°C)
T_e	equilibrium temperature (°C)
t_p	physiological time (h)
U	grain moisture content (d.b.)
u_a	air velocity (m s^{-1})
U_e	equilibrium moisture content (decimal, d.b.)
U_s	initial moisture content (decimal, d.b.)
V_e	specific volume of air (m^3 kg^{-1})
V_m	mass airflow rate (m^3 s^{-1})
y	vertical coordinate (m)
ε	grain porosity (decimal)
Θ	grain temperature (°C)
ρ_a	density of intergranular air (kg m^{-3})
ρ_b	bulk density of the grain (kg m^{-3})

An equilibrium model, governed by partial differential equations and based on mass and energy balances, was formulated by Thorpe (1997) and presented in more detail in Thorpe (2001). This model has been used not only to simulate the aeration process, but also can be adapted for drying studies. Lopes, Martins, Melo, and Monteiro (2006) validated the Thorpe model with data from aerated maize and related some changes in the original equations in order to simplify it and decrease its computational time, without decreasing its accuracy.

Hukill (1954) developed the first logarithmic model for the analysing the drying phenomena taking place in a deep-bed. This model has been useful in approximating the drying rate of natural air and low temperature in bin dryers and was validated for different products and drying conditions, agreeing well with experimental data (Arnaud & Fohr, 1988; Li et al., 2011). The Hukill model also has been used in control strategies and didactic tools (Lopes, Martins, Steidle Neto, & Steidle Filho, 2005; Whitfield, 1988).

The two above mentioned models do not require computationally expensive solution techniques and can be used to evaluate the grain-drying behaviour regarding the process time, grain temperature and grain moisture content variations. The objective of this study was to evaluate the Thorpe and Hukill models, comparing the simulation results with experimental data found in the literature. The two models were also compared regarding predicted grain temperatures, grain moisture contents and drying times in order to evaluate differences between them. These results should contribute to a better understanding of these models and enable the most appropriate model to be selected for different drying applications.

2. Equilibrium model for grain drying (Thorpe model)

According to the simplified Thorpe model (Lopes et al., 2006), the differential equations that describe the heat and mass transfer in beds of ventilated grains can be expressed as

$$\begin{aligned}\frac{\partial\theta}{\partial t}\left\{\rho_b\left[c_g + c_w U\right] + \varepsilon\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T}\right)\right]\right\} &= \rho_b h_s \frac{\partial U}{\partial t} \\ &\quad - u_a\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T}\right)\right]\frac{\partial\theta}{\partial y} + \rho_b\frac{dm_s}{dt}\left(Q_r - 0.6h_v\right)\end{aligned} \tag{1}$$

$$\frac{\partial U}{\partial t} = -\frac{\rho_a u_a}{\rho_b}\frac{\partial R}{\partial y} + 0.6\frac{dm_s}{dt}(1 + 1.66U) \tag{2}$$

where θ is the grain temperature (°C), t is the time (s), ρ_b is the bulk density of the grain (kg m^{-3}), c_g is the specific heat of grain (J kg^{-1} °C^{-1}), T is the air temperature (°C), c_w is the specific heat of water (J kg^{-1} °C^{-1}), U is the grain moisture content (d.b.), ε is the grain porosity (decimal), ρ_a is the density of intergranular air (kg m^{-3}), c_a is the specific heat of air (J kg^{-1} °C^{-1}), R is the humidity ratio of air (kg kg^{-1}), h_v is the latent heat of vapourisation of water (J kg^{-1}), h_s is the differential heat of sorption (J kg^{-1}), u_a is the air velocity (m s^{-1}), y is the vertical coordinate (m), m_s is the grain's dry matter loss (decimal) and Q_r is the heat of oxidation of grain (J s^{-1} m^{-3}).

The partial differential equations that describe the Thorpe model are coupled and solved numerically using finite difference numerical method. As the solution of one affects the solution of the other and there are non-linear terms, it is impossible to obtain closed form solutions so that the grain conditions can be expressed directly as a function of distance along the grain bed and time from the start of the drying (Lopes et al., 2006; Navarro & Noyes, 2001).

The grain bulk was divided into layers in the direction of the airflow (Fig. 1). At the start of simulations, the distribution of grain moisture content and temperature within the bed of grain are known. The layer limits are called nodes and at the first node it is assumed that the mass and temperature conditions are at equilibrium with the blown air and the surface of the grain bulk. The temperature and moisture content of each other node are calculated by approximations to the first and second derivatives that appear in the model equations, as

$$\theta_i^{m+1} = \theta_i^m + \frac{\Delta t(A+B)}{\{\rho_b[c_g + c_w U_i^m] + \varepsilon\rho_a[c_a + R_i^m(c_w + D_v)]\}} \tag{3}$$

$$A = \rho_b h_{s\,i}\left(-\frac{\rho_a u_a}{\rho_b}\frac{R_i^m - R_{i-1}^m}{\Delta y} + 0.6M_{s\,i}^m(1+1.66U_i^m)\right) \tag{4}$$

$$B = -u_a\rho_a[c_a + R_i^n(c_w + D_v)]\frac{\theta_i^m - \theta_{i-1}^m}{\Delta y} + \rho_b M_{s\,i}^m(Q_r - 0.6h_{v\,i}^m) \tag{5}$$

$$U_i^{m+1} = U_i^m + \Delta t\left(-\frac{\rho_a u_a}{\rho_b}\frac{R_i^m - R_{i-1}^m}{\Delta y} + 0.6M_{s\,i}^m(1+1.66U_i^m)\right) \tag{6}$$

where i denotes the nodes, m denotes the temporal step, D_v is the differential of latent heat of vapourisation with relation to temperature (J kg^{-1} °C^{-1}) and M_s is the rate at which dry matter is lost (s^{-1}).

Therefore, the temperature and the moisture content of each layer are the mean of its boundary nodes conditions. The first layer values are estimated by applying Lagrange interpolation over the first three nodes. During the simulation process, the grain moisture contents and temperatures were calculated after each time interval (0.01 h or 36 s) for each layer in an iterative way, but the results shown every 1 h. This is the main difference between aeration and drying simulations using the Thorpe model. Since aeration airflows are low (from 0.02 to 0.2 m^3 min^{-1} t^{-1}), the adopted time interval is generally equal to 3600 s when the model is applied to simulate this process. As during drying processes greater air velocities are observed, the use of smaller time intervals allows a better agreement between equations in each iteration step, allowing a more accurate simulation of the simultaneous heat and moisture transfer processes within the grain bulk.

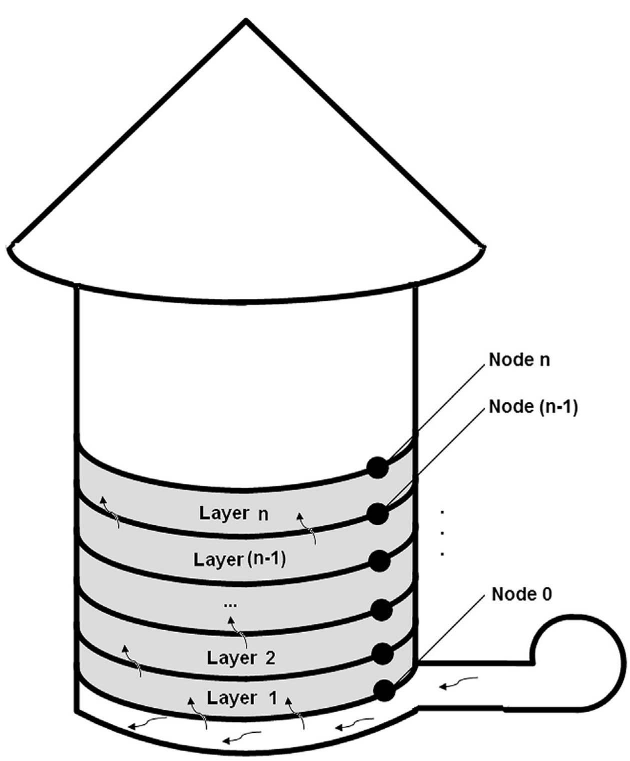

Fig. 1 – Scheme used to characterise the grain layers inside the dryer.

The iterations were carried out until the grain average moisture content reach the equilibrium with the inlet air (average moisture content (%w.b.) ≥ equilibrium moisture content (% w.b.) + 0.05) or a preset value (average moisture content (% w.b.) ≥ preset moisture content (% w.b.) + 0.05). The first stop criterion was used for low temperature drying and the second one for high temperature drying. During simulations the humidity ratio of air was calculated by using the psychrometric method (Melo, Lopes, & Corrêa, 2004). Also, the equilibrium relative humidity (ERH) for each layer was calculated in each iteration step by using one of the equations approved by the ASAE for this purpose, such as those developed by Henderson and the Chung–Pfost (Brooker et al., 1992).

The specific heats of water and air are well-established quantities and can be considered as constant values (4186 and 1000 J °C kg^{-1}, respectively) as suggested by Navarro and Noyes (2001). The specific heat of grain changes according to the grain moisture content variation and can be calculated in each time interval for each grain layer by using empirical equations (Brooker et al., 1992; Lopes et al., 2008).

As suggested by Thorpe (2001), the differential heat of sorption was estimated in each iteration step by applying Eq. (7). This method is based on the Clapeyron equation and compares the vapour pressures of water in equilibrium with moist grain and free water.

$$h_s = h_v\left(1 + \frac{D_e^{-EU}}{(\theta + C)^2}(\theta + 273.15)\left(-5 + \frac{6800}{\theta + 273.15}\right)\right) \tag{7}$$

where C, D and E are constant values that depend on the stored product.

The value of the differential of latent heat of vapourisation with relation to temperature (D_v) should be considered equal to −2363 from Eq. (8), presented by Cengel and Boles, according to Thorpe (2001). This equation was obtained by fitting a linear equation to thermodynamic data given in standard textbooks and it gives values of latent heat from vapourisation of water within a maximum error of 0.02% in the temperature range from 0 to 50 °C.

$$h_v = 2,501,330 - 2363T \tag{8}$$

The heat from oxidation of grain is considered equal to 15,778 kJ s^{-1} m^{-3} since the oxidation of 1 kg of grain substrate liberates 15,778 kJ of heat and forms 1.47 kg of carbon dioxide and 0.6 kg of water (Thorpe, 2001).

The grain bulk porosity can also be considered a constant value (40%), since the intergranular void volume is 35–55% of the grain bulk volume for most product types (Brooker et al., 1992).

The velocity of the air is estimated by Eq. (9) and depends on the dryer dimensions and on the required airflow rate

$$u_a = \frac{q}{S} \tag{9}$$

where q is the total airflow rate ($m^3\ s^{-1}$) and S is the dryer or bin area (m^2).

A method developed by Thompson (1972) was used to determine the rate of dry matter loss (M_s). Thus, an empirical equation was applied considering that the dry matter loss is time dependent (Eq. (10)).

$$M_s = \frac{14.72 \times 10^{-10} e^{1.667\times10^{-6} t_p + 2.833\times10^{-9}}}{M_m M_t} \tag{10}$$

According to Thorpe (2001), because the temperature and moisture content of the grains vary with location in the grain store, it is necessary to map the value of the real time into some physiological time (t_p), thus

$$t_p = \frac{t}{M_m M_t} \tag{11}$$

The terms M_m and M_t modify the grain conditions depending on its moisture content and temperature. M_t was calculated by Eq. (12) when moisture content was lesser or equal to 19% w.b. or temperature was lesser or equal to 15.5 °C. The same term was calculated by Eq. (13) when moisture content was between 19 and 28% w.b. and temperature was greater than 15.5 °C. Finally, M_t was calculated by Eq. (14) when moisture content was greater or equal to 28% w.b. and temperature was greater than 15.5 °C. M_m was always obtained by Eq. (15).

$$M_t = 32.2e^{-0.1044\theta - 1.856} \tag{12}$$

$$M_t = 32.2e^{-0.1044\theta - 1.856} + \frac{(U-19)}{100} e^{0.0183\theta - 0.2847} \tag{13}$$

$$M_t = 32.2e^{-0.1044\theta - 1.856} + 0.09e^{0.0183\theta - 0.2847} \tag{14}$$

$$M_m = 0.103\left(e^{455/U^{1.53}} - 0.00845U + 1.558\right) \tag{15}$$

3. Logarithmic model (Hukill model)

This model assumes that the energy required for evaporating moisture from the grain is equal to the change in enthalpy of the air passing through the grain. Also, the sensible heat of the grain is neglected (Brooker et al., 1992).

In the logarithmic model Eqs. (16) and (17) describe the changes in grain temperature and moisture content during the thin-layer drying.

$$\theta = \frac{2^X((T_a - T_e) + T_e)}{2^X + 2^Y - 1} \tag{16}$$

$$U = \frac{2^Y((U_s - U_e) + U_e)}{2^X + 2^Y - 1} \tag{17}$$

where U_s is the initial moisture content (decimal, d.b.), T_a is the drying air temperature, T_e (°C) and U_e (decimal, d.b.) are the equilibrium temperature and moisture content between the blown air and the surface of the grain bulk, respectively.

The moisture ratio of the grain is estimated as a function of dimensionless bed-depth (X) and dimensionless time (Y), thus

$$X = \frac{S\rho_b N V_e h_v (U_s - U_e)}{(1+U_s)(0.24 H V_m (T_a - T_e))} \tag{18}$$

$$Y = \frac{t}{H} \tag{19}$$

where N is the grain depth calculated from the bulk base to the middle of the considered layer (m), V_e is the specific volume of air ($m^3\ kg^{-1}$), V_m is the mass airflow rate ($m^3\ s^{-1}$) and H is the half-response time of grain moisture ratio (from 1.0 to 0.5 at T_a).

An equation for the half-response time can be obtained from empirical thin-layer drying equations. Generally, these equations relate the moisture ratio to temperature, relative humidity and drying time. Thus, considering the moisture ratio equal to 0.5 and expliciting the time, it is possible to estimate the half-response time (Silva, Queiroz, Lopes, & Sousa, 2009).

The equilibrium temperature is that at which air would be in equilibrium with the grain at its initial moisture content after the air has cooled along a wet-bulb temperature. This value was obtained by an iterative method, which consists in following the adiabatic line by keeping the enthalpy constant until finding a value for the equilibrium temperature at which relative humidity is equal to the equilibrium relative humidity. This was performed using a numerical method, by calculating and recalculating the relative humidity as a function of absolute humidity and equilibrium temperature by using the psychrometric relationships, until it converges. In each iteration the equilibrium temperature was incremented or decremented accordingly by a predefined step value. In the first iteration the equilibrium temperature was equal to the drying temperature decremented by 0.1 step value (Martins, Mota, & Fonseca, 2000).

During simulations, the grain bulk was divided into layers in the direction of the airflow, as mentioned above for the equilibrium model. At the start of simulations, the distributions of grain moisture contents and temperatures within the bed of grain were also known. However, in the logarithmic model only the layers are considered. That is, the model equations are applied to each layer, including the first one, and not to its boundaries (nodes). Also, iterations consider a time interval of 1 h (3600 s). As well as the equilibrium model, the iterations were carried out until the grain average moisture content reach the equilibrium with the inlet air (average moisture content (% w.b.) ≥ equilibrium moisture content (% w.b.) + 0.0001) or a preset value (average moisture content (% w.b.) ≥ preset moisture content (% w.b.) + 0.0001). Since the time interval used by the logarithmic model was greater than for the equilibrium model, a smaller difference between the equilibrium and the average moisture content was considered.

4. Comparing the models

The two models were implemented in a software tool called SECADERO, which was specially developed for this work and written in C++ language. All simulation results were saved in electronic worksheet files for analysis.

Both models were validated by comparing the drying time given they produce with experimental values of deep-bed maize drying from the literature (Cavariani, Silva, Miranda, Nakagawa, & Belgiorno, 1999; Houssain, Bala, & Satter, 2003; Martinello & Giner, 2010; Neményi, Czaba, Kovács, & Jáni, 2000; Souza, Queiroz, & Lacerda Filho, 2002). Considering these data, simulations were performed with airflows varying from 2 to 25 $m^3\ min^{-1}\ t^{-1}$, initial grain temperatures varying from 20 to 33 °C, initial moisture contents varying from 14 to 20% d.b., drying air temperatures varying from 40 to 50 °C and drying air relative humidities varying from 60 to 80%. A validation graph of the experimental drying times against the predicted times was plotted. The accuracy of the estimates was determined by the *t* test applied to the intercept of the linear regression to verify whether it was significantly different than 0, and to the line angular coefficient to test whether it was significantly different than 1, at the level of 5% probability. The root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE) and index of agreement (d) were used to evaluate the accuracy of the implemented models and calculated as Eqs. Eqs. (20)–(23) (Mayer & Butler, 1993; Willmott, 1981; Yang & Huffman, 2004).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{j=1}^{n}\left(P_j - O_j\right)^2}{n}} \tag{20}$$

$$\mathrm{MAE} = \frac{\sum_{j=1}^{n}\left|P_j - O_j\right|}{n} \tag{21}$$

$$\mathrm{MBE} = \frac{\sum_{j=1}^{n}\left(P_j - O_j\right)}{n} \tag{22}$$

$$d = 1 - \frac{\sum_{j=1}^{n}\left(P_j - O_j\right)^2}{\sum_{j=1}^{n}\left(\left|P_j - \overline{O}\right| + \left|O_j - \overline{O}\right|\right)^2} \tag{23}$$

The index of agreement is dimensionless. The units of RMSE, MAE and MBE depend on the evaluated parameter of the model. Thus, in this study they were expressed in hours. P is the predicted drying time (h), O is the experimental drying time (h) and n is the number of testing data (dimensionless).

A comparative study between the predicted grain temperatures, grain moisture contents and drying times of both models was also performed in order to evaluate the differences between them. For this, new simulations were performed. In this second analysis no experimental data was used, since most of the reviewed works which presented all the required drying variables for simulation, did not present temperature and moisture content profiles. Thus, some scenarios were simulated by varying airflow rate, initial moisture content and temperature difference of drying air and grain (Table 1). In all simulations, drying was performed until average grain moisture content reached equilibrium (~13% w.b.). It was also considered a maize bulk density of 750 kg m^{-3} (Martinello & Giner, 2010), grain porosity of 40% (Brooker et al., 1992) and atmospheric pressure of 102.325 kPa. The dryer diameter and height were fixed as 1.5 and 0.5 m, respectively. Since airflow rate was expressed as $m^3\ min^{-1}\ ton^{-1}$ and the models depend on the air velocity ($m\ s^{-1}$) and the mass airflow rate ($m^3\ s^{-1}$), variations on the dryer dimensions did not interfere on the simulation results.

Table 1 – Simulated drying conditions.

Drying variables	Simulation set		
	01	02	03
Initial moisture content (% w.b.)	21	From 14 to 22	16
Initial grain temperature (°C)	25	30	20
Drying air temperature (°C)	30	32	From 22 to 30
Drying air relative humidity (%)	65	70	65.5
Equilibrium moisture content (% w.b.)	12.8	13.5	From 13 to 13.5
Airflow ($m^3\ min^{-1}\ t^{-1}$)	From 1 to 10	3	2

5. Results and discussion

Figure 2 shows the validation graph of the experimental drying times, obtained from literature review, plotted against the predicted values. It can be observed that all the points fall close to the 1:1 line, indicating a good fit between simulated and measured data. Also, most of the points are above this line, showing that both models slight overestimate the experimental values. The intercept values of 1.590 and 2.719 for Hukill and Thorpe models, respectively, were not significantly different than 0, indicating the absence of constant deviations. The values of line angular coefficient (1.046 and 1.010 for Hukill and Thorpe models, respectively) did not significantly deviate from 1, indicating the absence of systematic deviations. Also, determination coefficients between experimental and predicted values were 98.4% for the Hukill model and 99.1% for the Thorpe one, indicating high accuracy.

As shown by Table 2, the good results obtained with the validation graph were confirmed by the performance indicators. Both models gave good prediction performance, but Thorpe model was slightly better than the Hukill one. RMSE and MAE values allowed a term by term comparison of the difference between the predicted and observed values. Both models presented very small values (less than 24 h), except for the RMSE of Hukill model which was 26 h. The small and positive values observed for MBE indicator reflected that both models slightly overestimated the results. On the other hand, the high values observed for the index of agreement indicated that observed variations were accurately estimated by the simulated ones. This index varies from 0 to 100% where the maximum percentage reflects a perfect agreement between observed and predicted data. As affirmed by Willmott (1981), this is an important index since it is not a measure of correlation or association in the formal sense, but rather a measure of the degree to which the model's predictions are error free. Also, it is a standardised measure in which cross-comparisons for a variety of models, regardless of units, can be made.

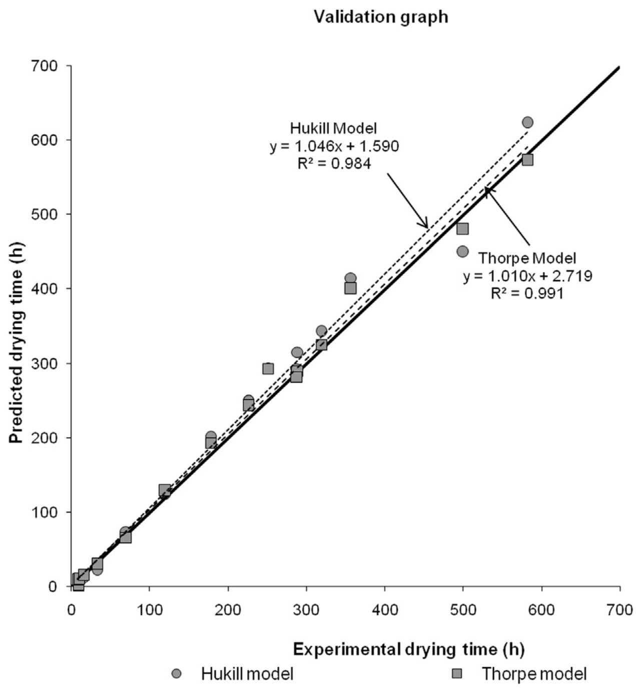

Fig. 2 – Validation graph of experimental drying times against the predicted ones.

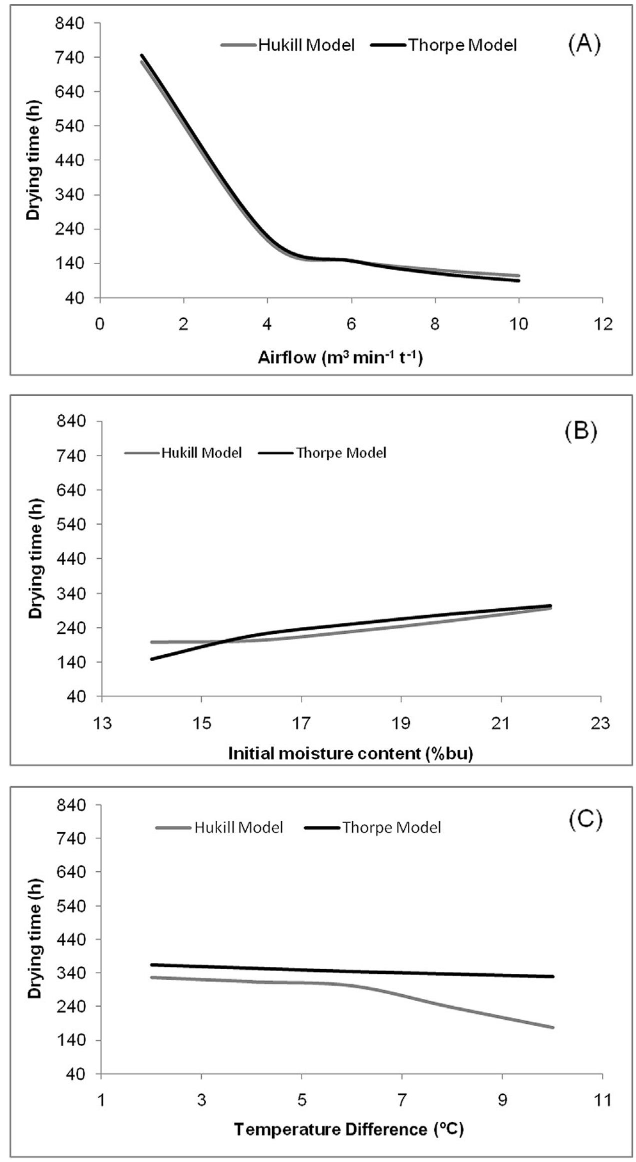

Fig. 3 – Predicted drying times by varying drying airflow rate, initial moisture content and temperature difference between grain and air.

Considering the second comparison procedure, drying time, grain moisture content and temperature variations, simulated by Hukill and Thorpe models, were coherent with the expected from the grain-drying process, as discussed follow.

Figure 3 shows the predicted drying times by varying drying airflow rate, initial moisture content and temperature difference between grain and air. Major differences were observed when temperature differences between grain and air were varied, mainly for values above 6 °C. The minimum difference (1 h) was obtained at 6 m^3 min^{-1} t^{-1} and the maximum one (152 h) was observed at temperature difference between grain and air of 10 °C. When initial moisture contents were varied, differences between drying times ranged from 8 to 51 h. The average difference between the drying times simulated by Thorpe and Hukill models was 17 ± 12 h. As expected from theory and practical observations, the variable that most influenced the drying time was the airflow rate.

Figures 4–9 show the average grain temperatures and moisture contents predicted for the models by varying airflow rate, initial moisture content and temperature difference between grain and air. The simulations well predicted the drying process, with grain temperatures slowly increasing towards air temperature and moisture contents decreasing until the equilibrium was reached.

Table 2 – Performance indicators of Thorpe and Hukill models.

Index	Thorpe model	Hukill model
RMSE (h)	17	26
MAE (h)	11	19
MBE (h)	5	10
d (%)	99.6	99.1

Generally, Thorpe model predicted more gradual variations in the average grain temperatures and moisture contents than the Hukill one. Also, when the Thorpe model was applied, the changes in these variables were more accentuated at the beginning of drying process and the drying rate gradually slowed down until equilibrium was achieved. This behaviour agrees well with the drying theory presented by Aversa, Curcio, Calabrò, and Iorio (2007) where at the start of drying, when the process is mainly controlled by external heat transfer and the water leaving the grain is not bound to food structure, the drying rate attains its maximum value. Afterwards, when the process rate is controlled by mass transfer and the water leaving the grain is bounded to the food structure, a progressively decrease of drying curve slope is

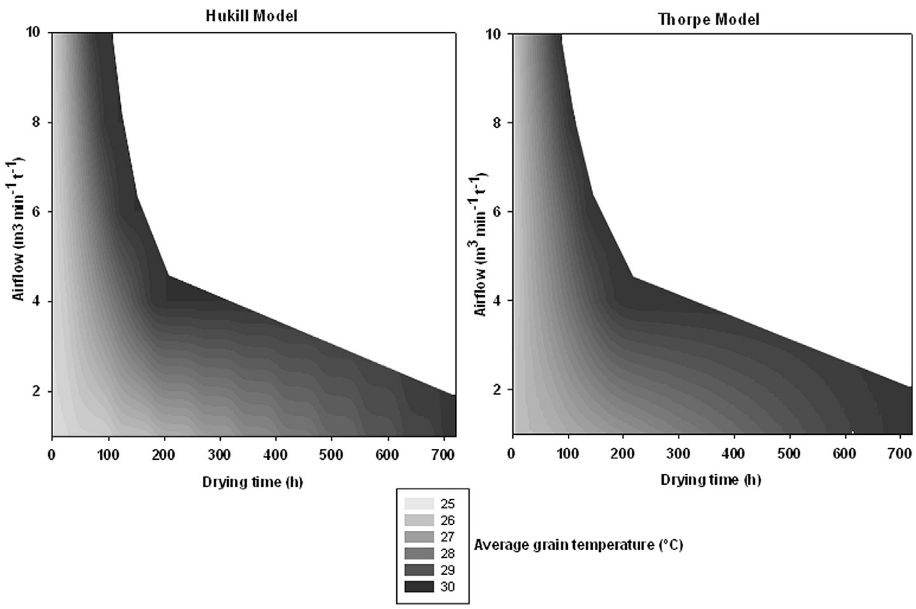

Fig. 4 – Average grain temperatures predicted for the models by varying airflow rate.

observed. These trends were more evident for airflows below than 4 m^3 min^{-1} t^{-1}, higher initial moisture contents and higher temperature differences between grain and air.

For both models, it was observed that the average grain temperature initially falled when initial moisture contents varied from 18 to 22% b.u., which could be due to the greater energy required for heating the water and the greater evaporative cooling effect in the high moisture contents than in the low ones.

For airflows close to 1 m^3 min^{-1} t^{-1} and temperature differences between grain and air greater than 8 °C, the Hukill model was more unstable than the Thorpe model. That is, during the simulation process both temperature and moisture content presented a coherent behaviour with the drying process, but resulted in an oscillatory pattern. This result agrees with the affirmed by Aregba et al. (2006) who interpreted the logarithmic model as the propagation of boundary conditions along characteristic lines throughout the bed. According to these authors, this propagation depends on drying air velocity. Therefore, the dimensionless bed-depth, which is dependant of the mass airflow rate, is a relevant parameter that can strongly influence the behaviour of the Hukill model. The same dimensionless bed-depth depends on the difference between the drying air and the equilibrium temperatures.

As show in Fig. 7, simulations performed for the two studied models also agree with the findings of Khatchatourian

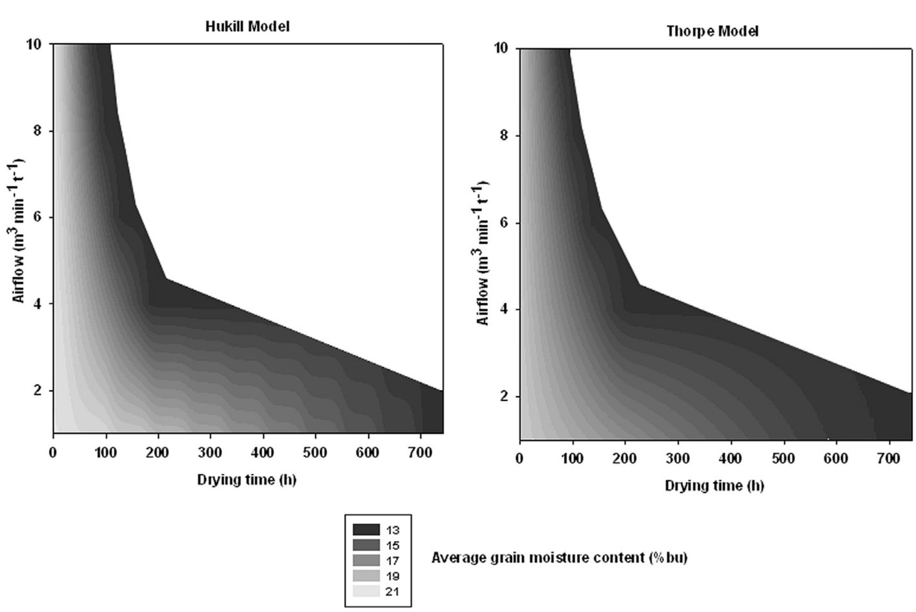

Fig. 5 – Average grain moisture contents predicted for the models by varying airflow rate.

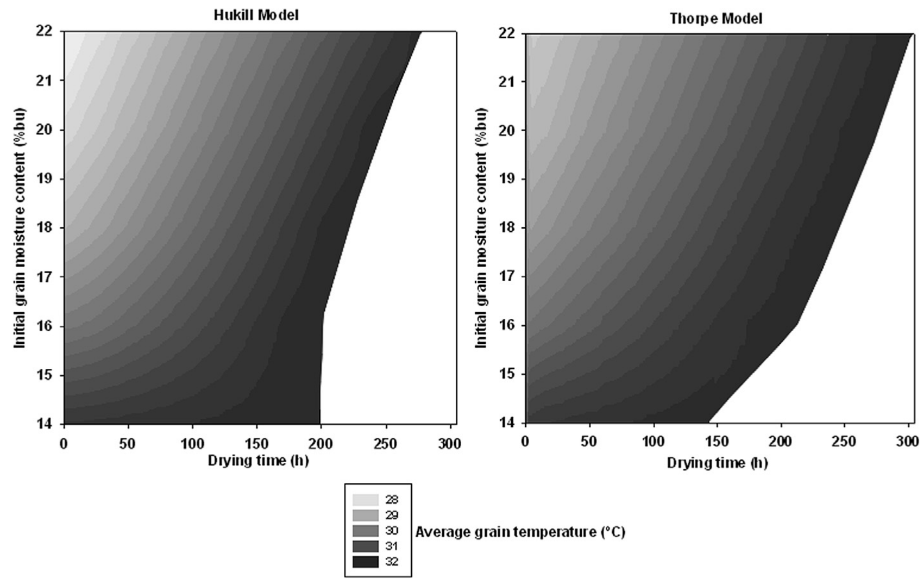

Fig. 6 – Average grain temperatures predicted for the models by varying initial moisture content.

(2012) that with increase in the initial grain moisture content at the same temperature the drying rate in the initial stage increases. With time this rate decreases and ceases to depend on initial grain moisture content.

In all simulations, it was found that at start of the drying process there was a steep fall of moisture content and later, with time, it fell more gradually. This behaviour was also verified by Hacıhafızoglu, Cihan, and Kahvenci (2008) and Srivastava and John (2002).

As stated by Brooker et al. (1992), for simulations in which the effect of varying inlet air conditions is investigated the Hukill model will probably not be suitable or at least should be adapted. This is because some of its equations assume that the inlet air temperature and relative humidity are constant. However, this logarithmic model is a reduced equation set involving few variables and parameters, and is useful for the investigation of dryers and drying characteristics, decision-support, energy optimisation and other research where speed of solution and simplicity are required.

However, the Thorpe model is based on equations in which mass and energy source terms associated with the moisture bound to the grains substrate are considered. This, associated with the use of differential equations, makes the model more complex. But, as Thorpe model was derived from the theoretical analysis of the physics of the drying process, it tends to be a more flexible and accurate approach for the drying

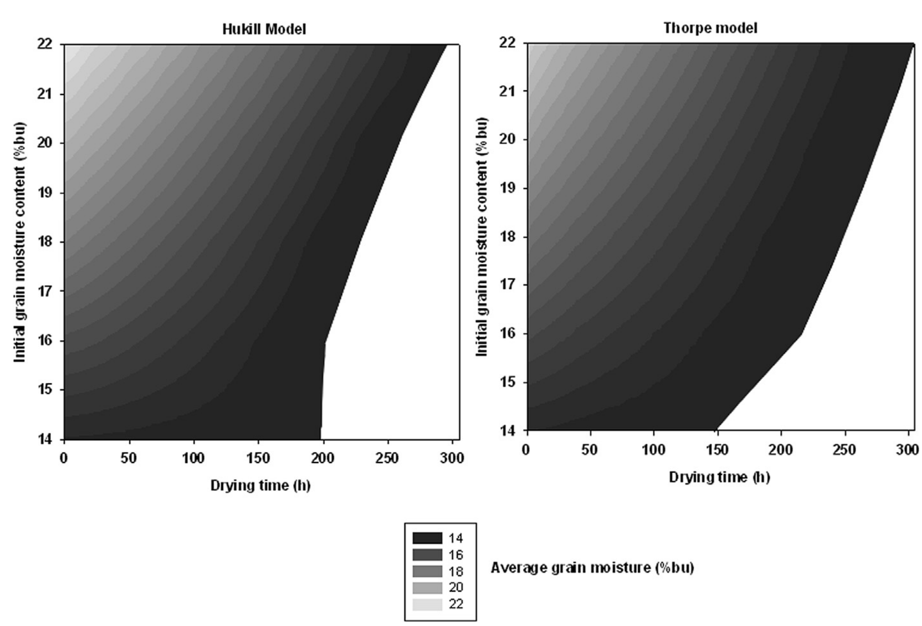

Fig. 7 – Average grain moisture contents predicted for the models by varying initial moisture content.

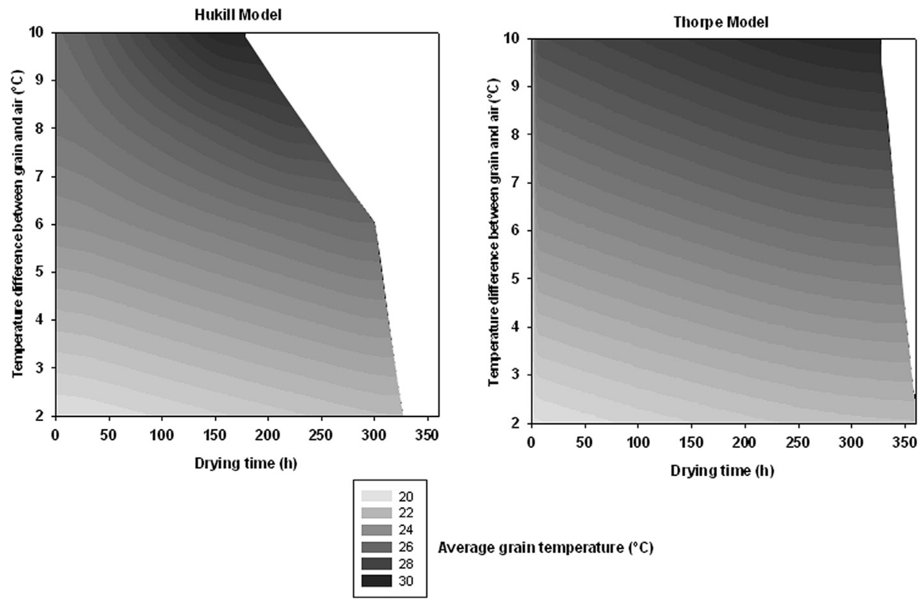

Fig. 8 – Average grain temperatures predicted for the models by varying temperature difference between grain and air.

understanding and analysis, as well as more suitable for complex decision-support.

6. Conclusion

The logarithmic (Hukill) and equilibrium (Thorpe) models presented good correlations between experimental and predicted drying times. Also, the temperature and moisture content profiles simulated by the two models were similar and coherent with what might be expected from the grain-drying process. Sometimes, when the dynamics of drying are evaluated, detail profiles are not required and only the overall behaviour is required. For example, how the moisture content decreases and how this decrease is related with the drying time. For more detailed analyses, more studies are required that explore experimental and simulated grain moisture contents and temperatures during drying processes. Further studies are also required to validate these models for other cereals and drying conditions.

The equilibrium model can be applied over a wider range of drying situations, including processes with variable inlet air conditions. It provides a more fundamental understanding of the drying physics, making this model useful for

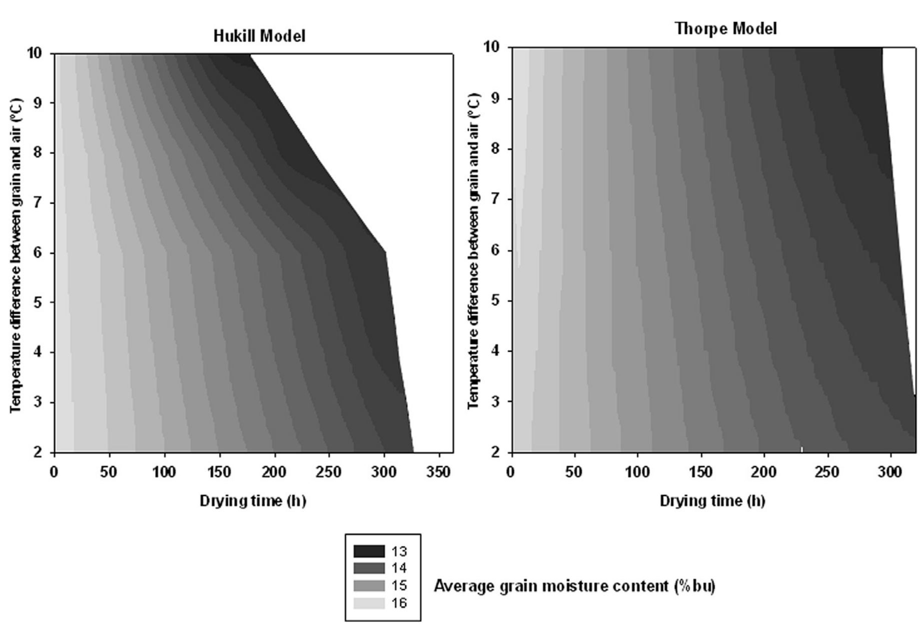

Fig. 9 – Average grain moisture contents predicted for the models by varying temperature difference between grain and air.

understanding the drying process and for more complex decision-support. The logarithmic model, however, has advantages with respect to simplicity and speed of solution, being appropriated for the investigation of drying characteristics, decision-support, energy optimisation and other research. This kind of model could also be useful in control systems based on simulation procedures, which can be implemented by using microprocessors, requiring simple solution techniques.

Acknowledgements

The authors would like to acknowledge the FAPEMIG/Brazil (Fundação de Amparo à Pesquisa do Estado de Minas Gerais) and the CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for their financial support.

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