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Simulation of Intermittent Drying of Corn

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Abstract **–**In this study, drying behavior of single layer corn for different drying air temperature (40−70°C) and drying air velocity 2 ms^{-1} was simulated by means of a liquid diffusion model numerically by a finite element modeling and simulation software. The results show that temperature is an effective factor on the drying rate. The results also show that as drying proceeds, a moisture gradient develops within the grain. This slows down the drying rate considerably. In addition, the analysis shows that intermittent drying provides energy saving up to 40%-50% with respect to continuous drying. Therefore, it can be concluded that performing drying with an intermittent period instead of continuous drying will cause a considerable energy-saving.

Keywords**:** Intermittent corn drying, Comsol simulation, drying time, energy consumption

1. Introduction

Corn is one of the most important cereal crops after rice and wheat in the world. It is estimated that 60% of the corn produced worldwide is used for animal feed, 20% of for direct human nutrition, 10% of for processed food and 10% as the rest for other consumptions and seed (Web-1). Moisture content of 24-25% (db) during the harvest should be reduced below 14% (db) to prevent it from deterioration during storage.

As it absolutely known that drying of hygroscopic materials takes place two or three different stages. First drying stage is called as constant rate drying stage. It is apparent that removing unbounded moisture from surface requires relatively less energy and takes relatively less time. Second and/or third stages takes longer time relative to the first stage and these drying stages are called as falling drying rate stage (Mujumdar, 2015). Drying process is generally performed by heating the ambient air and then sending it by forced convection over the crops to be dried. The drying rate of corn is affected by a number of factors such as initial moisture content, drying air temperature, relative humidity, and airflow rate. There are many studies in the literature dealing with the aforementioned parameters on the drying rate of corn (Hacıhafızoğlu et al., 2009). Nowadays, a number of new or modified drying methods are proposed in the professional literature, especially methods improving the effectiveness of drying in an aspect of energy saving or shortening the drying time but also in the aspect of quality of dried products (Pillai et al., 2010, Gollei et al., 2009). Among these methods the intermittent drying should be mentioned, in which a special attention is paid just on the quality of dried products. Intermittent drying or tempering drying is non-continuous drying processes. A tempering period allows moisture diffusion from the interior to the external surface of the grain kernels to decrease the moisture gradients and to improve the drying rate. Kowalski&Pawłowski (2011) were used the cylindrically shaped kaolin samples in their studies. It was shown that drying at intermittent conditions leads to products of much better quality than drying at stationary conditions by almost the same duration of these processes. The energy consumption was smaller by intermittent drying realized with variable air temperature and greater by variable air humidity in comparison to drying at stationary conditions. Prachayawarakorn et al. (2004) have concluded that high moisture corn should be dried to 23% (db) and tempered for 40 min in order to maintain quality and reduce energy consumption. Steffe and Singh (1980) observed similar trends of decreasing tempering time with increasing temperature. A mechanistic model has been employed to demonstrate the significant advantages of intermittent drying of an agricultural product. The model shows tempering of the product and increased surface moisture content when the air temperature was switched from the ‘on’ period to the ‘off’ period. The time-evolution of the product surface temperature and moisture has been investigated for both constant and intermittent drying schemes (Chou et al., 2000). Takhar (2011) predicted stress generation during drying of corn kernels using the hybrid mixture theory based general fluid transport equation of Singh et al. (2003a) and the viscoelastic stress equation in their work. The strain in a corn kernel was assumed to be caused by shrinkage due to loss of water. The volume change during drying was assumed of uniform type that causes the shape of a kernel remaining geometrically similar to its initial shape. The moisture transport and stress development mechanisms were elucidated for corn kernels using numerical solution of three-scale fluid transport equation. Intermittent drying simulations indicated that fan on/off strategies with suitable time step-size would be a viable option for drying corn with lower stress-cracking and additional energy savings (Takhar et al., 2011).

The aim of this study is to simulate by means of Comsol Multiphysics software the drying behavior of single layer corn by the liquid diffusion model based on an spheroidal geometry.

2. Material and Method

In this study drying simulations of corn seed in the spheroid form, are obtained by using diffusion equation. Corn grains of approximately 20 g of total weight are spread onto each grid, in a manner to form thin layers. Sieves containing corn grains of thin layer were placed in drying zones of the experimental setup. The experiments were carried out for different drying air temperature (40°C–70°C) and 2m/s velocity. A digital anemometer with an accuracy of $\pm 0.1\ ms^{-1}$ is used to measure the air velocity at the outlet of the sieves. The progress of the drying process is followed by weighting the sieves containing corn grains at regular time intervals on a digital scale, with an accuracy of ± 0.001g. The intermittent period was chosen as 0.5h after successive drying period in this study. The dry mass is determined by drying the corn in an oven at a temperature of 110°C for 48 hours 8 (Steffe&Singh 1980, Ece&Cihan, 1993). The equilibrium moisture content of corn grains is determined according to the model proposed by Krokida et al. (2003). Drying data are determined by taking the average of three measurements. Hybrid type corn obtained from Trakya Agricultural Research Institute is used in the experiments and the drying process is conducted immediately after harvest without applying any pre-treatment. An spheroid geometry is defined on Comsol Multiphysics finite element analysis software. The values of semi-axis values are entered as 3.71mm, 3.71mm and 4.65mm and spheroid form of the corn seed is obtained as shown in the Fig.1.

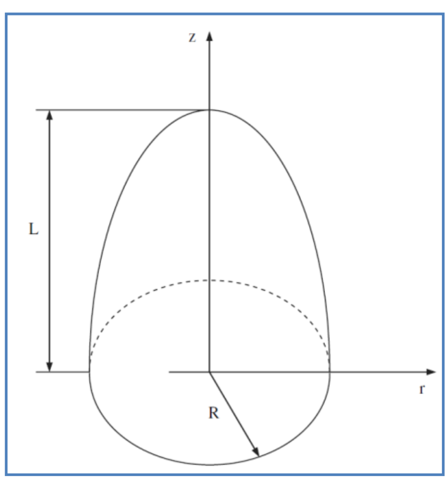

Fig. 1. Assumed geometry for corn grain

The liquid diffusion equation is given the following form:

where X is the moisture content, D is the liquid diffusion coefficient and t is the time.

$$\vec{\nabla} \cdot \left(D_{eff} \vec{\nabla} X\right) = \frac{\partial X}{\partial t} \tag{1}$$

When defining boundary conditions it is assumed that surface of the corn seed is in equilibrium moisture content. Finally boundary and initial conditions are defined as followings.

$$X|_{s} = X_{e} \tag{2}$$
$$X|_{t=0} = X_{o} \tag{3}$$

The previously obtained dimensions and diffusion coefficients for corn geometry were adapted to this study (Yılmaz S, 2010). These dimensions and drying conditions are given in Table 1-2.

Table. 1. Diffusion coefficients, initial and equilibrium moisture contents (db) and relative humidity for various drying temperatures

T(°C)	40	50	60	70
$D \times 10^{7} (m^{2}\ h^{-1})$	3.0034	3.8851	4.1206	4.9803
X_o	0.2488	0.2499	0.2402	0.2403
X_e	0.0840	0.0747	0.0648	0.0523
φ	0.2357	0.1820	0.1291	0.0923

Table. 2. Dimensions of corresponding spheroidal geometry

Geometry	Dimensions	Volume
Prolate Spheroid	L=4.65 mm R=3.71 mm	V=268 mm^3

3. Conclusion

Accurate determination of drying rate is important because drying conditions affect the quality of the food stuff. Analytical solution of the above unsteady diffusion equation is difficult to obtain. Therefore, solution was obtained numerically by Comsol, which is a finite element modeling and simulation software. Simulations of moisture distributions inside the corn seed during drying are obtained for each cases as shown in Fig. 2-5 respectively. As it can be seen from the figures, showing moisture distribution inside the seed, one can conclude that moisture more rapidly decreases as temperature increases. Before the seed reach to the equilibrium moisture content, there always be seen moisture gradient inside the seed. At the beginning of the drying, moisture gradient is relatively bigger and this causes drying to be fast at that stage. This explains the reason of the falling rate period when drying is modelled by diffusion. The accuracy of finite element solution of diffusion equation depends on the mesh size selected. The boundary element mesh size was taken as 0.04. In intermittent drying with 30 min tempering, total drying time to reach the same level of moisture content is 196 min for 40°C, 133 min for 50°C, 99 min for 60°C and 72 min for 70°C. In addition, the energy consumption analysis shows that intermittent drying provides energy saving up to 40%-50% with respect to continuous drying (Hacıhafızoğlu et al. 2010). On the other hand, intermittent drying led to more uniform temperature and moisture distributions, which improve grain quality.

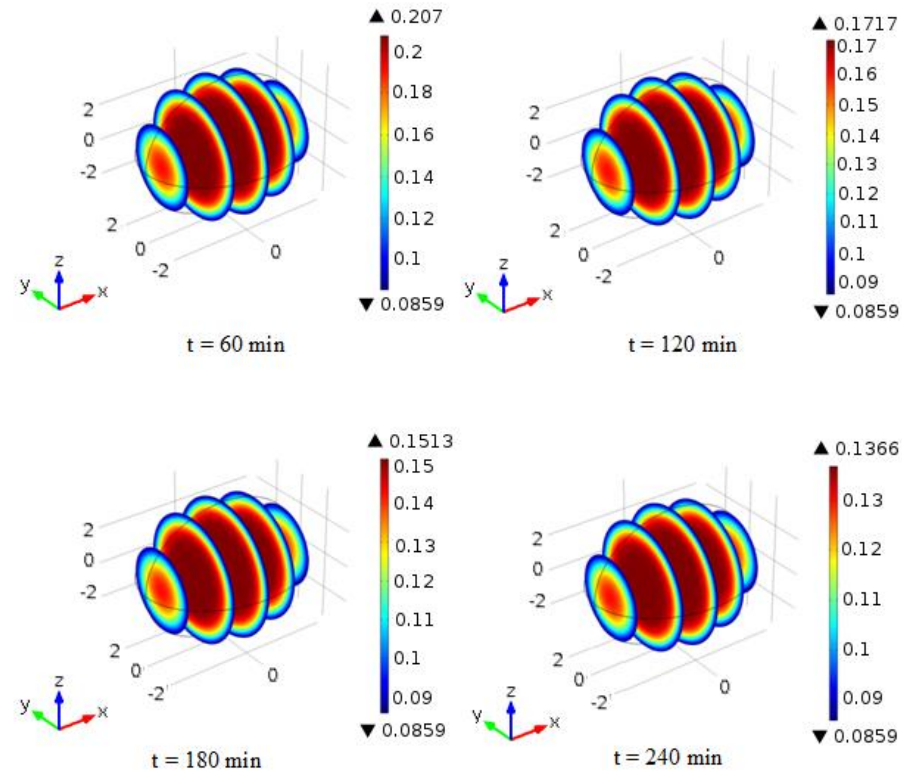

Fig. 2. Iso-concentration lines for drying temperature T=40°C

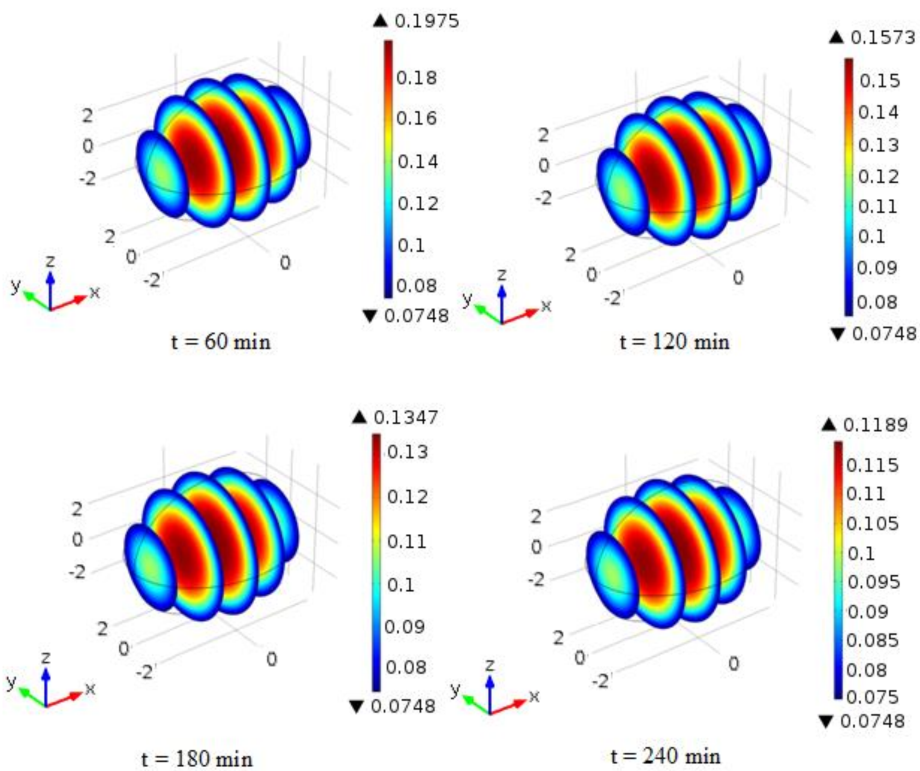

Fig. 3. Iso-concentration lines for drying temperature T=50°C

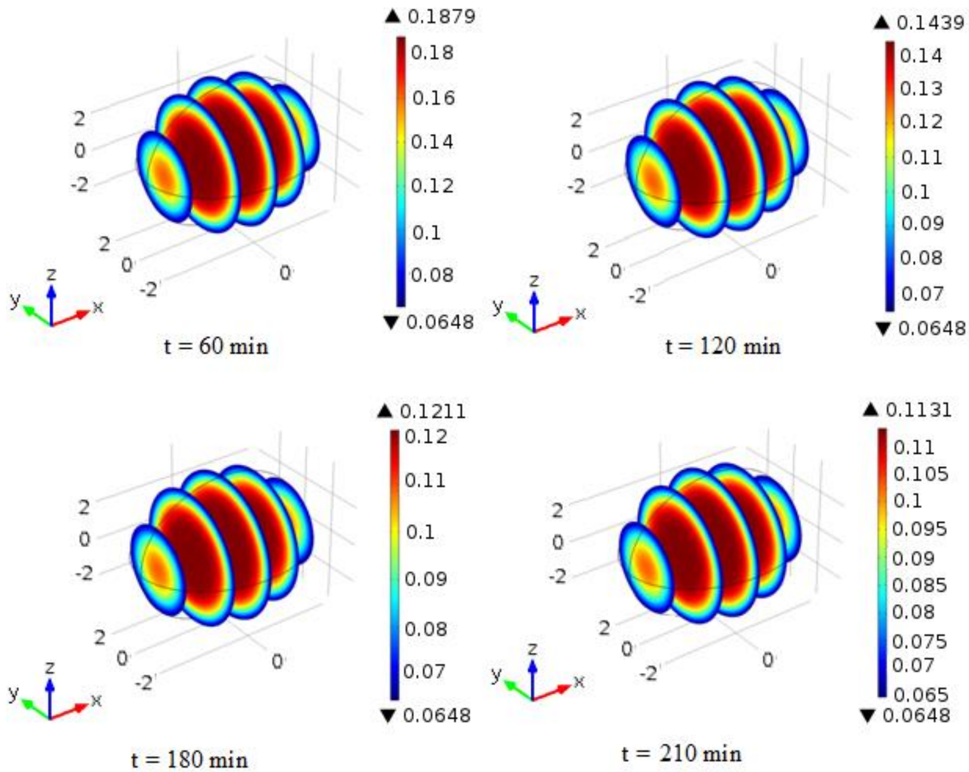

Fig. 4. Iso-concentration lines for drying temperature T=60°C

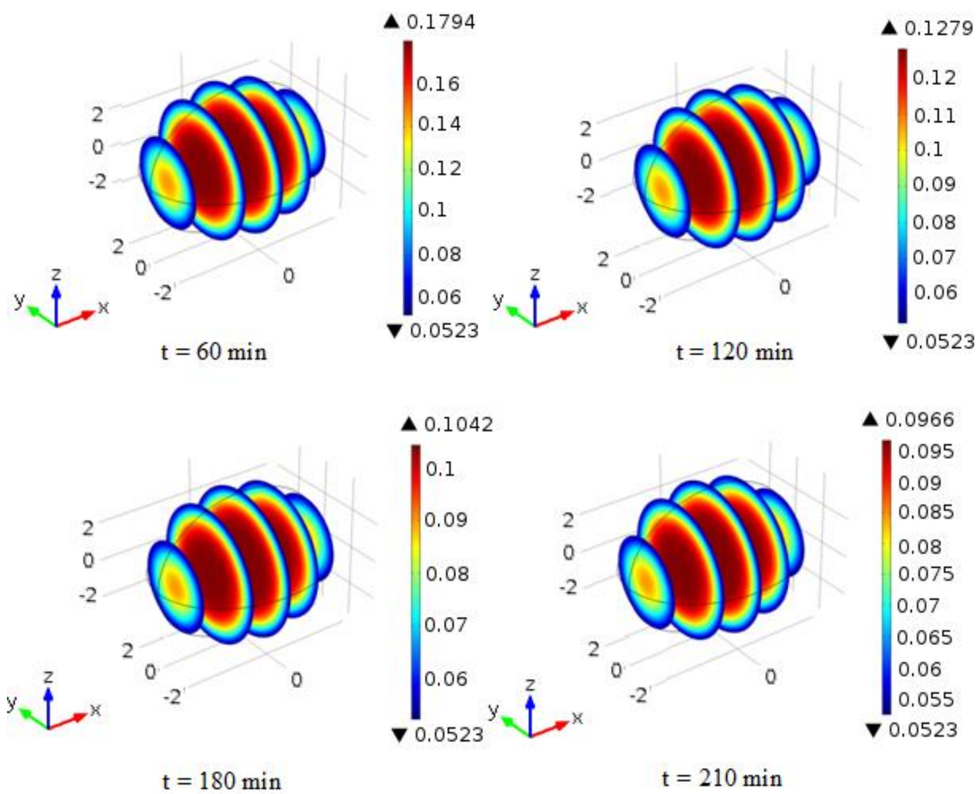

Fig. 5. Iso-concentration lines for drying temperature T=70°C

Nomenclature

D_{eff} effective diffusion coefficient, m^2h^{-1}
T drying air temperature,°C
t time, s
V volume, mm^3
R radius of a corn grain, mm
L half-length of a corn grain, mm
X_e equilibrium moisture content in dry basis, kg/kg
X_o initial moisture content in dry basis, kg/kg

Greek letters

∇^2 Laplacian operator
φ relative humidity

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