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INVESTIGATION OF SHELLED CORN DRYING IN A MICROWAVE ASSISTED FLUIDIZED BED DRYER USING ARTIFICIAL NEURAL NETWORK

ALI ZOMORODIAN[1], LEILA MOMENZADEH[1], DARIUSH MOWLA[2]

[1] A. ZOMORODIAN, Graduate student and associate prof. of Agricultural Engineering Department, Shiraz University, Shiraz, Iran, zomorod@shirazu.ac.ir.
[1] L. MOMENZADEH, leilymomen@yahoo.com.
[2] D. MOWLA, Professor of Chemical Engineering Department, Shiraz University, Shiraz, Iran, dmowla@gmail.com.

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ABSTRACT Drying characteristics of shelled corn (Zea mays.L) with an initial moisture content of 26% dry basis (db) was studied in a fluidized bed dryer assisted by microwave heating at four air temperatures (30, 40, 50 and 60ºC) and six microwave powers (zero, 180, 360, 540, 720 and 900W). Several experiments were conducted to obtain data for sample moisture content versus drying time. The results showed that increasing the drying air temperature resulted in a decrease of at most 5% 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. Furthermore, in the present study, the application of Artificial Neural Network (ANN) for predicting the drying time (output parameter for ANN modeling) was investigated. Microwave power; drying air temperature and grain moisture content were considered as input parameters for the model. An ANN model with 170 neurons was selected for studying the influence of transfer functions and training algorithms. The results revealed that a network with the Tansig (hyperbolic tangent sigmoid) transfer function and trainrp (Resilient back propagation) back propagation algorithm made the most accurate predictions for the shelled corn drying system. The effects of uncertainties in output experimental data and ANN prediction values on root mean square error (RMSE) were studied by introducing small random errors within a range of ±5%.

Keywords: Shelled corn, Fluidized bed, Microwave, Artificial Neural Network.

1) Introduction Moisture removal from agro-industrial plants by thermal drying is an integral part of food processing. In the past, continuous efforts of the food processing industry for producing dehydrated foods have been directed towards enhancing drying rate, reducing energy consumption and minimizing thermal degradation of food constituents. Increasing mass transfer rates with the help of using higher drying air temperature would result in high energy cost (Tripathy and Kumar, 2008).

In fluidized bed dryers, the kernels of drying products are thoroughly mixed and uniformly exposed to drying air. A disadvantage of this technique is the long period of time required especially in the falling rate period (Chen et al., 2001). On the other hand, in microwave drying, the radiation energy penetrates the object during the drying period but the products are not equally exposed to the radiation beam. In this drying method, although the drying duration is short, the particles are not dried uniformly and consequently the product quality is adversely affected by moisture stresses (Abbasi Souraki et al., 2008d). Microwave-assisted fluidized bed drying provides an effective mean to overcome the above mentioned limitations. Microwave energy penetrates the material, facilitating rapid heating and as a result resulting in shorter processing time compared with fluidized bed drying alone. Other advantages include space saving and high energy efficiency as most of the microwave energy is converted to heat in the drying object.

Mathematical modeling of different drying processes has been focused in numerous studies. However, such models are not widely used because of their complexity and long computing times required (Tripathy and Kumar, 2008). In such situations, where the relationship between various variables describing the drying problem is complex and ill-defined, the widely used Artificial Neural Network (ANN) can provide a platform where these problems can be solved with reasonable accuracies and computation times. Extensive studies on the application of ANN in a variety of applications have been published in the literature for modeling and prediction purposes in energy engineering systems (Kalogirou, 2001).

Several studies have been conducted on the experimental investigation and modeling of fluidized bed dryers as well as experimental investigations on microwave heating of food products. This subject has been of special interest in recent years (Abid et al., 1990; Turner and Jolly, 1991; Ormos and Haidu, 1997; Statish and Pydi Setty, 2004; Chen et al., 2001; Jumah, 2005; Romano et al., 2005; Hatamipour and Mowla, 2003a, 2003b and 2006; Abbasi Souraki and Mowla, 2008a and 2008c).

The major objectives of the present study were to study the drying behavior of shelled corn in a microwave-assisted fluidized bed dryer at different microwave energy levels and drying air temperatures and also to develop and evaluate ANN model of this drying configuration to predict the shelled corn drying time based on measures of error deviation from experimental data.

2) Materials and Methods

2.1) Experimental apparatus

An experimental apparatus was designed and implemented. A schematic diagram of this apparatus is presented in figure 1. Shelled corn (*Zea mays.*L) with average initial moisture content of 26% (db) was chosen as the drying material.

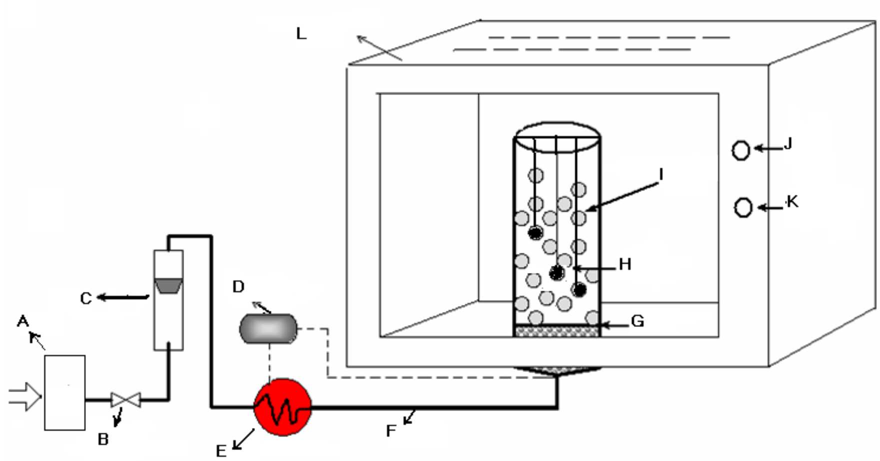


Figure1. Schematic diagram of the experimental apparatus

A: Compressor	G: Air distributor
B: Flow rate regulating valve	H: Drying samples
C: Rota meter	I: Shelled corn
D: Air temperature controller	J: Timer
E: Electrical heating	K: Microwave power controller
F: Air duct	L: Microwave oven

A cylindrical Pyrex column of 90 mm diameter (100 mm outside diameter) and 280 mm height was used as the fluidized bed dryer chamber. The chamber was placed in a domestic microwave oven (LG, MC-2003TR(S)) with the frequency of 2450 MHz and approximate cavity volume of 0.075 m^3 (outside dimensions of 574 mm × 376 mm × 505 mm). This oven was equipped with 5 power level settings of Low (180W), Medium low (360W), Medium (540W), Medium high (720W) and High (900W). Since the cylinder diameter to height was greater than 10, the wall effect was negligible. A porous plate was placed at the bottom of the cylinder to act as air distributor. High pressure drying air was introduced at the bottom of the Pyrex column with a constant flow rate (650 lit/min) to maintain the fluidization condition in the chamber. An air compressor (type: TCS-SCLL, 7 bar pressure, 15 hp) was employed to supply high pressure and constant air flow rate. Air flow rates were measured by a rotameter with an accuracy of ±10 l/min. An electrical heating unit equipped with a thermostat (±1^o C) was provided to maintain different levels of drying air temperature of 30, 40, 50 and 60^o C.

2.2) Experimental procedure

A bulk of shelled corn was dried in the fluidized bed chamber. In this bed, three kernels of shelled corn were randomly marked in the bulk and were hung over the bed using very thin strings (Figure 1). These kernels were thoroughly mixed in the fluidized bed and could be easily traced for any moisture content reductions during the drying processes. All experiments were carried out in triplicates. Sample weighing was undertaken no longer than 10 seconds using an electrical balance (MW-15Ot, max weighing capacity of 150g, ±0.005g accuracy). The accuracy of this method for generating reproducible drying curves has been demonstrated by previous studies (Zhou *et al*. (1998); (Ajibola, 1989)).

Several sets of experiment were conducted to obtain data for drying sample moisture contents versus time. At the end of each drying period, when the moisture content of the shelled corn reached the equilibrium stage (no appreciable changes in three successive samples' weighing), the exit air temperature profile remained at a nearly constant level. This temperature leveling phenomenon showed that in this stage of drying, the absorbed energy was balanced by the surface convective cooling and represented the end of the drying process.

2.3) Artificial Neural Network modeling (ANN)

Artificial Neural Networks have been successfully used in the prediction and optimization problems in bioprocess and chemical engineering. ANN has been developed as a generalization of mathematical models of human cognition and neural biology (Satish and Pydi Setty, 2004).

In this technique, the available data set was divided into two parts; one used to train the network and the other used to validate the model. The network consists of an input layer, an output layer and a number of hidden layers. At each node in a layer the information is received, stored, processed and communicated further to nodes in the next layer. All the weights are initialized to small random numeric values at the beginning of training. These weights are updated or modified iteratively using the generalized delta rule or the steepest-gradient descent principle. The training process converges when no considerable change is observed in the values associated with the connection links or when a termination criterion is satisfied (Erenturk and Erenturk, 2007).

In this study, the ANN model was trained using 120 randomly selected data points and the remaining 30 data points were utilized to test network performance. MATLAB 7.0 was used for training and testing of neural network.

The methodology used for the assessment of network performance involves obtaining the minimum statistical measures of error between experimental and predicted transient time predicted by the model. In this study, statistical parameters namely, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Standard Error (SE) and correlation coefficient (R^2) represented by equations 1 to 4 were computed to check the performance of the developed model (Tripathy and Kumar, 2008).

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|\overline{T}_{p,\exp,i} - \overline{T}_{p,cal.ir}|$$

(1)

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(\overline{T}_{p,\exp,i} - \overline{T}_{p,cal.i})^2\right]^{1/2}$$

(2)

$$SE = \frac{\sqrt{\sum_{i=1}^{N}(T_{p,\exp,i} - T_{p,cal.ir})^2}}{N-1}$$

(3)

$$R^2 = \sqrt{\frac{\sum_{i=1}^{N}(T_{p,\exp,i} - \overline{T}_{p,\exp,i})^2 - \sum_{i=1}^{N}(T_{p,\exp} - T_{p,cal,i})^2}{\sum_{i=1}^{N}(T_{p,\exp,i} - \overline{T}_{p,\exp,i})^2}}$$

(4)

In order to obtain the optimum number of neurons in the hidden layer for each of sample geometry, the ANN model was trained with varying numbers of neurons and randomly chosen Tansig transfer functions and Trainrp algorithm. The maximum neurons studied were 250, starting with a minimum of 1 neuron and then increasing the network size in steps by adding a neuron each time. Errors increased rapidly when the number of neurons was less than 100. The predictions were highly sensitive to the number of neurons. In addition, based on error analysis results, it was found that the ANN model was not very sensitive until 200 numbers of neurons for samples and the lowest error was obtained with 170 hidden neurons. The values of error were essentially constant between 170 and 200 neurons. Thus the ANN model with 170 neurons was selected for studying the influence of transfer functions and training algorithms on model prediction capability.

Microwave power (6 levels), drying air temperature (4 levels) and grain moisture content in each time were chosen as input layers and the appropriate drying time in each step was set as the output layer. Figure 2 depicts the schematic structure of the applied neural network, with its three inputs and single output. There is no feedback from the output to the inputs. In the hidden layer, 170 hidden neurons were used. The classical back-propagation algorithm was used to train the network. Furthermore, a logarithmic Tansig activation function was applied and mathematical definition of the transfer function was trainrp.

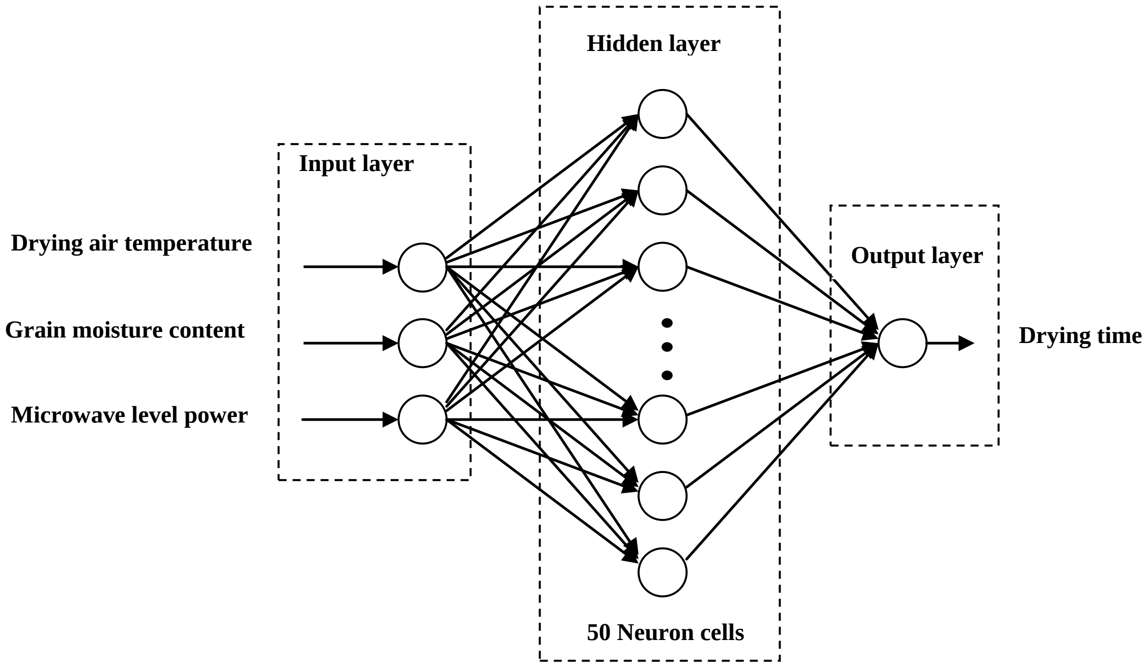


Figure 2. Selected artificial neural network structure

3) Results and Analysis In order to show the effects of various drying parameters on drying time of shelled corn, the drying processes continued until the final moisture content of the grain reached to a safe moisture content of 12.5% (d.b). The temperature in the drying chamber increased quickly in initial stages of drying since microwave heating was more efficient in higher moisture content of the sample. The drying process was terminated when the dry bulb temperature of exit air was nearly equal to the drying air temperature.

The effects of air temperature and microwave power on shelled corn drying time were studied in four levels of air temperature (30, 40, 50 and 60º C) and six levels of microwave power (0, 180, 360, 540, 720 and 900 W). MSTAT-C (version 2.10) statistical package was used for statistical analysis and the results were presented in table 1.

Table 1 Statistical design used in this analysis.

Variables	Sum of squares	Degree of freedom	F value
Air drying temperature (A)	5918.4	3	187.7**
Microwave power levels (B)	84262.8	5	1535.2**
A×B	5661.65	15	34.5**
Error	74.7	69	

** Significant at p=0.01

3.1) Effect of drying air temperature and microwave power on drying time:

Figures 4 and 5 show the variations of sample moisture content in fluidized bed and microwave-assisted fluidized bed dryers respectively. As expected, increasing the air temperature resulted in increase in the drying rate. This effect can be attributed to the controlling rate of water vapor transfer inside the drying sample due to moisture diffusion towards the surface. Therefore, the water vapor concentration on outer surface of the drying object reached the equilibrium conditions more rapidly at higher drying air temperature. Similar results were reported by other researchers (Feng et al., 2001 for drying of apple, Sanga et al., 2002 for drying of carrot, Jumah, 2005 for drying of corn and Abbasi Souraki and Mowla 2008b for drying of green beans). The combined effect of microwave power and drying air temperature on drying time are showed in figure 5. The results indicated that by increasing the drying air temperature and using microwave energy power as an assisting heat source, the values of drying rate or moisture diffusivity were increased. This increase can be due to the penetration of microwave energy into the sample and also due to the creation of a large vapor pressure difference between center and surface of grain. Similar results were reported by other researchers (Abbasi Souraki and Mowla, 2008c).

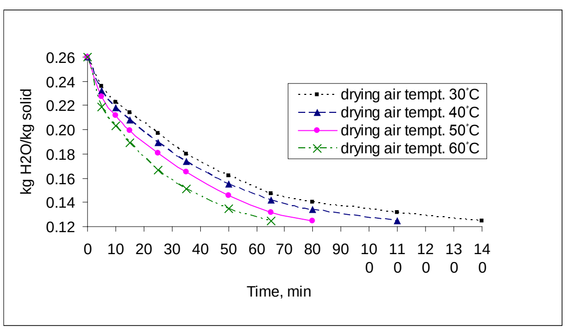
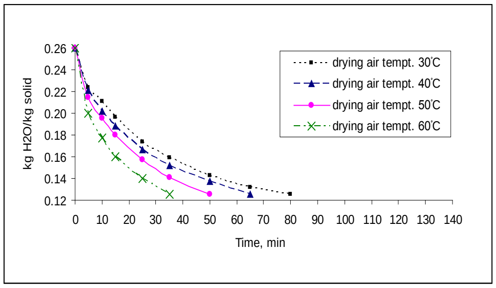
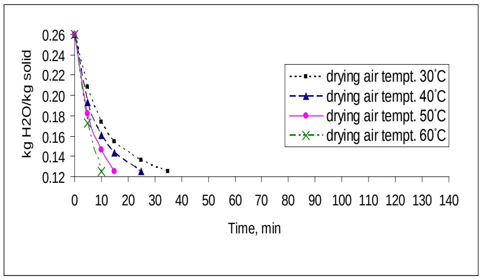


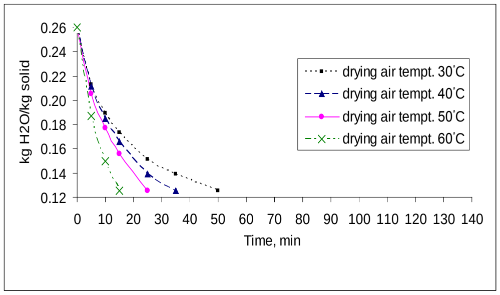
Figure 4 Effect of drying air temperature on drying time of shelled corn without microwave radiation energy


kg H2O/kg solid
Time, min
drying air tempt. 30°C
drying air tempt. 40°C
drying air tempt. 50°C
drying air tempt. 60°C

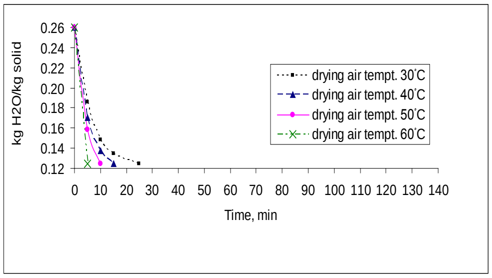
(a)


kg H2O/kg solid
Time, min
drying air tempt. 30°C
drying air tempt. 40°C
drying air tempt. 50°C
drying air tempt. 60°C

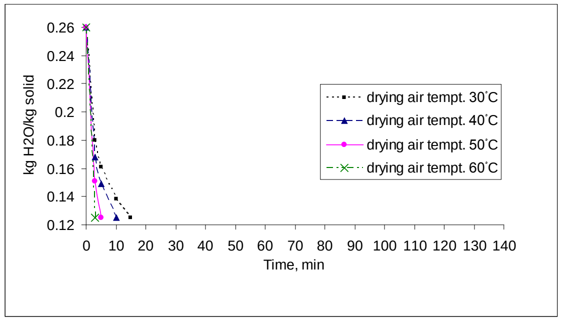
(c)


kg H2O/kg solid
Time, min
drying air tempt. 30°C
drying air tempt. 40°C
drying air tempt. 50°C
drying air tempt. 60°C

(b)


kg H2O/kg solid
Time, min
drying air tempt. 30°C
drying air tempt. 40°C
drying air tempt. 50°C
drying air tempt. 60°C

(d)



(e)

Figure 5 Effect of drying air temperature on drying time of shelled corn at different microwave power (a: 180, b: 360, c: 540, d: 720 and e: 900W) levels.

The results showed that increasing the drying air temperature (30^{o}C to 60^{o}C) resulted in up to 5% decrease in drying time while increasing the microwave energy level (180 W to 900W) in the microwave-assisted fluidized bed system, the drying time decreased dramatically up to 50%. The results of this investigation were illustrated in Table 2. The present work showed a very good agreement with the work of (Abbasi Souraki and Mowla 2008b).

Table 2 . Drying time reduction at different microwave energies and drying air temperatures with respect to zero microwave power**.**

Air drying temperature	**Microwave power W**	**% of decrease in drying time**	**Air drying temperature**	**Microwave power W**	**% of decrease in drying time**
30º C Average time reduction=47%	180	42	50º C Average time reduction=49%	180	44
	360	64		360	69
	540	75		540	81
	720	82		720	87
	900	89		900	93
40º C Average time reduction=48%	180	43	60º C Average time reduction=50%	180	46
	360	68		360	76
	540	77		540	84
	720	86		720	92
	900	91		900	96

3.2) Sensitive analysis in ANN prediction

The data set was first normalized and then divided into two parts; one used for training the network and the other for validation. The training phase was carried out until an optimal architecture was attained. Network performance was evaluated by plotting the ANN model output against the testing data and analyzing the percentage error between the predicted and desired values (experimental data). A comparison between the experimental moisture content versus predicted moisture content by ANN is shown in figure 6.

The effect of uncertainty in output experimental and ANN prediction values on root mean square error (RMSE) was studied by introducing small random errors within a range of ±5% (Tripathy and Kumar, 2008). Table 3 represents the results of sensitivity analysis on shelled corn experimental data. It can be seen that the ANN prediction results have a very strong dependence on input parameters. The present work was consistent with the works of Satish and Pydi Setty, 2004 and Tripathy and Kumar, 2008.

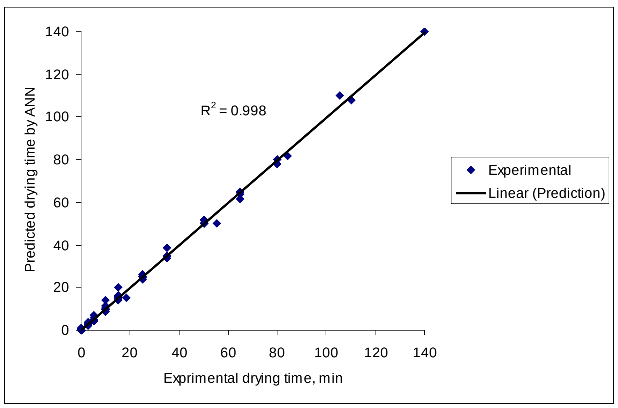


Figure 6 Comparing the experimental moisture content vs. prediction moisture content by ANN

Table 3 Results of measures of error in drying time prediction results of ANN model considering Tansig transfer function and trainrp algorithm for 170 neurons.

Source of error	**Measures of error**
Mean absolute error (MAE)	0.018
Root mean square error (RMSE)	0.104
Standard error (SE)	0.105
Mean square error (MSE)	0.010
Correlation coefficient (R^2)	0.998

Conclusions:

Considering the results obtained in this work, the following conclusions can be drawn:

1) Increase in drying air temperature caused up to 5% decrease in drying time.

2) In the microwave assisted fluidized bed system, the drying time decreased dramatically up to 50%. Therefore, addition of microwave energy to the fluidized bed drying is recommended to enhance the drying rate of shelled corn.

3) Based on error analysis results, it was found that the neural network with 170 neurons and Tansig transfer function with trainrp back propagation algorithm was the most appropriate ANN configuration for drying time prediction purposes.

Nomenclature

MAE	Mean absolute error
N	Exponent
N	Number of observations
R^2	Correlation coefficient
RMSE	Root mean square error
SE	Standard error
$T_{p, exp, i}$	Average experimental drying time for the ith observation
$T_{p, cal, i}$	Calculated drying time for the ith observation

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