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DETERMINING THE INFLUENCE OF DRYING CONDITIONS ON EHD DRYING PROCESS

Mohammad Jafar Dalvand, Seyed Saeid Mohtasebi and Shahin Rafiee
Department of Agricultural Machinery, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran
E-Mail: Dalvand@ut.ac.ir

ABSTRACT

Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. The influence of drying condition on the drying rate of ElectroHydroDynamic (EHD) has been experimentally evaluated in this study. Sample weight and moisture content were measured during drying and drying curves were obtained for each experimental data. The moisture content data were performed using linear and non-linear regression analysis by SPSS (Vers. 15, SPSS, Inc., Chicago, Ill.) computer program to estimate a suitable model, and the models were compared based on their determination coefficient (R^2), the root meat square error (RMSE). The cubic and exponential models were found to satisfactorily describe the drying rate of kiwi fruit with its moisture content. Based on the results, when the applied voltage is not changed, the drying rate is changed with field strength, Moreover when the field strength is not changed; the drying rate is changed with applied voltage.

Keywords: electrohydrodynamic drying process, heat transfer, field strength, applied voltage, drying rate, kiwi fruit.

Nomenclature

E	Electric field strength (kV/cm)
V	Electric voltage (V)
∇	Vector gradient operator
ρ_e	Space charge density ($C\times m^{-3}$)
ρ_g	Mass density of air ($kg\times m^{-3}$)
ν	Ionic wind velocity ($m\times s^{-1}$)
ε_0	Permittivity of free space ($F\times m^{-1}$)
d	Gap between food surface and electrode (m)
M	Moisture content (kg water/kg dry matter)
k	Relative dielectric constant
F	Volumetric force ($N\times m^{-3}$)
t	Duration of experiment
MR	Moisture ratio (kg water/kg dry matter)
M_o	Initial moisture content (kg water/kg dry matter)
M_e	Equilibrium moisture content (kg water/kg dry matter)

INTRODUCTION

It is well known that when air flows over a body of water, a thin layer of relatively inert air exists on the surface of water. This saturated air layer interferes with diffusion of water molecules from water surface to the bulk air flow. As the air velocity over the surface reduces thickness of saturated air layer increases and evaporation rate degrades, so any method which can disturb this boundary layer might improve evaporation rate [1]. Applying ElectroHydroDynamic (EHD) can enhance water evaporation substantially with producing a secondary air flow called corona wind. To practice this, a high voltage is applied between two electrodes. In this method, moist material is placed on the surface of a flat electrode. Corona wind impinges the surface of the material and disturbs the saturated air layer which leads to evaporation enhancement [1-2]. Electrohydrodynamic (EHD) drying is a relatively new, non-thermal drying technique. It utilizes the secondary flow induced by a high-intensity electric field [3].

The dehydration of food is an industrially critical processing step that is often necessary to produce a stable, saleable product and which, if it be incomplete, can render the product inedible and useless. However for many processes, the final post-production dehydration is inefficiently managed for fear of perceived risks such as flavor degradation, surface tarnishing or formation of an internal moisture gradient. Novel drying methods that do not affect the properties of a product and have no negative economic impact on a process are therefore of potential industrial interest [4].

At present, the conventional drying processes of agricultural products are sun drying and hot air drying. The latter often causes heat damage and adversely affects texture, color, flavor, and the nutritional value of dried products. Since the material to be dried only absorbs a fraction of the energy conveyed by air or generated by heat exchanger, these techniques are normally low in the efficiency of energy utilization [5]. Sun drying does not need special equipment and technology, and neither does it incur high expenses. However, it has some problems related to the contamination with dust, sol, sand particles and insects [6], and its drying conditions are difficult to be controlled. As a result, the product quality is often poor [7]. In response to the disadvantages of conventional drying processes, there is now a growing interest in non-thermal processing of food and similar materials [8-9].

MATERIALS AND METHODS

Materials

Kiwi fruit (cv. *Hayward*) were used for all the experiments which were obtained from the Seed and Plant Breeding and Improvement, Karaj, Iran (Longitude: 51^{o}21'N, Latitude: 36o12'E). Initial moisture content of samples was determined using oven method based on ASAE standard [11] and obtained as 84% w.b.

Theoretical considerations of EHD

Mainly due to the interactions of the numerous charges in a strong electric field, a detailed mathematical description of EHD drying is highly complex, Moreover, the presence of liquid water and dry matter in the material being dried makes theoretical treatment even more complex due to the different dielectric properties of the liquid and solid states. It is well known that there are three body forces acting on a dielectric medium in an electrostatic field with following equation [1]:

$$F = \rho_e E + \frac{\varepsilon_0}{2}\left[\nabla(E^2 \rho_g \frac{dk}{d\rho_g}) - E^2 \nabla k\right] \qquad (1)$$

The first term is the Coulomb force, which results from an interaction between the free charges and the imposed electric field. The second and third terms represent the polarization forces, which are created when pairs of charges transmit the electric force to the medium. Specifically, the second term results from a non-uniformity of the dielectric constant and the third term is the electrostrictive force resulting from a non-uniform electric field and a variation in the density of the medium. For EHD-enhanced water evaporation, the Coulomb force remains the main driving force and the polarization forces have a small but not necessarily negligible effect on the results [12]. EHD drying depends on the strength of the ionic wind, which impinges on the material being dried and produces turbulent, vortex-like motions and enhances the mass transfer rates of the liquid and volatile components. Thus, EHD drying results from a conversion of electrical to mechanical energy. The relationship between the ionic wind velocity and the electric field was derived by Goodenough *et al*. as follows [4]:

$$v = (\frac{\varepsilon_0}{\rho_g})^{\frac{1}{2}} E \qquad (2)$$

Experimental setup

The experimental setup, shown in Figure-1, consisted of a direct current at high voltage was applied to the electrode from a power supply. This power supply (Design and manufacture in laboratory) has a maximum output voltage of 30 kV for both polarities. However, for the present study, only positive polarity was utilized. The accuracy of the power supply is 100 V for voltage and 0.002 mA for current. In this point-to-plane configuration, needles (0.1 mm in point diameter) were made of stainless steel and were connected to the high voltage source, vertically above the center of plane (25cm×28cm) which was used as an electrically earthed reception plane. The distance between the cathode and the anode is adjustable between 0 to 8 cm. Electric field was applied to the samples by adjusting the voltage and the electrode spacing.

Temperature measurement

The ranges for temperature and humidity measurement instrument are -40 to 125 ºC and 0 to 100% RH (non-condensing), respectively. The accuracy for the temperature measurement is 0.3 at 25 ºC. The accuracy for the humidity measurement is 2% over 10 to 90% RH at 25 ºC. The resolution for the temperature measurement is 0.01 ºC and for the humidity measurement is 0.03% RH. Infrared thermometer applied for measurement of sample surface temperature. The measurement resolution is 0.01 ºC and range for measurement is -70 to 380 ºC.

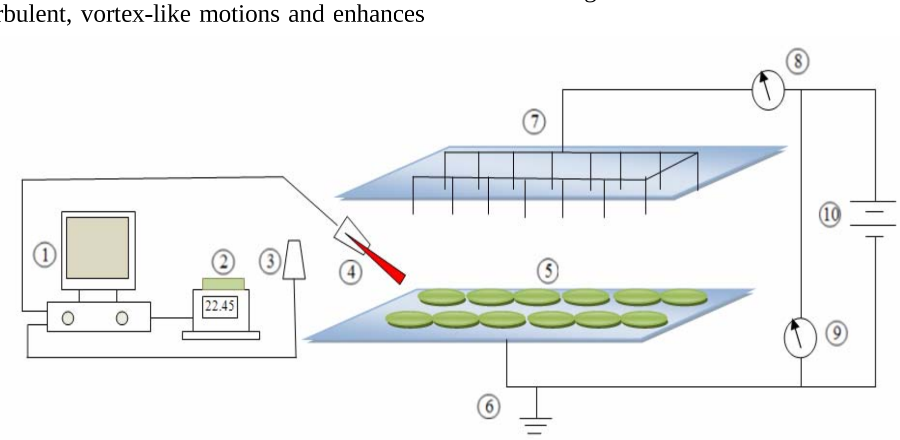

Figure-1. Schematic of the experimental setup.

1. Computer, 2. Digital balance, 3. Humidity/ Temperature sensor, 4. Infrared thermometer, 5. Kiwi samples, 6. Grounded electrode, 7. Discharge electrode, 8. Ammeter, 9. Voltmeter, 10. High voltage power supply.

Determination of moisture

The slice of samples with diameters of 3.5-5 cm was placed on the plane electrode (Figure-1).

To measure the weight loss of water with time (i.e., the drying rate), a digital balances manufactured by AND Corporation were used. The capacity for these digital balances is 0 to 1000 g and 0 to 3000 g (dual ranges) and the readability for these ranges are 0.01 g and 0.1 g, respectively.

METHODS

The initial weight of the samples was taken and samples were prepared for drying. The Ambient conditions in the laboratory during EHD drying were 24 ºC and 20.8% relative humidity. Moisture ratio (MR) of kiwi during drying experiments was calculated using the following Equation [13-14]:

$$MR = (M - M_e)/(M_o - M_e) \quad (3)$$

where M, M_o, and M_e are moisture content at any drying time, initial moisture content and equilibrium moisture content (kg water/kg dry matter), respectively. The values of M_e are relatively small compared to those of M or M_o, hence the error involved in the simplification is negligible [15].The drying rate (DR) of kiwi fruit during drying experiments was calculated using following equation [16]:

$$DR = (M_{t+dt} - M_t)/dt \quad (4)$$

Where M_{t+dt} is moisture content at time t+dt (kg water/ kg dry mater), M_t is moisture content at time t (kg water/ kg dry mater) and dt is drying time (min).

EHD drying experiments were performed at voltages of 6, 10.5, and 15 kV and with field strength of 4.5 kV/cm. The samples were exposed continuously to drying during all experiments; weight was measured at 10 min intervals. Each set of measurements was completed in less than 30 second. Over the entire experiment period, the change of ambient temperature was minimal since the lab was under well temperature control. However, the change in humidity in some cases was substantial, which might have contributed to the scattering of data that reported in the following discussion.

For describing the drying rate curve of kiwi fruit with different factors six different mathematical models (Table-1) were applied to find the best suited model. The linear and non-linear regression analysis was performed using SPSS (Vers. 15, SPSS, Inc., Chicago, Ill.)) Computer program for selecting the best model to describe drying curves for kiwi fruit. The goodness of fit on model was checked via the determination coefficient (R^2) and the root mean square error (RMSE). The higher the values of R^2 and the lower the values of RMSE is indicated better goodness of the fit.

Table-1. Mathematical model applied for drying curves.

Model	Equation
Exponential	$y=ae^{bx}$
Linear	$y=a+bx$
Quadratic	$y=a+bx+cx^2$
Cubic	$y= a+bx+cx^2+dx^3$
power	$y=ax^b$

RESULTS AND DISCUSIONS

Effect of ambient temperature on moisture content

Figure-2 presents the variations of moisture content versus ambient temperatures being dried with EHD system. It is clear from Figure-2 that the moisture content decreased slower at a lower ambient temperature. The experimental data of moisture content obtained at different ambient temperature were predicted by linear and non-linear regression analysis according to Table-2

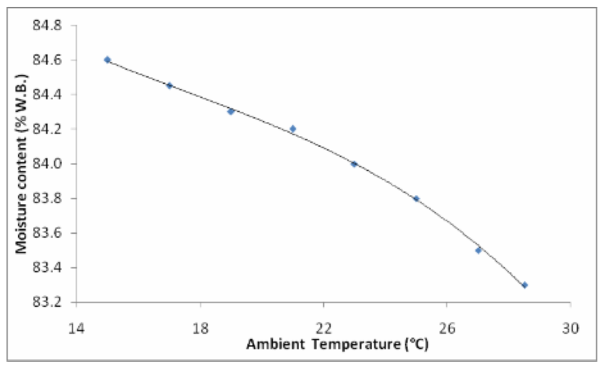

Figure-2. Trend line of moisture content versus different ambient temperature.

As seen in Table-2 cubic equation was found is the best descriptive model: where y is the moisture content of kiwi fruit in %, x is the ambient temperature in °C. In this case, the value of R^2 (0.998) meant that only 0.2% of the variability in the responses was not explained by the model. A lower root mean square error (RMSE=0.012) indicated a good agreement between the experimental and predicted values of the moisture content of kiwi fruit, thus suggesting a high significance for the model. Bai *et al*., reported similar data, and for moisture content predication of Spanish mackerel based on ambient temperature suggested a quadratic model [17].

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Table-2. Fitting model applied for initial moisture of samples.

Model	Equation	R^2	RMSE
Exponential	$y= 86.111e^{-0.001x}$	0.973	0.084
Linear	y= 86.08 - 0.094x	0.973	0.102
Quadratic	$y= 84.350+ 0.071x-0.003x^2$	0.996	0.019
Cubic*	$y= 87.187- 0.340x +0.016x^2 - (3e-4)x^3$	0.998	0.012
power	$y= 90.255x^{-0.023}$	0.939	0.146
*: Best model			

Table-3. Fitting model applied for drying rate at voltage of 6 kV.

Model	Equation	R^2	RMSE
Exponential	$y= 0.710e^{0.029x}$	0.935	0.512
Linear	y= -0.224+0.076x	0.962	0.364
Quadratic	$y= 0.412+0.036x +(5e-4)x^2$	0.978	0.332
Cubic*	$y= -0.424+ 0.121x-0.001x^2+(2e-5)x^3$	0.983	0.285
power	$y= 0.064x^{1.017}$	0.969	0.389
*: Best fitting model			

Variations of drying rate with moisture content

The drying rate for kiwi fruit versus moisture content in constant voltage of 6 kV is shown in Figure-3. As seen in Figure-3, during drying time decreasing in moisture content of samples drying rate was decrease. This indicate that in first of drying period, drying rate have highest value respect to entire period and is reduced by time.

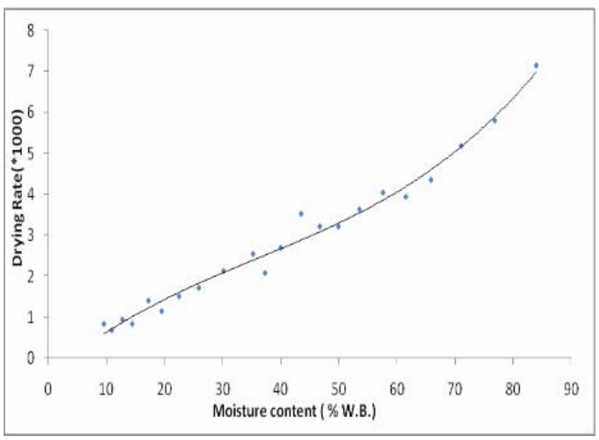

Figure-3. Trend line of drying rate versus different moisture content in voltage of 6 kV.

In this case, results for drying rate modeling with moisture content reported in Table-3. As seen in Table-3, best fitting model was cubic with following equation:

$$Y = - 0.424 + 0.121x - 0.001x^2 + (2e-5)\, x^3 \quad (5)$$
$R^2 = 0.983$

The drying rate curve for kiwi fruit dried with applied voltage of 10.5 kV is shown in Figure-4. From Figure-4, it can be seen that the drying rate and the moisture content have a certain correlation. When the moisture content is 84% (w. b.), the drying rate is the largest. Trend of experimental data indicated that the drying rate of samples reduced with decreasing in moisture content of kiwi fruit due to, the amount of surface water samples decreases with time to remove water in under layers must consume more energy. Constant values of fitting models were reported in Table-4. As seen in this Table in the case of 10.5 kV, power model was best fitting model for predicate drying rate base on moisture content of sample.

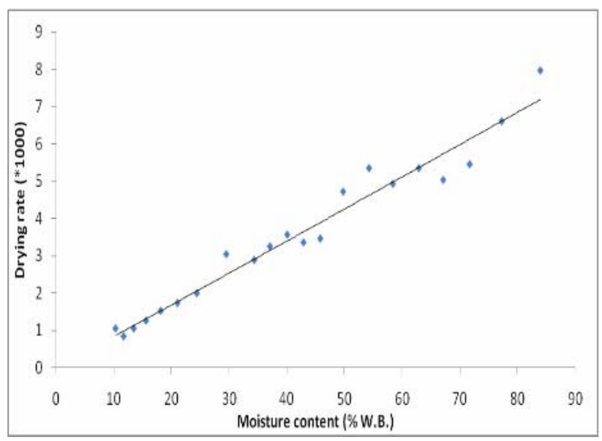

Figure-4. Trend line of drying rate versus different moisture content in voltage of 10.5 kV.

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Table-4. Fitting model applied for drying rate at voltage of 10.5 kV.

Model	Equation	R^2	RMSE
Exponential	$y= 0.927e^{0.027x}$	0.901	0.482
Linear	y= -0.054+0.086x	0.933	0.412
Quadratic	$y= 0.209+ 0.071x + (2e-4)x^2$	0.936	0.363
Cubic	$y= -1.300+0.219x-0.003x^2+(3e-5)x^3$	0.948	0.324
Power*	$y= 0.081x^{1.011}$	0.971	0.296
*: Best fitting model			

Figure-5 illustrates the changes of drying rate versus moisture content of kiwi fruit for voltage of 15. It is clear from Figure-5 that the drying rate decreases continuously as the moisture content of samples decreases. The experimental data of drying rate obtained at different moisture content of kiwi fruit were predicted by linear and non-linear regression analysis, Table-5 presents the drying constants and the values of R^2 and RMSE of the six models (Table-1), and the cubic model was found as the best descriptive model to express the changes of drying rate with moisture content of samples according to the highest R^2 (0.972), the lower RMSE (0.284) of it (Table-5). Therefore, it can be said that the cubic model could satisfactorily describe the drying rate of kiwi fruit with its moisture content.

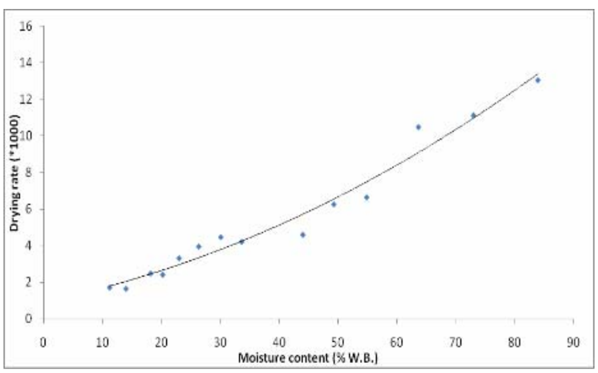

Figure-5. Trend line of drying rate versus different moisture content in voltage of 15 kV.

Table-5. Fitting model applied for drying rate at voltage of 15 kV.

Model	Equation	R^2	RMSE
Exponential	$y= 1.512e^{0.027x}$	0.938	0.418
Linear	y= -0.572+0.154x	0.954	0.397
Quadratic	$y= 0.963+ 0.064x+0.001x^2$	0.969	0.322
Cubic*	$y= 0.954+0.065x + 0.001x^2+(2e-6)x^3$	0.972	0.281
power	$y= 0.122x^{1.029}$	0.961	0.359
*: Best fitting model			

Variations of drying rate with field strength

In Figure-6 variation of drying rate based on field strength and applied voltage illustrated via histogram chart. It can be concluded that the drying rate increases continuously as the applied voltage increases from 6 to 15 kV/cm. In the other hand, highest values of drying rate for each voltage was obtained for field strength of 4.5 kV and this indicate that, there was an optimal strength field between 3 and 6 kV/cm. Alemrajabi *et al*. reported that the electric field strength of 5.2 kV led to minimum moisture content for EHD drying process for carrot slice [18].

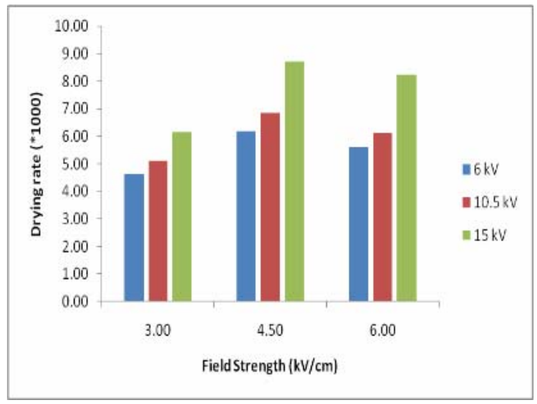

Figure-6. Effect of applied voltage on drying rate in different field strength.

The average value of drying rate for applied voltage of 6 kV obtained as 5.48×10^{-3} (kg water/ kg dry mater. time) varying from 4.64×10^{-3} to 6.17×10^{-3}, while this value for applied voltage of 15 kV was calculated as 7.70×10^{-3} (kg water/ kg dry mater. time) ranging from 6.16×10^{-3} to 8.70×10^{-3}.

CONCLUSIONS

Some structural parameters in drying rate of kiwi fruit are presented in this study. From this study it can be concluded that:

a) The moisture content of kiwi fruit decreased slower at a lower ambient temperature;
b) Drying rate of kiwi fruit reduced with reducing in applied voltage;
c) Best fitting model for predicating drying rate of kiwi fruit based on moisture content in applied voltages of 6, 10.5 and 15 kV were cubic, exponential and cubic, respectively;
d) Minimum valve of drying rate was obtained in the applied voltage of 6 kV/cm and field strength 3 kV/cm; and
e) Trend of experimental data indicated drying rate of kiwi fruit reduced with decreasing in its moisture content.

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