NUMERICAL INVESTIGATION OF INTERMITTENT DRYING OF A CORN FOR DIFFERENT DRYING CONDITIONS

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In this study, intermittent drying process of corn was studied numerically for various intermittent periods and drying air temperatures. An Arrhenius type diffusion coefficient $D=e^{(-b/T)}\cdot 10^{-9}$ m^2 s^{-1} was proposed for the moisture diffusion inside the corn. Numerical simulations were performed by choosing the suitable value for drying constant b that yields the best agreement with experimental drying rates. The experimental results were obtained via an experimental setup for intermittent periods of 30 and 60 min. and drying air temperatures of 40℃, 50℃, 60℃ and 70℃. The results show that overall agreement between the experimental and theoretical prediction is good. On the other hand, the theoretical results overestimate the moisture ratio at the initial stage and underestimate it at the later stage of drying.

Key words: Intermittent drying, corn, moisture content, diffusion coefficient, Sherwood number

1. Introduction

Corn (Maize) is ranked as the most important cereal in the world due to its high consumption, that makes studies on corn drying process more attractive among researchers. The moisture content of foodstuff should be reduced in order to prevent deterioration during storage after harvesting. The moisture content of the corn after harvesting is around 24-25% (db) and must be reduced below 14% (db) by a suitable drying process [1].

There are a number of studies in the literature on investigation of drying behavior of corn. Soponronnarit *et al*. [2, 3] studied the drying behavior of corn in a batch fluidized bed dryer for various drying conditions and concluded that the diffusion has a significant effect on the moisture transfer. Similarly, the experimental study conducted by Krokida *et al*. [4] showed that drying air temperature has an important effect on the drying rate of corn, while the effect of drying air velocity is relatively insignificant.

The drying process of food materials is rather complex and therefore it is generally modelled by empirical and semi-empirical models. Doymaz and Pala [5] used empirical exponential model and Page model for describing the thin layer drying process of corn and found that the Page model is better than the exponential model. Hacıhafızoğlu *et al*. [1] used a liquid diffusion model for the simulation of continuous drying of corn with an initial moisture content of 25%. They made three assumptions for the geometry: a slab, a finite cylinder and a sphere. The results indicate that the sphere geometry is the most suitable geometry to obtain the best fit between theoretical and experimental results. Hacıhafızoğlu *et al*. [6] used empirical and semi-empirical models to model the continuous and intermittent drying behavior of corn and found that Page, Midilli *et al*. and Diffusion Approach models are the most suitable models. Janas *et al*. [7] developed a numerical heat and mass transfer model using Fourier's law and Fick's second law for the prediction of the temperature and the moisture content of maize grains in fluidized-bed drying. Hatamipour and Mowla [8] investigated corn drying in a fluid bed dryer with inert particles. They found that drying rate enhances considerably due to inert particles. Prachayawarakorna *et al*. [9] conducted an experimental study and observed that to reduce energy consumption and maintain quality, it is necessary for the high moisture corn to be dried to 23% (db) and tempered for 40 min. After correlating the drying behavior of supersweet corn by empirical and semi-empirical models, Yoshida and Menegalli [10] found that the two–term exponential model fits better. Jittanit [11] made a study on the two-stage corn drying for various drying conditions and concluded that the best models among other empirical and semi-empirical models are modified Page and modified two-term exponential models. Kaleta and Gornicki [12] investigated the drying behavior of apple particles in a laboratory type convective dryer and they fitted the experimental results to theoretical, semi-theoretical and empirical models. Kaleta *et al*. [13] investigated the drying behavior of apple samples (Ligol) in a fluidized bed dryer considering the effect of drying air temperature. The suitability of three new empirical models proposed by the authors in addition to the theoretical, semi-theoretical and empirical models in the literature was examined. The proposed models are modifications of the Page model. Chua and Chou [14] studied drying of potato and carrot samples experimentally using both intermittent microwave (MW) and infrared (IR) drying methods. They observed that there is a significant decrease in drying time and color change for the intermittent microwave (MW) drying compared to convective or intermittent IR (infrared) drying. They showed that with a suitable combination of convective microwave drying, the drying time can be shortened by 42% and 31% for potato samples and carrot samples respectively. Defraeye [15] presented a review on computational modelling of drying processes. Jian *et al*. [16] developed empirical, semi-theoretical and finite element models for the simulation of water sorption of kidney beans. They observed that effective diffusion coefficient predicted by the finite element model decreases with the increase in soaking time. Kahveci [17] showed that the assumption of constant material temperature during drying process results in a higher drying rate due to the higher diffusion coefficient.

As it can be concluded from the studies in the literature that drying is generally modelled by assuming constant temperature and constant equilibrium moisture content on the surface of material. On the other hand, more realistic modelling is needed for better understanding of the drying behavior of materials. In this context, intermittent drying behavior of corn was modelled in this study by considering the heat and mass transfer between the material and surrounding drying air and the flow around the corn. An Arrhenius type diffusion coefficient ($D=e^{(-b/T)}\cdot 10^{-9}$ m^2 s^{-1}) is proposed for the moisture transport inside the corn in the developed numerical model. As opposed to most of the studies in the literature that assume constant temperature for the material and constant equilibrium moisture content on the surface of material, the theoretical model presented in this study takes into account heat and mass transfer between air and material. The values of the parameter b in the suggested Arrhenius type diffusion coefficient were obtained for each drying conditions (drying air temperatures of 40°C, 50°C, 60°C, 70°C and intermittent periods of 30 min. and 60 min.).

2. Analysis

The geometry and coordinate system considered in this study is seen in Figure 1. The corn is assumed to have a spherical geometry with radius r_c=0.004 m. The radius is specified by considering the average volume of corn used in this study. The drying is carried out by sending the hot air in a channel to the corn. The surfaces of the channel at the height of H=1.2 m and radius of R_c=0.05 m were assumed to be adiabatic. The parameters, thermo-physical properties of drying air and corn and models assumed in this study are given in Table 1. The thermo-physical properties of the drying air were taken at the constant temperature of 330 K considering the mean value of the drying air temperatures.

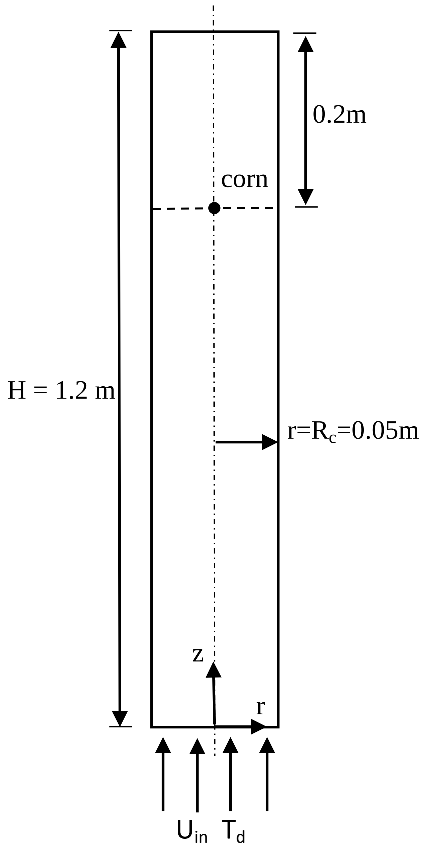


Figure 1. Geometry and coordinate system of the problem

Table 1. Parameters, thermo-physical properties and models assumed in the study

Radius of the drying channel	R_c = 0.05 m	
Height of the drying channel	H = 1.2 m	
Radius of corn	r_c = 0.004 m	
Thermal conductivity of air Density of air Specific heat of air Dynamic viscosity of air	k_{air} = 0.02852 W $m^{-1}K^{-1}$ ρ_{air} = 1.06156 kg m^{-3} $c_{p\ air}$= 1008.2 J $kg^{-1}K^{-1}$ $\mu_{air} = 1.9876 \cdot 10^{-5}$Pas	[18]
Thermal conductivity of corn	k_{corn}= 0.174 W $m^{-1}K^{-1}$	[19]
Density of corn	ρ_{corn} = 1170 kg m^{-3}	[20]
Specific heat of corn	c_{corn} = 2470 J $kg^{-1}K^{-1}$	[21]
Initial temperature	T_{in} = 25 ^oC	
Inlet velocity	U_{in} = 2 m s^{-1}	
Drying air temperature	$T_d = 40\ ^oC, 50\ ^oC, 60\ ^oC, 70\ ^oC$	
Coefficients for the diffusion coefficient of water vapor in air	$c_1 = -2.775 \cdot 10^{-6}$ $c_2 = 4.479 \cdot 10^{-8}$ $c_3 = 1.656 \cdot 10^{-10}$	[17]
Diffusion coefficient of corn	$D=e^{(-b/T)} \cdot 10^{-9}$ $m^2\ s^{-1}$ (T in K)	
Diffusion coefficient of water	$D_{a,w}=c_1+c_2T+c_3T^2$ $m^2\ s^{-1}$	[17]

vapor in air	(T in K)	
Sherwood number	$Sh = 2 + 0.6Re^{1/2}Sc^{1/3}$	[22]

The flow inside the channel is turbulent for the values of parameters considered ($Re = \frac{U_{in}2R_c}{\nu_{air}} > 2300$). The k-ε turbulent model is used to model the tree dimensional turbulent flow. It is also assumed that drying air is incompressible and Newtonian. As the most important mass transfer mechanism is molecular diffusion in the drying of corn, diffusion equation is assumed to govern mass transfer inside the corn. Arrhenius type diffusion coefficient is proposed for the diffusion coefficient and effects of other transfer mechanisms were considered to be lumped into diffusion coefficient. Gravity effect was neglected. Therefore, the governing equations with the assumption of constant thermo-physical properties are as follows.

$k - \varepsilon$ Turbulence model for drying air

$$\vec{\nabla} \cdot \vec{V} = 0 \tag{1}$$

$$\rho_{air}\frac{\partial \vec{V}}{\partial t} + \rho_{air}(\vec{V} \cdot \vec{\nabla})\vec{V} = -\vec{\nabla}p + \vec{\nabla} \cdot \left((\mu_{air} + \mu_T)\left(\vec{\nabla}\vec{V} + (\vec{\nabla}\vec{V})^T\right)\right) - \frac{2}{3}\rho_{air}\vec{\nabla}k \tag{2}$$

$$\rho_{air}\frac{\partial k}{\partial t} + \rho_{air}(\vec{V} \cdot \vec{\nabla})k = \vec{\nabla} \cdot \left(\left(\mu_{air} + \frac{\mu_T}{\sigma_k}\right)\vec{\nabla}k\right) + P_k - \rho_{air}\epsilon \tag{3}$$

$$\rho_{air}\frac{\partial \epsilon}{\partial t} + \rho_{air}(\vec{V} \cdot \vec{\nabla})\epsilon = \vec{\nabla} \cdot \left(\left(\mu_{air} + \frac{\mu_T}{\sigma_\epsilon}\right)\vec{\nabla}\epsilon\right) + C_{\epsilon 1}\frac{\epsilon}{k}P_k - C_{\epsilon 2}\rho_{air}\frac{\epsilon^2}{k} \tag{4}$$

$$\mu_T = \rho_{air}C_\mu\frac{k^2}{\epsilon} \tag{5}$$

$$P_k = \mu_T\left[\vec{\nabla}\vec{V}: \left(\vec{\nabla}\vec{V} + (\vec{\nabla}\vec{V})^T\right)\right] \tag{6}$$

Where $\vec{V}$ is velocity vector, p is pressure, k, ϵ, P_k are turbulent kinetic energy, dissipation rate of turbulence energy and production term, respectively, ρ_{air} is air density, μ_{air} is dynamic viscosity for air and μ_T is dynamic turbulent viscosity. The constant parameters for the $k - \varepsilon$ turbulence model are also given below. Standard turbulence model parameters were used [23, 24].

Turbulence model parameters

$C_{\epsilon 1} = 1.44$
$C_{\epsilon 2} = 1.92$
$C_\mu = 0.09$
$\sigma_k = 1$
$\sigma_\epsilon = 1.3$
$K_v = 0.41$ (Von Karman constant)
$B = 5.2$ (Empirical constant)

Energy equations for drying air

$$\rho c_{p\,air}\left(\frac{\partial T}{\partial t} + \vec{V} \cdot \vec{\nabla}T\right) = \vec{\nabla} \cdot \left((k_{air} + k_T)\vec{\nabla}T\right) \tag{7}$$

where $c_{p\,air}$ is the specific heat and k_{air} is the thermal conductivity for air. Viscous heating is assumed neglegible.

Governing equations for corn

$$\frac{\partial m}{\partial t} = \vec{\nabla} \cdot (D\vec{\nabla}m) \tag{8}$$

$$\rho_{corn}c_{corn}\frac{\partial T}{\partial t} = k_{corn}\nabla^2 T \tag{9}$$

where m is the moisture content on dry basis, D is the effective diffusion coefficient, ρ_{corn}, c_{corn} and k_{corn} are density, specific heat and thermal conductivity of the corn respectively. An Arrhenius type relation for the diffusion coefficient is assumed in this study:

$$D=e^{(-b/T)}\cdot 10^{-9}\ m^2\ s^{-1} \quad (T\ in\ K) \tag{10}$$

The boundary and initial conditions for the corresponding governing equations are given below for both fluid and corn.

For drying air:

The effect of walls on flow is generally considered by wall functions. Analytical solutions of the boundary layer equations serve as a bridge between the no-slip boundaries and turbulent flow region [25]. Wall functions given below ignore flow field in the buffer region near the wall due to its very low thickness [26].

Wall functions for the channel and corn walls:

$$\vec{V}\cdot\vec{n}=0 \tag{11}$$

$$\left((\mu_{air}+\mu_T)\left(\vec{\nabla}\vec{V}+\left(\vec{\nabla}\vec{V}\right)^T\right)-\frac{2}{3}\rho_{air}k\right)\vec{n}=-\rho_{air}\frac{u_\tau}{\delta_w^+}\vec{V}_{tang} \tag{12}$$

$$\vec{V}_{tang}=\vec{V}-(\vec{V}\cdot\vec{n})\vec{n} \tag{13}$$

$$\vec{\nabla}k\cdot\vec{n}=0, \qquad \epsilon=\rho_{air}\frac{C_\mu k^2}{K_v\delta_w^+\mu_{air}} \tag{14}$$

$$\delta_w^+=\rho_{air}u_\tau\delta_w/\mu_{air} \tag{15}$$

$$u_\tau={C_\mu}^{1/4}\sqrt{k} \tag{16}$$

where K_v is von Karman constant, δ_w is the distance from the solid wall where the computational domain is assumed to start and u_τ is friction velocity. δ_w is automatically computed by the software.

On the other hand, the optimum value of the δ_w^+ is 11.06. It could easily be found from the iterative solution of the following equation for $K_v=0.41$ and $B=5.2$ [25].

$$\delta_w^+=\frac{1}{K_v}ln\delta_w^++B \tag{17}$$

For the corn surface:

Thermal boundary conditions at the surface of the corn are based on the continuity of temperature and heat flux:

$$\vec{n}\cdot(\vec{q}_1-\vec{q}_2)=0 \tag{18}$$

$$T_1=T_2 \tag{19}$$

where $\vec{n}$ is the unit normal vector. The subscripts 1 and 2 represents the air and corn, respectively.

$$-D\frac{\partial m}{\partial n}\bigg|_S=h_m(m-m_e) \tag{20}$$

where h_m is the mass transfer coefficient and m_e is the equilibrium moisture content. The values of m_e for different drying air temperatures are given in Table 2.

Inlet boundary condition:

$$\vec{V}\big|_{r,z=0} = -U_{in}\vec{n}\ ,\ k|_{r,z=0} = \frac{3}{2}(U_{in}I_T)^2\ \ ,\ \epsilon|_{r,z=0} = C_\mu{}^{3/4}\frac{k^{3/2}}{L_T} \quad (21)$$

where I_T the turbulence intensity and it is selected as 0.05. L_T is the turbulence length scale and it is 0.01m.

$$T|_{r,z=0} = T_d \quad (22)$$

Outlet boundary condition:

$$p|_{r,z=H} = p_{atm} \quad (23)$$

$$\left[(\mu_{air} + \mu_T)\left(\vec{\nabla}\vec{V} + \left(\vec{\nabla}\vec{V}\right)^T\right) - \frac{2}{3}\rho_{air}k\right]\vec{n}\Big|_{r,z=H} = 0 \quad (24)$$

$$\vec{\nabla}k\cdot\vec{n}\big|_{r,z=H} = 0\ ,\ \vec{\nabla}\epsilon\cdot\vec{n}\big|_{r,z=H} = 0 \quad (25)$$

where p_{atm} is atmospheric pressure (101325 Pa)

$$\frac{\partial T}{\partial z}\Big|_{r,z=H} = 0 \quad (26)$$

The boundary condition of $\frac{\partial T}{\partial r}\Big|_{r=R_c} = 0$ is also valid on the channel walls due to the assumption of adiabatic surfaces.

Initial conditions

$\vec{V}\big|_{t=0} = 0$ (initial condition for drying air) (27)

$$T|_{t=0} = T_{in} \quad (28)$$

$$m|_{t=0} = m_{in} \quad (29)$$

$$k|_{t=0} = 0 \qquad \epsilon|_{t=0} = 0 \quad (30)$$

The mass transfer correlation for the flow over a single solid sphere is defined as follows [22]:

Mass transfer coefficient

$$Sh = 2 + 0.6Re^{1/2}Sc^{1/3} \quad (31)$$

where Sh, Re and Sc are the Sherwood, Reynolds and Schmidt numbers, respectively. They are defined as:

$$Sh = \frac{h_m d}{D_{a,w}},\qquad Re = \frac{U_{in}d}{\nu_{air}},\qquad Sc = \frac{\nu_{air}}{D_{a,w}} \quad (32)$$

where d is the diameter of the corn, U_{in} is the inlet velocity, ν_{air} is the dynamic viscosity of the air and $D_{a,w}$ is the diffusion coefficient of water vapor in air. The following temperature dependent correlation for $D_{a,w}$ was used in this study [17].

$D_{a,w}=c_1+c_2T+c_3T^2$ $m^2\ s^{-1}$ (T in K) (33)

Equilibrium moisture contents for different drying air temperatures and measured initial moisture contents are given in Table 2.

Table 2. Equilibrium and measured initial moisture contents

Intermittent drying period	**T_d (°C)**	**m_e**	**m_{in}**
30 min	40	0.0859	0.24878
	50	0.0748	0.24990
	60	0.0648	0.24020
	70	0.0523	0.24031
60 min	40	0.0859	0.24584
	50	0.0748	0.23980
	60	0.0648	0.24730
	70	0.0523	0.24253

Local and average moisture ratios can be defined as:

$$\mathrm{mr} = \frac{m - m_e}{m_{in} - m_e} \quad (34)$$

$$mr_{ave} = \frac{1}{V}\int mr\, dV \quad (35)$$

3. Results and Discussion

The computational results were obtained by Comsol Multiphysics finite element modeling and simulation software. An iterative solver GMRES (Generalized Minimal Residual) was used. The mesh in the domain is presented in Figure 2 and consists 29233 elements. Mesh dependency has been performed for this study. According to Table 3 and 4, mesh 2 was chosen. Mesh type is free tetrahedral.

Table 3. mr_{ave} values for 30 min. intermittent period, T_d=40°C (b=1150) after 0.5h and 1h

Mesh type	Number of elements	after 0.5h	after 1h
1	6012	0.81848	0.66989
2	29233	0.82816	0.68602
3	96105	0.82949	0.68807

Table 4. mr_{ave} values for 30 min. intermittent period, T_d=50°C (b=1050) after 0.5h and 1h

Mesh type	Number of elements	after 0.5h	after 1h
1	6012	0.78483	0.61594
2	29233	0.79147	0.62644
3	96105	0.79187	0.62752

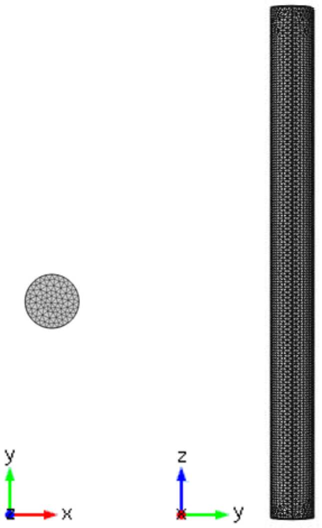
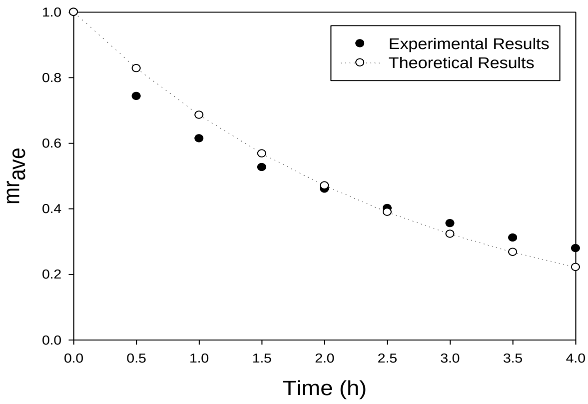


Figure 2. Mesh in the computational domain

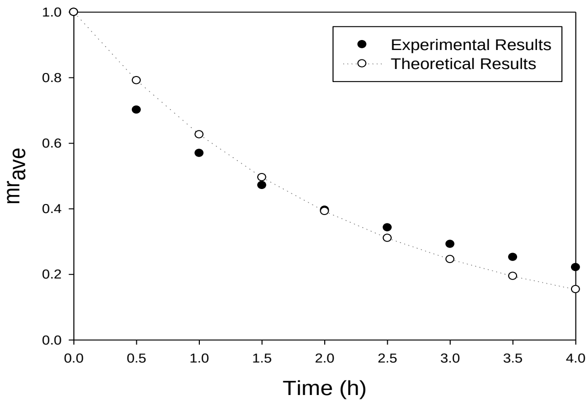
The values of parameter b in the Arrhenius type diffusion coefficient $D=e^{(-b/T)} \cdot 10^{-9}$ m^2 s^{-1} for each intermittent drying condition were obtained iteratively by comparing the experimental and computational moisture ratios. It was performed by taking 50 increments on the parameter b. Increase in parameter b less than 50 gives no significant difference on the drying curves. As the flow inside the channel is turbulent, $k-\varepsilon$ turbulence model was used for the numerical simulation. The $k-\varepsilon$ turbulence model was preferred among other turbulence models due to its good convergence rate and relatively low memory requirements [26].

For all investigated drying conditions, maximum values of wall lift-off in viscous units in the investigated domain were checked. After observing maximum values are 20.8 or 20.9 (less than 100 as mentioned in [26]) we concluded the boundary layer mesh is good enough. This value on the surface of the corn is 11.06. Secondly, wall lift-off (in length units), which is related the assumed thickness of the viscous layer, was checked for all investigated drying conditions. It was observed that this value is considerably small relative to the surrounding dimensions of the geometry and it was concluded the mesh in these regions is good enough (as mentioned in [26]). Analysis for only 0.5 h of drying process with Reynolds number (according to drying channel $Re = \frac{U_{in} 2R_c}{\nu_{air}}$) of 10681.83, took 57 min. 49 sec. in the computer with an Intel (R) Xeon (R) 3.40 GHz CPU. It was observed that when Reynolds number was doubled, 0.5 h of drying process took 1 hour, 19 min, 52 sec. in this computer.

Variation of the average moisture ratio inside the corn for different drying temperatures (T_d=40°C - 70°C) and intermittent periods (t_i=30 min. and t_i=60 min.) is presented in Figure 3 and 4. It is observed that drying rate is higher at the beginning of the drying and decreases when drying proceeds. At the beginning of drying, drying is governed by external resistance as the surface of the corn is moist. As the drying proceeds, moisture transfer becomes internally controlled as the moisture on and near the surface of the corn is removed in the early stage of drying. The moisture inside the corn must be brought towards to the surface from the inner part of the corn to transfer extra moisture to the drying air. During this stage, diffusion is the dominant moisture transfer mechanism. The drying rate takes lower values at this later stage of drying because of slow diffusion mechanism. As drying air temperature increases, drying rate takes higher values as a result of decrease at relative humidity of drying air. As intermittent period increases, drying rate gets higher values as a result of decrease in internal resistance to moisture transfer due to moisture brought to the surface at the intermittent period. As it can be observed from Figure 3 and 4 that, although computational results overestimate the moisture ratio in the early stage of drying and underestimate the moisture ratio in the later stage of drying, overall agreement is reasonably good. It was observed that the most suitable value of parameter b decreases with drying air temperature and intermittent period. Another result obtained from this study is, the same value of the most suitable b parameter was obtained for drying air temperature of 50°C and 60°C for both intermittent drying periods. It is a result of experimental results for 50°C and 60°C drying air temperatures to be close to each other.



T_d=40°C, t_i=30 min. (b=1150)



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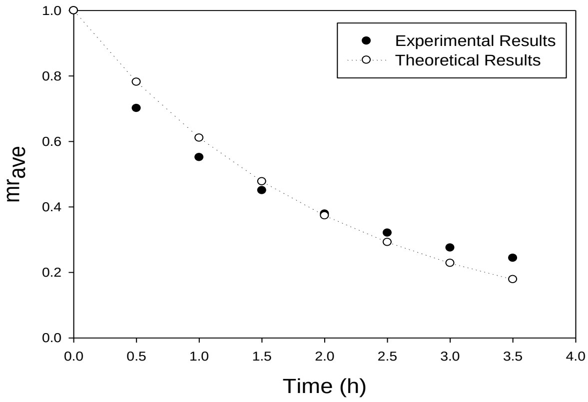
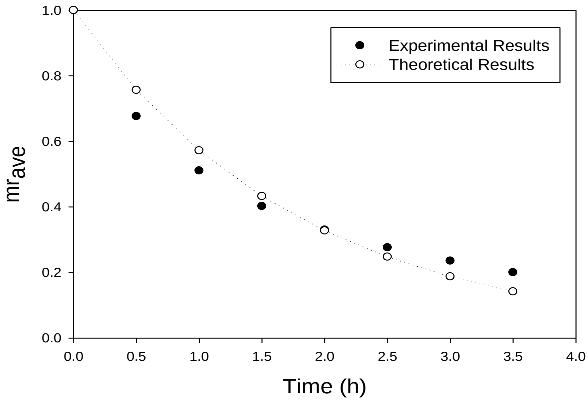
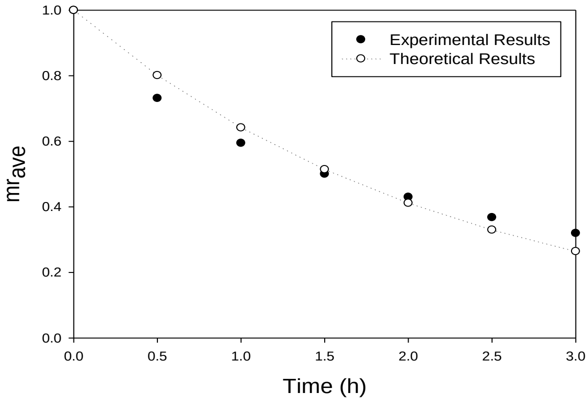


T_d=60°C, t_i=30 min. (b=1050)

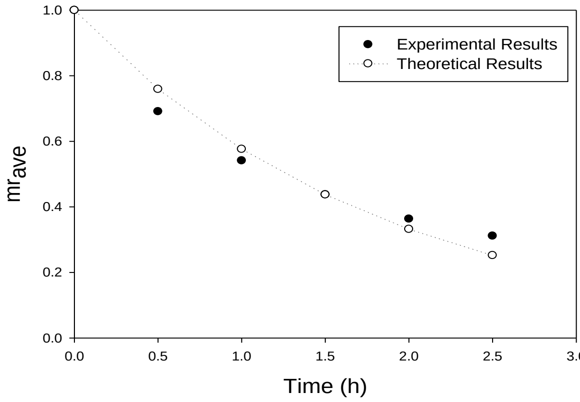


T_d=70°C, t_i=30 min. (b=1000)

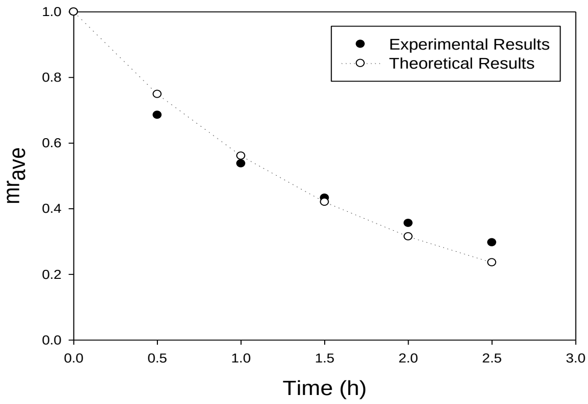
Figure 3. Drying curves for the intermittent period of 30 min.



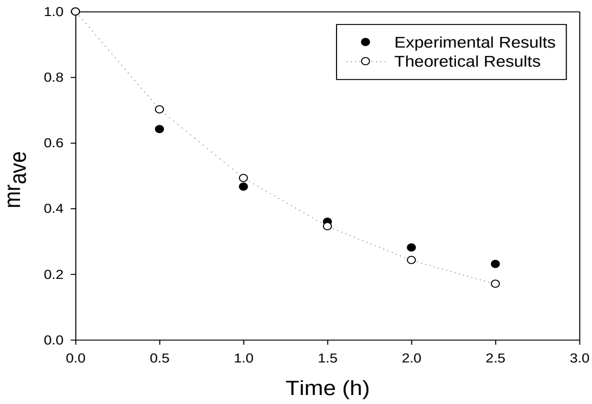
T_d=40°C, t_i=60 min. (b=1050)



T_d=50°C, t_i=60 min. (b=950)



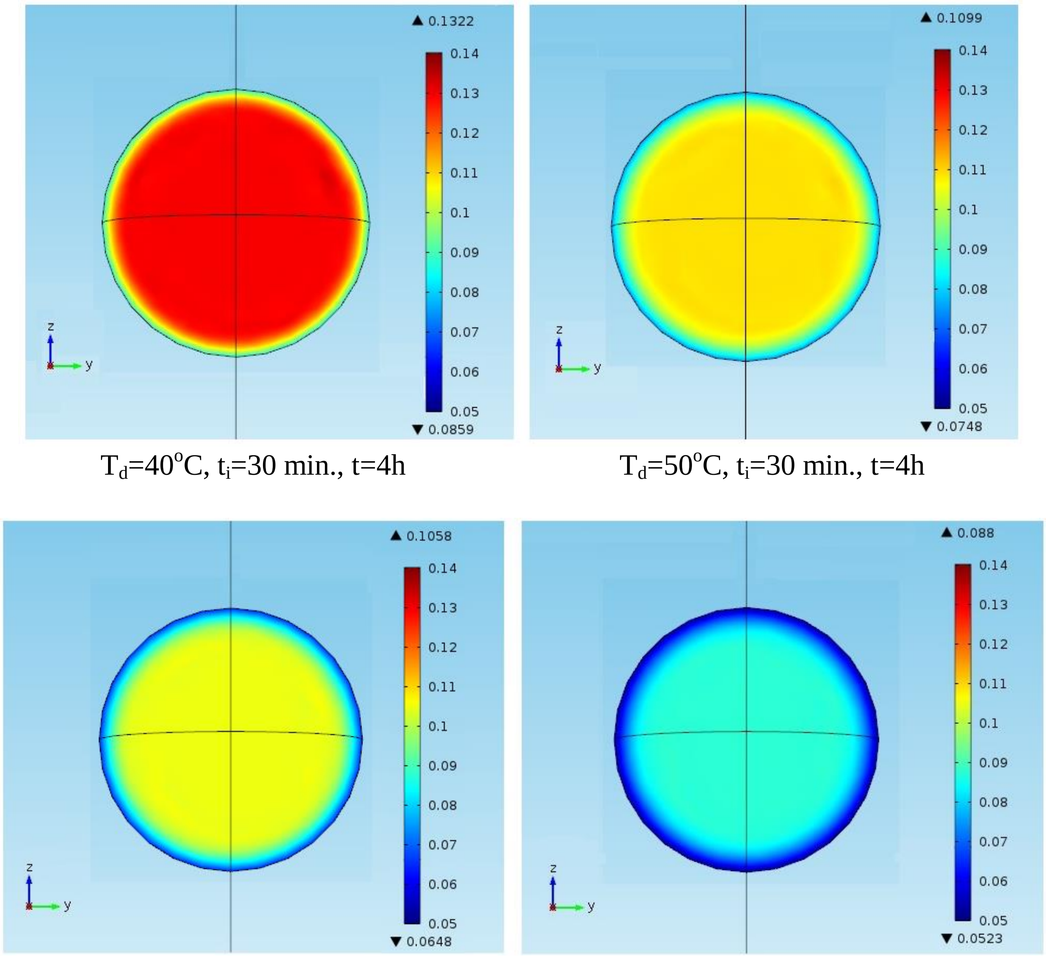
T_d=60°C, t_i=60 min. (b=950)



T_d=70°C, t_i=60 min. (b=850)

Figure 4. Drying curves for the intermittent period of 60 min.

Figure 5 and 6 show the moisture content distribution inside the corn for the intermittent drying period of 30 min. and 60 min., respectively. As the drying air temperature increases, drying shortens as a result of positive effect of decrease in the relative humidity of air on the drying. Increase in the intermittent period also shortens the drying rate considerably as it allows moisture to move to the surface. As it can be seen from Figure 5 and 6, drying decreases the moisture content on and near surface considerably and a tempering period is needed to bring the moisture to the surface.



T_d=40^{o}C, t_i=30 min., t=4h T_d=50^{o}C, t_i=30 min., t=4h

T_d=60^{o}C, t_i=30 min., t=3.5h T_d=70^{o}C, t_i=30 min., t=3.5h

Figure 5. Moisture content inside the corn for intermittent drying period of 30 min.

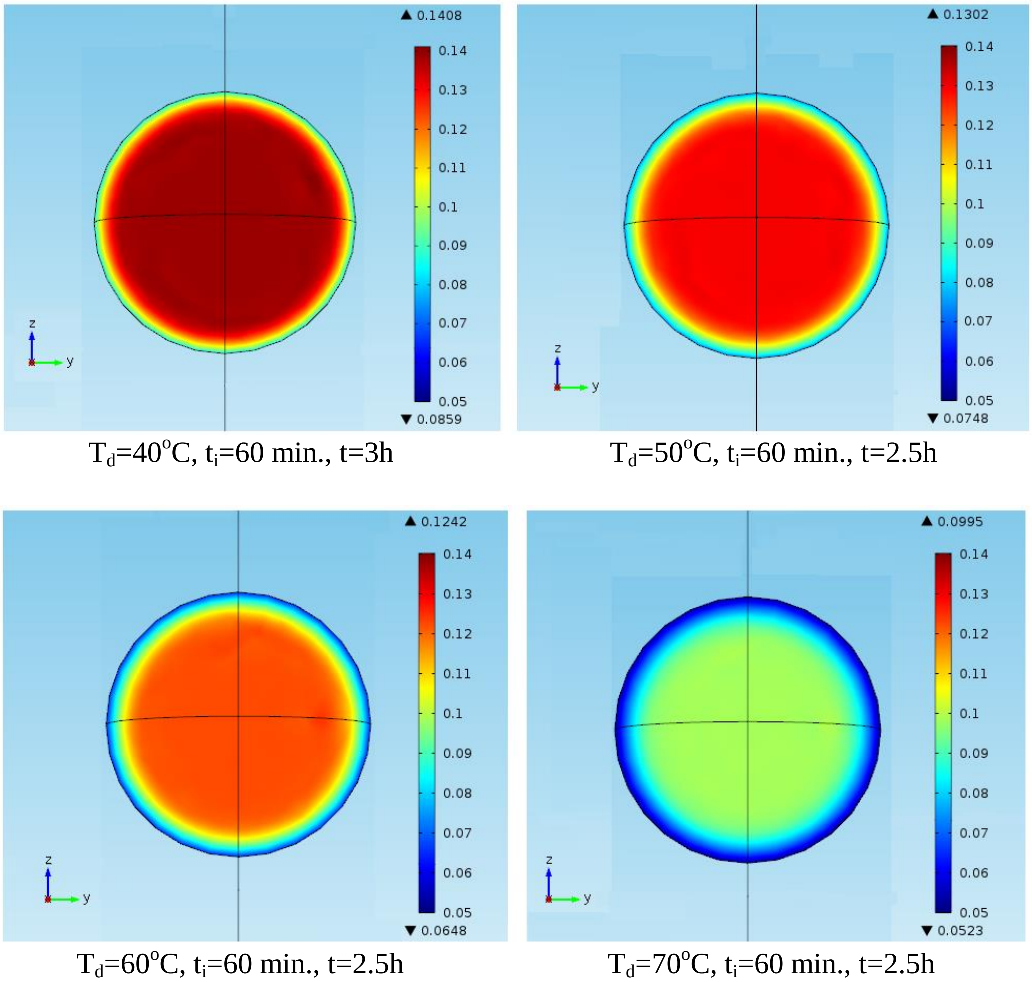


Figure 6. Moisture content inside the corn for intermittent drying period of 60 min.

4. Conclusions

In this study, drying behavior of corn was investigated both numerically and experimentally for drying air temperatures of 40°C, 50°C, 60°C and 70°C and intermittent periods of 30 min. and 60 min. It was observed that drying rate decreases during the drying process due to the internal resistance to moisture transfer. The results also indicate that drying rate increases considerably by an increase in drying air temperature and intermittent period. The most suitable values of the parameter b in the proposed Arrhenius type diffusion equation ($D=e^{(-b/T)} \cdot 10^{-9}$ m^2 s^{-1}) for each drying condition were obtained. It was seen that the most suitable value of the parameter b in the proposed Arrhenius type diffusion equation decreases with drying air temperature and intermittent period due to increased diffusion coefficient. In other words, drying rate increases with temperature and intermittent period. The results also indicate that theoretical moisture ratios during drying show a good agreement with experimental moisture ratios.

Nomenclature

B	empirical constant
b	coefficient in the Arrhenius type diffusion coefficient of moisture inside the corn
c	specific heat [J $kg^{-1}K^{-1}$]
c_1, c_2, c_3	coefficients for the diffusion coefficient of water vapor in air
c_p	specific heat [J $kg^{-1}K^{-1}$]
$C_{\epsilon 1}$	a constant parameter for the $k-\varepsilon$ turbulence model

$C_{\epsilon 2}$	a constant parameter for the $k-\varepsilon$ turbulence model
C_{μ}	a constant parameter for the $k-\varepsilon$ turbulence model
D	diffusion coefficient of the corn [m^2 s^{-1}]
$D_{a,w}$	diffusion coefficient of water vapor in air [m^2 s^{-1}]
d	diameter of the corn [m]
H	height of the drying channel [m]
h_m	mass transfer coefficient [m s^{-1}]
I_T	turbulence intensity
K_v	von Karman constant
k	thermal conductivity [W $m^{-1}K^{-1}$], turbulence kinetic energy [m^2 s^{-2}]
L_T	turbulence length scale [m]
m	moisture content (dry basis)
mr	dimensionless moisture ratio
$\vec{n}$	unit normal vector
P_k	production term [Pa s^{-1}]
p	pressure [Pa]
p_{atm}	atmospheric pressure [Pa]
$\vec{q}$	heat flux [W m^{-2}]
Re	Reynolds number ($=U_{in}\, d/\nu_{air}$), ($= U_{in} 2R_c/\nu_{air}$)
R_c	radius of the drying channel [m]
r, z	r and z coordinate respectively
r_c	radius of the corn [m]
Sc	Schmidt number ($=\nu_{air}/D_{a,w}$)
Sh	Sherwood number ($=h_m\, d/D_{a,w}$)
T	temperature [^oC, K]
T_d	drying air temperature [^oC]
t	time [s]
U_{in}	inlet velocity [m s^{-1}]
u_τ	friction velocity [m s^{-1}]
V	volume [m^3]
$\vec{V}$	velocity vector [m s^{-1}]

Greek Symbols

δ_w	distance from the solid wall (Wall lift-off) [m]
$\delta_w{}^+$	wall lift-off in viscous units
ϵ	dissipation rate of turbulence energy [m^2 s^{-3}]
ρ	density [kg m^{-3}]
σ_ϵ	a constant parameter for the $k-\varepsilon$ turbulence model
σ_k	a constant parameter for the $k-\varepsilon$ turbulence model
μ	dynamic viscosity [Pas]
ν	kinematic viscosity [m^2 s^{-1}]
$\vec{\nabla}$	Nabla operator

Subscripts

1, 2	represent air and corn, respectively
ave	average
e	equilibrium
in	initial
S	surface
T	turbulent

tang tangential

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