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Modelling Mass Transfer during Hot Air Drying of Banana Using Cellular Automaton

Z. Farhaninejad[1], M. Fathi[1*], and M. Shahedi[1]

ABSTRACT

Cellular Automaton (CA) was applied, for the first time, to model mass transfer during the drying process. CA is a discrete model with powerful potential application for simulating complex systems. In this paper, a two-Dimensional (2D) model was applied to simulate drying process of banana slices. The system was designed for a grid with size of 30×90 square cells, four possible states, and von Neumann neighborhoods. The logical trends of the model results were examined by running program for different process conditions such as various temperatures, air relative humidity values, air flow velocities, and sample thicknesses. Validation of the model was performed by comparing estimated and experimental data of banana drying for three temperatures (60, 70, and 80°C). The model showed high accuracy for predicting moisture content (R^2 values higher than 0.99). Notable accuracy based on simple rules to pattern the complexity of the system and flexibility indicated the superior application of cellular automaton for modeling food processes.

Keyword: Discrete model**,** Drying process, Modeling food processes.

INTRODUCTION

Banana (*Musa spp. AAA*) is a perennial fruit that originated in Southeast Asia, while today is grown in every humid tropical region and considered as the fourth most harvested agriculture product after rice, wheat, and maize (Hailu *et al*., 2013). According to FAO, production of banana reached approximately 106 million tons in 2011. Banana popularity comes from its sensory characteristics and high nutritional value (vitamins A and C, potassium, calcium, sodium and magnesium) (da Silva *et al*., 2013). The considerable level of starch and sugar makes it a calorific fruit (Fernandes *et al*., 2006). However, it is perishable due to its high moisture content. The post-harvest loss is approximately 40% of product in the main producer countries (Baini and Langrish, 2007).

The use of preservation methods is necessary for banana to enhance shelf-life or decrease product waste. Drying creates new ranges of products and provides an extension of shelf-life, lighter weight for transportation, and less space for storage by reducing moisture content (Boudhrioua *et al*., 2002; Fernandes *et al*., 2006; Baini *et al*., 2007). Hot air drying is a simple and common method for drying of vegetables or fruits with high moisture content (Orikasa *et al*., 2008).

Kinetic study and modeling knowledge are important to have a good control over the process and food quality (Baini and Langrish, 2008). For on-line state prediction and control operation, mathematical description of temperature and moisture profile during processing is necessary. The dynamics of the food drying process includes simultaneous heat and mass transfer due to the water movement from inside of

[1]Departments of Food Science and Technology, College of Agriculture, Isfahan University of Technology, Isfahan, 84156-83111, Islamic Republic of Iran.
*Corresponding author; e-mail: mfathi@cc.iut.ac.ir

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the moist material towards the surface layer of the material by diffusion and from the interface to the air flow by convection mechanism and conduction of heat to the food sample (Hernandez-Perez *et al*., 2004).

Nowadays, there are two approaches for evaluation of dynamic behaviors of systems: (i) Continuous representation of phenomenon that is illustrated by differential equations, and (ii) Discrete representation of the phenomenon that is illustrated by Cellular-Automaton (CA) approach (Bandman, 1999). Although differential equations simulate the behavior of systems with high precision, they work only for the systems with few independent components and variables. Additionally, with the increase in the degree of freedom and the complexity of systems, the solution of differential equations becomes difficult. Besides, the numerical solutions such as finite difference are disadvantageous for irregular geometry and for finite element, and finite volume methods round-of error is the main limiting factor (Yang and Y., 2005).

Cellular automaton is a rule-based computing machine with a great potential for mathematical modeling of a wide range of complex phenomena by only modest computational resources. In a CA model, both time and space are in discrete form, the structural details and the interactions between the cells are controlled by determining simple local rules. Therefore, often hidden factors underlying a host of complex phenomena could be extracted (Kier *et al*., 2000; Ivanov *et al*., 2011). A simple cellular automation consists of a grid of cells in which the state of a certain cell at a given time depends only on its own state and the states of its local neighbors and a set of deterministic or probabilistic local transition rules that control the behaviors of the cells in the grid. Computation process is iterative, at each step, state changes being performed simultaneously in all cells of the array. CA simulates physical phenomena in more detail than partial deferential equations, because the latter artificially represent continuous phenomenon, while CA is based on Boolean operations which shows the physical phenomena as a discrete system executed with absolute accuracy (Bandman, 1999; Engelbrecht, 2008).

Cellular automaton has been used for describing fat migration in chocolate confectionery by Van der Weeën *et al*. (2012). Ivanov *et al*. (2011) used 3D cellular automata for modeling heat and mass transfer in drying process. Drug release from polymeric devices with erosion and diffusion mechanisms was modeled using cellular automaton by Laaksonen *et al*. (2009). Describing diffusion phenomenon using cellular automaton was performed by Fathi *et al*. (2013) during hesperetin release from nano-carriers and their results showed high accuracy of the developed model.

This study aimed to present a discrete two-dimensional model based on cellular automaton for describing mass transfer phenomenon during banana hot air drying process and to test the capability of the model considering different factors such as temperature, air flow velocity, air relative humidity, and sample thickness.

MATERIALS AND METHODS

Theoretical Section

John von Neumann and Stanislaw Ulam were the first scientists who proposed the concept of cellular automaton (Ulam, 1952; Neumann, 1966). Cellular automaton, as rule-based computing machines, were initially developed to mimic self-reproduction of biological phenomena (Von Neumann, 1951; Yang and Y, 2005). This new mathematical system was then improved by numerous researches, from applying for the principles of well-known "game of life" (Gardner, 1970; Conway *et al*., 1982) to the recent book of Wolfram ' A New Kind of Science' (Wolfram, 2002). Cellular automaton is considered as discrete idealizations of the partial differential equations and used to describe natural

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systems in highly nonlinear regimes (Wolfram, 1998). Cellular automata can capture many essential features of the systems whose basic components are simple but the overall behavior is extremely complex and, therefore, provide some understanding of the basic mechanisms for the complexity. The cellular automaton is a lattice made up of small sites. These sites have discrete values and are in contact with their neighbors. The result of this relationship is to change their values in discrete time intervals.There is a fixed set of rules for controlling relationships between sites that depend on the state of a site and its neighbor states (Wolfram, 1986). Numerous researchers have developed different realizations of the CA paradigm for the study and simulation of a widespread range of physical, biological, chemical, and even sociological phenomena (Kier *et al*., 2000).

To understand cellular automaton modeling, introduction of the following concepts is necessary:

I. A discrete cellular space: It is a d-dimensional lattice composed of N identical cells.

II. Cells: each cell in the lattice is a representative for each component of the system having integer values and one of finite possible discrete states.

III. Neighborhood: The proximate environment of a cell is called its neighborhood. There are two common neighborhoods for a cell, namely, von Neumann and Moore neighborhoods.

IV: Transition rules: Several different types of rules govern the behaviors of ingredients on the grid, and thereby the configuration of system is accordingly updated (Kier *et al*., 2000). Transition rules are defined based on the physics of the problem being modeled (Fathi *et al*., 2012).

To model a system whose behaviors are extremely complex, one must find the relations between the ingredients. In fact, the benefit of CA method is helping to capture the mechanisms by which complexity is produced (Wolfram, 1986). Laaksonen *et al*. (2009) mentioned that the strong point of CA model is freely choosing the geometry of initial conditions and, therefore, simplicity and visual appearance have priority for selection of a suitable configuration.

In this paper, a deterministic 2D CA is used to simulate drying process. Geometry of banana slice is defined as a finite cylinder with axial symmetrical problem (Figure 1). This assumption refers to uniform distribution of heat and mass transfer between the cylinder surface and surroundings over the whole surface. Heat transfer and mass transfer depend on two spatial dimensions. The grid space composed of 30×90 square cells. The identical cells inside the cylinder are assigned as banana samples, while outside of the cylinder is considered as drying air and dryer tray. The length of cell is calculated by dividing diameter of cylinder by the number of banana cells located in R axis. For each discrete time, each cell in the grid has one of the finite states (i.e. wet solid, dry solid, hot air and dryer tray) (Table 1). Each cell was

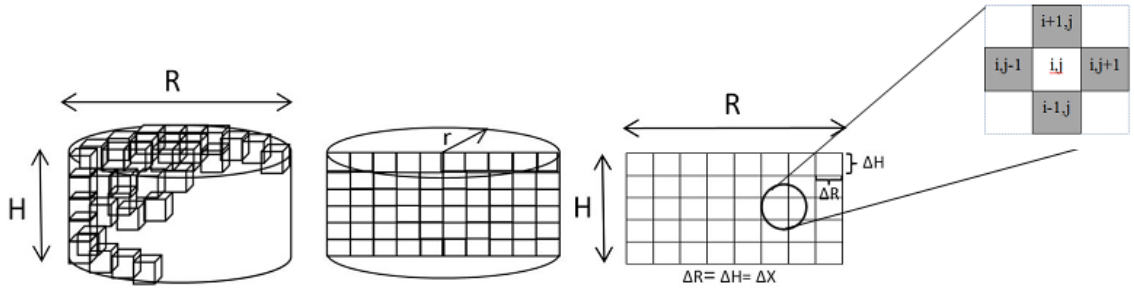

Figure 1. Inverting 3D cylinder to a 2D in case of axial symmetrical problem and Von Neumann neighborhood (Kier *et al*., 2004; Luikov, 1968).

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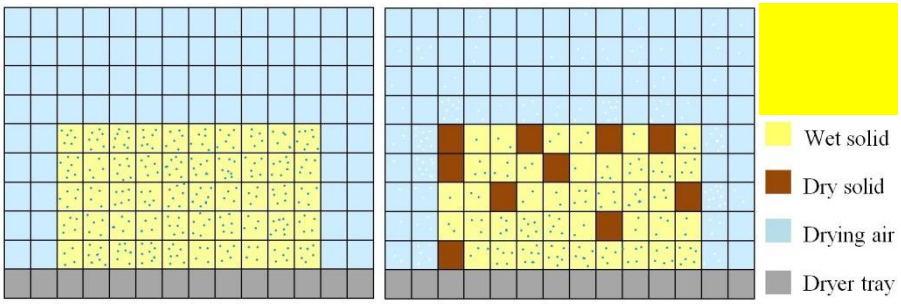
Table 1. States of cells in the grid and local transition rules used to describe the behavior of cellular automata.

Cell state	Symbol	State conversion rules
Wet Solid	WS	Refers to fresh banana pulp. It can be converted to DS cell when it's moisture content decreases to a threshold value.
Dry Solid	DS	Refers to dried banana cells. These cells are not initially exist and are created when a moisture content of WS decrease to a threshold value. These cells can be converted to WS when receive moisture from their wet neighbor.
Hot Air	HA	Refers to located exterior of banana cells and have constant temperature over the process time but their moisture content can change. The highest moisture content which a dryer air cell can receive depends upon saturation humidity at the given temperature.
Dryer Tray	DT	These cells are fixed and just have heat exchange with lower layer of banana cells. Physical properties of these cells are based on aluminum.

connected to four neighboring cells based on von Neumann neighborhood. The behavior of lattice was governed by some local transition rules described in Table 1.

It is notable that there are some restriction rules to control interaction between cells. For example, a target cell (i, j) interacts with neighbor cell (i+1, j) just if the neighbor cell has lower moisture content. This rule is reversed for neighbor cell with (i-1, j) index. These restriction rules help to keep moving up the exhausting and prevent dampening against saturation of drying air cells. After passing of water vapor to the boundaries of the system, water molecules are completely removed based on sink condition assumption (Fathi *et al*., 2012). A schematic representation of banana slice model under initial and next iterations showed in Figure 2.

To model the drying process, it is necessary to define the mechanism and make some assumptions. Drying is a simultaneous heat and mass transfer, and to calculate the rate of moisture loss, the heat quantity and temperature of cells inside the sample should be initially defined. Under the initial condition, it is assumed that heat quantity is distributed uniformly all over the sample cells which have the same temperature (25°C) (Ivanov *et al*., 2011). The heat quantity of target cell ($q_{i,j}^{t}$) at zero iteration was calculated by the



(a) (b)

Figure 2. Schematic representation of CA model consisting of banana slice, drying air and dryer tray: (a) Initial condition, and (b) Next iterations.

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following expression:

$$q_{i,j}^{t} = m_{i,j} \times C_{P_{i,j}} \times T_{i,j}^{t} \quad (1)$$

Where, $T_{i,j}^{t}$ is the cell Temperature (°C), $C_{P_{i,j}}$ is the heat Capacity (J kg^{-1} °C^{-1}), $m_{i,j}$ is the cell mass (kg).

Drying starts with heat transfer of top and lateral surface cells by conduction, convection, and evaporation mechanisms (Equation 2), while for inner cells and cells which are in contact with the dryer tray, conduction phenomena happens (Equation 3).

For each cell, the heat quantity for the next iteration ($q_{i,j}^{t+1}$) was calculated using the following equations:

$$q_{i,j}^{t+1} = q_{i,j}^{t} + \Delta t \times k \times A \times \frac{\Delta T}{\Delta x} + \Delta t \times h_c \times A \times (T_{air} - T_{i,j}) - \Delta t \times A \times k_m \times h_{fg} \times \rho_s \times (\theta_{i,j} - \theta_e) \quad (2)$$

$$q_{i,j}^{t+1} = q_{i,j}^{t} + \Delta t \times k \times A \times \frac{\Delta T}{\Delta x} \quad (3)$$

Where, Δt is duration of each iteration (s), k is thermal conductivity (W m^{-1} ^{o}C^{-1}), A is Area (m^2), Δx is the length of square cells (m), ΔT is Temperature difference between two cells (^{o}C), h_c is convective heat transfer coefficient (W m^{-2} ^{o}C^{-1}), k_m is the convective mass transfer coefficient (m.s^{-1}), h_{fg} is latent heat of vaporization (J kg^{-1}), ρ_s is density of dry matter (kg m^{-3}), $\theta_{i,j}^{t}$ is the moisture content of target cell (i, j) at present time, θ_e is the equilibrium moisture content, and T_{air} is Temperature of the drying air (^{o}C). The cells temperature was calculated by dividing heat quantity by the cell mass and heat capacity.

Thermal conductivity, density, and specific heat are temperature dependent factors and, therefore, were updated for each iteration by the below equations:

$$k = \sum_{i=1}^{n} k_i \times \varepsilon_i + k_{air} \times \varepsilon_{air} \quad (4)$$

$$\varepsilon_i = \frac{\rho_{app} \times x_i}{\rho_i} \quad (5)$$

$$\varepsilon_{air} = 1 - \sum \varepsilon_i \quad (6)$$

$$C_p = \sum_{i=1}^{n} C_{p_i} \times x_i \quad (7)$$

Where, k_i is thermal conductivity of ingredients and k_{air} is thermal conductivity of air, both of which were computed by Choi and Okos Equations (1986) as a function of temperature, ε_i is the volume ratio of ingredients, ε_{air} is the volume ratio of air, ρ_{app} is apparent density (kg m^{-3}), x_i is the mass ratio of ingredients, ρ_i and C_{p_i} are the density and heat capacity of ingredients, respectively, which were also computed by Choi and Okos Equations.

Convective heat transfer coefficient (h) was determined by Equation (6) for a cylinder subjected to cross-flow air (Holman, 2001):

$$Nu_d = \frac{h_c L}{k} = C\,(\mathrm{Re})^n\,\mathrm{Pr}^{1/3} \quad (8)$$

Where, Nu_d is Nusselt number, d is the characteristic length (m), Re is the Reynolds number and Pr is the Prandtl number. C and n are equation constants depending on Reynolds number.

After calculation of heat quantity, the next step was calculation of cells temperature, so the following equation was applied:

$$T_{i,j}^{t+1} = \frac{q_{i,j}^{t+1}}{C_{pi,j} \times m_{i,j}} + T_{i,j}^{t} \quad (9)$$

Similarly, at initial condition, it is assumed that moisture is distributed uniformly all over the sample cells in wet solid state. This amount is calculated by dividing initial moisture content of banana slice to the number of banana cells.

Similar calculation is done for drying air cells based on relative humidity of drying air. To attribute discrete concept for

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moisture concentration, moisture content of each cell was changed to water molecules using Avogadro's number. Therefore, the moisture content of target cell is defined by $\theta^{t}_{i,j}$ which is computed based on Equation (10):

$$\theta^{t}_{i,j} = \frac{\text{banana slice moisture}(g)\times 6.022\times 10^{23}}{\text{banana cells}\times 18(g)} \quad (10)$$

For the next iteration, the mass transfer was performed from top and lateral surfaces, while bottom surface, which was in contact in dryer tray, was considered as an isolate surface. The considered mechanisms for mass transfer from top and lateral surfaces were diffusion and convection (Equation 11), while for inner cells diffusion was the governing phenomenon (Equation 12). The external resistance effect against the internal resistance as well as gravity effect on water molecules moving up was ignored. Therefore, the moisture content of the target cell for the next iteration ($\theta^{t+1}_{i,j}$) was calculated by considering its location and using the following equations:

$$\theta^{t+1}_{i,j} = \theta^{t}_{i,j} + \frac{\Delta t}{\Delta x^{2}}\sum D_{eff}\times(\theta^{t}_{\Gamma} - \theta^{t}_{i,j}) + \Delta t\times A \times k_m \times(\theta^{t}_{air} - \theta^{t}_{i,j}) \quad (11)$$

$$\theta^{t+1}_{i,j} = \theta^{t}_{i,j} + \frac{\Delta t}{\Delta x^{2}}\sum D_{eff}\times(\theta^{t}_{\Gamma} - \theta^{t}_{i,j}) \quad (12)$$

Where, $\theta^{t+1}_{i,j}$ is the moisture content of target cell (i, j) at the next iterations, Γ is the group of neighbors, D is the effective Diffusion coefficient between target and neighbor cell, k_m is convective mass transfer coefficient (m s^{-1}) which was calculated by the following equations for laminar flow:

$$\mathrm{Sh} = \frac{k_m\times d}{D_{eff}} = 0.664\times \mathrm{Re}^{1/2}\times \mathrm{Sc}^{1/3}$$
$$\mathrm{Sc} \geq 0.6 \quad (13)$$

Where, *Sh* is Sherwood number, d is the characteristic length (m) and *Sc* is Schmidt number.

To extract the effective diffusion coefficient, the second Fick's law of diffusion in unsteady-state was used (Equation 14). The following equation describes the mass transfer profile as a function of time for a finite cylinder with diameter of *2r* and thickness of *l* (Luikov, 1968): (see equation14 in the bellow)

Where, *M* (r, z, t) is the Moisture content, *r* is the radius of cylinder (m), *z* is the height of cylinder (m), *t* is the time (s), *D* is the effective diffusion coefficient (m^2 s^{-1}).

The initial condition and boundary conditions are as follows:

$$M(r,z,0) = M_o \quad \text{At t=0} \quad (15)$$

$$M(r,-l,t) = M_e \quad (16)$$

$$M(R,z,t) = M_e \quad (17)$$

$$\frac{\partial M}{\partial t} = 0 \quad \text{At R=0, z=+l; t>0;} \quad (18)$$

Based on above conditions:

$$\mu_m = (2m-1)\frac{\pi}{2} \quad (20); \qquad K_l = \frac{R}{l} \quad (21);$$

$$B_n = \frac{4}{\mu_n^{2}} \quad (22)$$

$$\frac{\partial M(r,z,t)}{\partial t} = -D\left\{\frac{\partial^2 M(r,z,t)}{\partial r^2} + \frac{1}{r}\frac{\partial M(r,z,t)}{\partial r} + \frac{\partial^2 M(r,z,t)}{\partial z^2}\right\}$$
$$\left(t > 0;\quad 0 < r < R;\quad -l < z < +l\right) \quad (14)$$

$$W_{w/s} = \frac{M - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} B_n \times B_m \times \exp[-(\mu_n^{2} + \mu_m^{2}k_l^{2})(\frac{D_{eff}\times t}{R^{2}})] \quad (19)$$

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$$B_m = \frac{2}{\mu_m^2} \quad (23)$$

Where, $W_{w/s}$ is the dimensionless moisture content ratio, M, M_o and Me are Moisture content, initial Moisture content, and equilibrium Moisture content, respectively (kg water kg^{-1} solid), μ_n is the first kind of zero order for Bessel function [$J_o \times (\lambda_n \times R) = 0$].

Thermal dependence of effective diffusion coefficient during process (25-80°C) was estimated by Arrhenius Equation (Nguyen and Price, 2007):

$$D = D_o \times \exp(\frac{-E_a}{R_A \times T}) \quad (24)$$

Where, D_o is a reaction rate constant, E_a is activation Energy (kJ mol^{-1}), R_A is universal gas constant (0.008314 kJ mol^{-1} K^{-1}) and T is the Temperature (K).

After calculation of moisture content of cells, finally, the average moisture content of banana slice at any iteration was computed:

$$\text{Average moisture}^t(g) = \frac{\Sigma \theta_{i,j}^t \times 18(g)}{\textit{Initial weight of banana slice} \times 6.022 \times 10^{23}} \quad (25)$$

Preparation of Samples

Banana fruits were purchased from a local market and stored at 10°C. Prior to drying operation, samples were taken out from refrigerator and hand peeled, then cut into 8 mm thickness using a cutting device designed for this purpose. The initial moisture content of samples was measured by drying at 105°C for 48 hours in an oven (OSK, vs-4, Japan) (79.01%).

Air Drying

Drying process was performed using a laboratory convective dryer which was developed in Department of Biosystems, College of Agriculture, Isfahan University of Technology. The dryer was equipped with a data acquisition system allowing controlling temperature, air velocity, and relative humidity. The air needed for drying was supplied by a centrifugal blower with maximum rotational speed of 2,800 rpm. The air was then heated by 9 electrical elements. To control the temperature of the air entering the drying, a PT100 temperature sensor as a feedback signal, was mounted on the air inlet to the enclosure. The relative humidity of the dry air was also measured by a humidity sensor (SHT15/75 model). Experiments were operated at three temperatures (60, 70 and 80°C) with air velocity of 3.3 m s^{-1}. At each temperature, the relative humidity was measured by the special sensor (6, 4, and 3%, respectively). Banana slices were first weighed and quickly transferred to dryer for 7 hours. Moisture loss was recorded after 0.5, 1, 2, 3, 4, 5, and 7 hours by a digital balance with the accuracy of 0.01 g (Shimadzu, AEU-210, JAPAN).

CA Modeling

CA algorithms were coded on MATLAB (R2011a) and run on FUJITSO PC (Lifebook A series). Calculations were performed on a 30×90 grid with square cells for 70,000 iterations and four states were defined for cells. To validate the described cellular automaton model, the results were compared to experimental data.

Statistical Analysis

Investigating the accuracy of model was performed using statistical indicators, namely, Regression coefficient (R^2) and Residual Predictive Deviation (RPD), which is defined as the ratio of the standard deviation of the reference data to the standard error of predicted data for the population tested (Pink *et al.*, 1998; Sinija and Mishra, 2011).

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RESULTS AND DISCUSSION

To investigate the capability and versatility of the developed cellular automaton model for estimating moisture content in various drying conditions, effects of four main factors including temperature, relative humidity, air flow velocity, and sample thickness were investigated. The model was finally validated by experimental data.

Effect of Drying Air Temperature

Drying air temperature is one of the most important factors that influence drying kinetics during constant and falling rate periods as well as food quality. An increase in drying air temperature lessens the drying time (Ertekin and Yaldiz, 2004). Model was run for three temperatures of 60, 70, and 80°C while relative humidity, air velocity and sample thickness were set constant as 6%, 3.3 m s^{-1}, 8 mm, respectively. As shown in (Figure 3-a), the rate of moisture diffusion increased with temperature increase. This observation is due to the increase of effective diffusion coefficient which was calculated as 4.44×10^{-10}, 6.40×10^{-10} and 8.80×10^{-10} at 60, 70, and 80°C, respectively. Similar results were obtained for convective air drying of thin layer of carrots (Doymaz, 2004) and figs (Babalis and Belessiotis, 2004).

Effect of Air Flow Velocity

Drying time decreases with increase in drying air velocity (Ertekin and Yaldiz 2004). In this study, the model was tested for three air flow velocities (1.3, 2.3, and 3.3 m s^{-1}) while temperature, relative humidity and sample thickness were set constant as 60°C, 6%, and 8 mm, respectively. The selected values for air flow velocity should mention laminar flow that makes Equation (10) usable. Demirel and Turhan (2003) reported that air flow velocity of 3.3 m s^{-1} was high enough to decrease the resistance to the surface moisture transfer and further raising of the air velocity did not affect the drying rate. Results showed very little increase in draying rate with increase of air flow velocity (Figure 3-b). This small increase of drying rate due to the increase of air flow velocity was also observed by Sankat *et al*. (1992) for dehydration of banana in the range of 0.62 to 1.03 m s^{-1} and Maskan *et al*. (2002) for hot air drying of gape leather at 0.86 to 1.82 m s^{-1}. On the contrary, Velić *et al*. (2004) observed significant increase in drying rate during convective drying of apple in the range of 0.64 to 2.75 m s^{-1}. They attributed this result to the increase in convective heat and mass transfer coefficient. Similar results were reported by Ertekin *et al*. (2004) for drying of eggplant.

Effect of Relative Humidity

Air relative humidity is another important factor affecting drying kinetic and food quality. Model was tested against three relative humidity values (6, 20, and 40%) while other parameters were kept constant (at 60°C, air flow velocity of 3.3 m s^{-1} and sample thickness of 8 mm). As (Figure3-c) shows, moisture content decreased with greater slop under lower relative humidity, which could be attributed to increase in driving force. Inazu *et al*. (2002) investigated the effect of air relative humidity (60, 70, and 80%) and temperature (20, 30, and 40°C) on drying kinetics of fresh Japanese noodle. They mentioned that relative humidity could affect the drying rate but less than temperature. They observed that effective diffusion coefficient increased by decrease in air relative humidity.

Effect of Sample Thickness

The effect of sample thickness was also examined by running the model for three sizes at constant temperature, air flow velocity, and relative humidity (60°C, 3.3 m s^{-1} and 6%, respectively). Results are depicted in (Figure 3-d) and show that there

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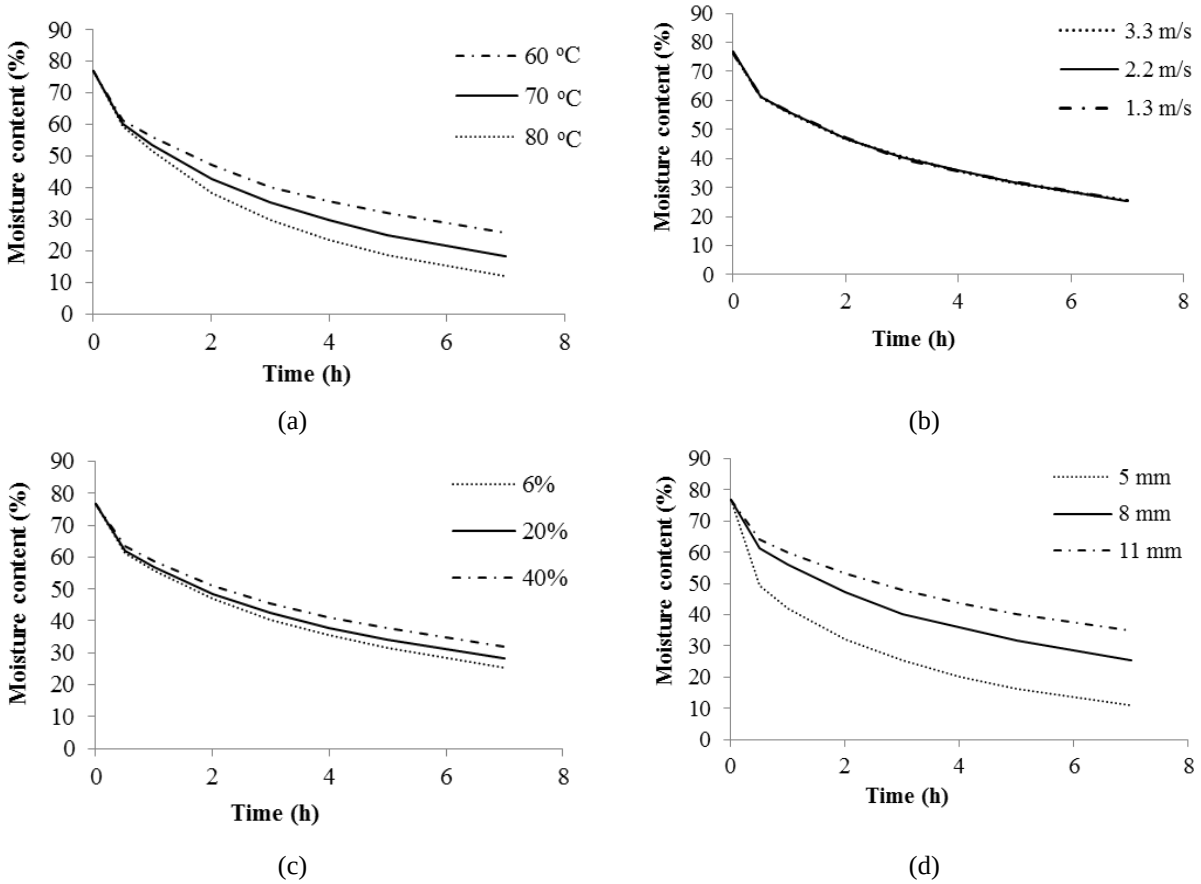

Figure 3. Model results of cellular automata for the effect of (a) drying air temperature (b) air flow velocity (c) relative humidity (d) sample thickness, on moisture content during hot air drying (V= 3.3 m s^{-1}, RH= 6%, Th=8 mm).

is an indirect relation between sample thickness and drying rate which is due to the longer distance that heat and moisture should migrate. Ertekin and Yaldiz (2004) mentioned that the thinner the layer of eggplant, the faster the drying rate, because of less distance for exhausting of water. These results were also in agreement with Maskan (2000) and Azizi and Peyghambarzadeh (2011) for convective hot air drying of banana slices and potato slabs, respectively.

Validation of Model

To validate the developed cellular automaton model, experimental data for three temperatures was compared with estimated data. Figure 4 shows the accordance between experimental and model data. The accuracy of the model was investigated using determination coefficient (R^2) and Residual Predictive Deviation (RPD), which were calculated as 0.9933 and 2.9922 for 60°C, 0.9985 and 2.9213 for 70°C, and 0.9956 and 2.9800 for 80°C. Results exhibited a good correlation between estimated and experimental data. Figure 5 depicts the schematic result of the model in various iterations. By increasing drying time, the dry matter front developed from surface to the central region. At the final step, the number of wet solid cells was equal to the amount of final moisture.

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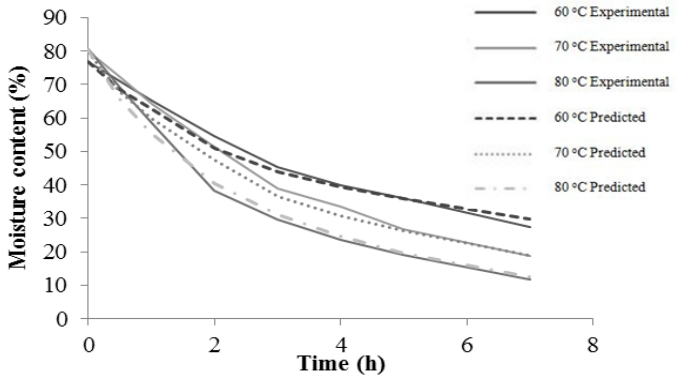

Figure 7. Accordance of predicted and experimental data.

(a) (b) (c) (d)

Figure 8. Schematic representation of moisture profile of cellular automata model during hot air drying of banana slice after: (a) 0 (0 s); (b) 20000 (7200 s); (c) 40000 (14400 s), (d) 70000 (25200 S) iterations. Outer rectangular= Drying chamber; Inner rectangular= Banana slice; Black area= Hot air cells; Dark gray area= Dry banana cells; Gray area= Wet banana cells, White area= Dryer tray cells.

CONCLUSIONS

This study presents Cellular Automaton (CA) application for modeling mass transfer phenomena during hot air drying of banana. CA showed high precision in simulating complex systems. A 2D grid was developed composed of square cells with a size of 30×90, and four possible states were considered for each cell with Von Neumann neighborhoods. The interaction between cells was controlled using local basic transition rules. CA model estimated the average moisture content as a function of temperature, air flow velocity, air relative humidity, and sample thickness. Simulation result revealed that the model can present the expected response to changing the drying conditions. Validation was performed for three temperature conditions and showed acceptable accuracy (R^2 values higher than 0.99). The results of the current research indicate that this model is flexible for simulation of drying process under different conditions. Future trends will focus on designing the model for 3 dimensions, investigating the effect of neighborhood, random collisions between ingredients regarding porous media, and capillary effect.

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مدل‌سازی انتقال جرم طی خشک‌کردن موز با استفاده از اتوماتای سلولی

ز. فرحانی نژاد، م. فتحی، و م. شاهدی

چکیده

برای اولین بار از اتوماتای سلولی جهت مدل‌سازی انتقال جرم طی فرآیند خشک کردن استفاده شد. اتوماتای سلولی یک روش مدلسازی گسسته با پتانسیل کاربردی قوی در شبیه‌سازی سیستم‌های پیچیده است. در این پژوهش از یک اتوماتای سلولی دو بعدی به منظور مدل‌سازی فرآیند خشک کردن برش‌های موز استفاده شد. سیستم در قالب یک شبکه با اندازه ۹۰×۳۰ سلول های مربعی شکل، با چهار حالت ممکن برای هر سلول و آرایش همسایگی ون نیومن طراحی شد. پیش‌روی منطقی مدل در شرایط مختلف فرآیند با تغییر عوامل مؤثر نظیر دمای خشک‌کن، رطوبت نسبی هوای خشک‌کن، سرعت جریان هوا و ضخامت‌های مختلف نمونه آزمایش شد. اعتبارسنجی مدل با مقایسه داده‌های تخمین زده شده توسط مدل و داده‌های تجربی بدست آمده از خشک کردن نمونه در دماهای متفاوت (۶۰، ۷۰ و ۸۰ درجه سانتی‌گراد) بررسی شد. دقت قابل توجهی که از این مدلسازی بدست آمد نتیجه پیاده سازی قوانین ساده‌ای بود که توانست پیچیدگی یک فرآیند را به طور انعطاف‌پذیر شبیه‌سازی کند و این پیامد نشان دهنده برتری کاربرد اتوماتای سلولی در مدل‌سازی فرآیند های غذایی است.

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