FINITE ELEMENT SIMULATION OF THIN LAYER DRYING OF CORN

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Abstract: Corn is one of the most important nutritious grains which has high moisture rates during harvest. Moisture content of 24-25% (db) at the harvest should be reduced below 14% (db) to prevent it from deterioration during storage. Drying process is generally performed by heating ambient air and then sending it by forced convection over the corn to be dried. The aim in heating air to a certain temperature is to reduce the relative humidity of the air, which has a positive effect on the drying potential. 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. Therefore, it can be concluded that performing drying with an intermittent period instead of continuous drying will cause a considerable energy-saving.

Key-Words: Drying, Moisture content, Corn, Liquid diffusion, Sphere, Finite element modeling

1 Introduction
Corn has emerged as a major economic crop throughout the world and also an important industrial raw material in starch industry due to its rich starch content and useful byproducts obtained during starch extraction [1]. Moisture content is one of the most important factors affecting the quality of corn during storage and it is at a high level at the time of harvest 24% (db) and must be reduced to about 12% (db) with an appropriate drying process. Drying process is generally performed by heating the ambient air and then sending it by forced convection over the crops to be dried. The aim in heating air to a certain temperature is to reduce the relative humidity of the air, which has a positive effect on the drying potential and to increase a liquid diffusion as well. Moreover, such method of drying reduces fissures on the product caused by thermal stresses due to the controllability of the speed of drying air. Chen et al. have developed a method for characterizing moisture diffusivity of corn kernel components. They used Comsol Multiphysics Package to estimate moisture transfer during drying and served as a function which was called by the optimization algorithm written in Matlab computer language. The optimization algorithm provided accurate estimation of the model parameters of moisture diffusivity from standard experimental drying data, which is normally expressed as average moisture content as a function of drying time. Since moisture diffusivity was determined from the pure components removed from corn kernels, the obtained moisture diffusivity values were more representative than those given in the literature [2]. Leila et al. have investigated drying characteristics of shelled corn with an initial moisture content of 26% dry basis in a fluidized bed dryer assisted by microwave heating. The experiments carried out for four air temperatures (30, 40, 50 and 60 °C) and five microwave powers (180, 360, 540, 720 and 900W). The results showed that increasing the drying air temperature resulted in up to 5% decrease in drying time while in the microwave-assisted fluidized bed system, the drying time decreased dramatically up to 50% at a given and corresponding drying air temperature at each microwave energy level. As a result, addition of microwave energy to the fluidized bed drying is recommended to enhance the drying rate of shelled Corn [3]. Soponronnarit et al. have studied the drying behavior of corn in a batch fluidized bed dryer at various drying temperatures. Their results
indicate that moisture transfer is controlled by internal diffusion [4]. Moisture adsorption tests were conducted using corn germ and composite corn kernels under the humid air conditions of 75, 80, and 90% relative humidity and 25, 30, 35, and 40°C temperature by Muthukumarappan and Gunasekaran [5]. Moisture diffusivity values were estimated based on the analytical Fick’s diffusion model assuming corn germ and corn as an infinite slab. The mean moisture diffusivity of corn germ increased with air temperature \((0.19 \times 10^{-7} \text{ to } 0.66 \times 10^{-7} \text{ m}^2 \text{h}^{-1})\) and decreased with air relative humidity \((0.27 \times 10^{-7} \text{ to } 0.60 \times 10^{-7} \text{ m}^2 \text{h}^{-1})\). Moisture diffusivity values of corn germ were about two to five times lower than those of the composite corn kernel. Thin-layer drying experiments of corn kernels using continuous and time-varying temperature and humidity profiles were conducted and the stress crack index was evaluated by Hundal and Takhar [6].

The aim of this study is to simulate the drying behavior of single layer corn by the liquid diffusion model based on an sphere geometry.

### 2 Problem Formulation

Corn grain was assumed to have an sphere geometry (see Figure 1) and the moisture transport was assumed to be in the liquid state and governed by the unsteady liquid diffusion equation based on Fick’s law. It was also assumed that diffusion coefficient was independent of moisture content for a given temperature. This assumption was also made by various authors [7-10]. It was also assumed that moisture concentration of a corn grain reached at its equilibrium value on the surface instantaneously at the onset of the drying process and that this equilibrium did not change by time. Besides, corn grain was considered to remain isothermal during drying. It was also assumed that corn grains did not shrink during drying.

![Fig.1 Assumed geometry for corn grain](image)

Dimensionless variables used in the analysis were defined as follows:

\[
c = \frac{c^* - c_e^*}{c_o^* - c_e^*}, \quad \nabla^2 = \frac{1}{R^2} \nabla^2, \quad t = \frac{D t^*}{R^2} \tag{1}
\]

where \(c\) is the volumetric moisture concentration, \(D\) is the liquid diffusion coefficient, \(t\) is the time, and \(R\) is the radius of the corn grain. The liquid diffusion equation then takes the following form:

\[
\frac{\partial c}{\partial t} = \nabla^2 c \tag{2}
\]

and is subject to the initial condition

\[
c|_{t=0} = 1 \tag{3}
\]

and the boundary condition

\[
c_s = 0 \tag{4}
\]

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.

### 3 Problem Solution

The radius of the sphere geometry were determined by Hacihafızoğlu et al. [11] by using the average volume of corn grains (see Table 1). The diffusion coefficient for various drying temperatures were also obtained by Hacihafızoğlu et al.[11] (see Table 2). These dimensions and diffusion coefficients were adapted to this study. The accuracy of finite element solution of diffusion equation depends on the mesh size selected. After some trials, it was observed that solution remains the same if the boundary element mesh size was taken as 0.05. Therefore this mesh size was used in the study.

<table>
<thead>
<tr>
<th>Table 1. Dimensions of a corn grain and corresponding sphere geometry [11]</th>
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</thead>
<tbody>
<tr>
<td><strong>Geometry</strong></td>
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<tr>
<td>Sphere</td>
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</table>
Table 2. Diffusion coefficients for various drying temperatures [11]

<table>
<thead>
<tr>
<th>T(°C)</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>D×10^7 (m^2 h^-1)</td>
<td>1.767</td>
<td>2.383</td>
<td>3.260</td>
<td>4.243</td>
</tr>
</tbody>
</table>

4 Conclusion
The results for various drying temperatures are shown in Figs. 3-6. As it is seen from these figures, drying temperature is an effective factor on the drying rate. With the increase of the drying temperature, a significant increase at the drying rate takes place as the diffusion coefficient gets higher values. It can also be concluded from Figs. 3-6 that, at the beginning of the drying process, moisture transfer takes place from the places near the surface. At this stage, moisture transport is dependent mainly on the external condition. As the drying proceeds, internal resistance to the moisture transport becomes gradually more effective as the moisture gradient normal to the grain surface reduces. This slows down the drying. Moisture is transferred from the core to the surface in this stage. Then, moisture is removed from the surface. From these results, it can be recommended that drying should be ceased periodically after some period in order to wait the movement of moisture from inner part towards outer part. This type of drying known as intermittent drying needs lower thermal energy; therefore, thermal efficiency of this type of drying is higher.

![Fig.3 Iso-concentration lines for drying temperature T=40°C](image-url)
**Fig. 4** Iso-concentration lines for drying temperature $T=50^\circ C$

**Fig. 5** Iso-concentration lines for drying temperature $T=60^\circ C$
Fig. 6 Iso-concentration lines for drying temperature $T=70^\circ C$

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$C$</td>
<td>dimensionless volumetric moisture concentration</td>
</tr>
<tr>
<td>$D$</td>
<td>diffusion coefficient ($m^2 \cdot h^{-1}$)</td>
</tr>
<tr>
<td>$R$</td>
<td>radius of a corn (mm)</td>
</tr>
<tr>
<td>$S$</td>
<td>surface area ($mm^2$)</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature ($^\circ C$)</td>
</tr>
<tr>
<td>$T$</td>
<td>time (h)</td>
</tr>
<tr>
<td>$V$</td>
<td>volume ($mm^3$)</td>
</tr>
</tbody>
</table>

**Greek letters**

$\nabla^2$ : laplacian

**Superscripts**

* : dimensional quantities

**Subscripts**

e : equilibrium condition
o : initial condition
s : surface condition

**References:**


