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ELECTROHYDRODYNAMIC DRYING: ENERGY AND QUALITY ASPECTS

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Summary - **in this study, effects of EHD on drying rate, energy consumption and color degradation of apple slices were studied. High voltage significantly increased drying rate by 1.5 to 4 times at high (5m/s) and low air velocity, respectively. Effect of EHD on color was insignificant at voltages below 10 kV, but higher voltage intensified progressively color degradation. Energy, used in EHD drying, was negligibly small (1-2%) as compared to the total energy consumption of AC/DC converter.**

Keywords: **EHD, convective drying, apple, color, energy efficiency.**

Introduction. Canada is a major supplierofdried apple slices with premium quality on the world market (Beaudin, 2005). The purpose of drying is to provide desirable texture and reduce water activity to the level securing long shelf-life of dried fruit (Krokida et al., 2003; Vega-Mercado et al, 2001).Convective apple slice drying has been thoroughly studied (Magee and Wilkinson, 1985; Sacilik et al., 2006;Figiel, 2007; Pakowski et al., 2012; Zarein et al., 2013) in the range of temperatures from 40 to 90^{o}C. Unfortunately, hot air drying of apples accelerates color and aroma degradation and may also lead to undesirable case hardening (Martynenko and Janaszek, 2014). Therefore, in the last decade significant efforts were made towards research and development of alternative technologies for apple slice drying, using microwaves (Andres et al., 2004; Figiel, 2007), infrared (Nowak et al., 2004) or vacuum freeze drying (Reyes et al., 2011). However, none of these technologies can satisfy industry requirements for high quality product and low energy consumption. This obstacle initiated research of hybrid apple drying technologies, such as combination of microwave and freeze drying (Huang et al., 2009), ultrasound and infrared(Brncic et al., 2010), heat pump and vacuum-microwave (Chong et al., 2014) and others. Effect of hybrid drying on composition, texture, aroma and microstructure of apple slices is well documented (Huang et al., 2012). However, all aforementioned technologies are still on the research stage.

Since hot air drying is the only option commercially available, industry expressed interest in the development of efficient non-thermal technology. One of the potential candidates is electro hydrodynamic (EHD) technology, which applies high voltage to enhance single-phase convective heat and mass transfer (Lai and Lai, 2002). Previous research showed advantages of EHD technology for drying of biological materials, such as potato, apple, tomato, mushroom slices, spinach, rapeseed, wheat, okara cake (Singh et al., 2012). However, the only publication on EHD apple drying (Hashinaga et al., 1999) had very low practical impact, because of limited range of experimental conditions and randomly chosen design parameters. Recent research showed advantages of proper electrode configuration and the use of direct current (DC) over alternating current (AC).Efficient corona wind can be obtained by applying a DC high voltage between two electrodes with significantly different radii of curvatures, such as pin-to-plate configuration (Fig. 1).

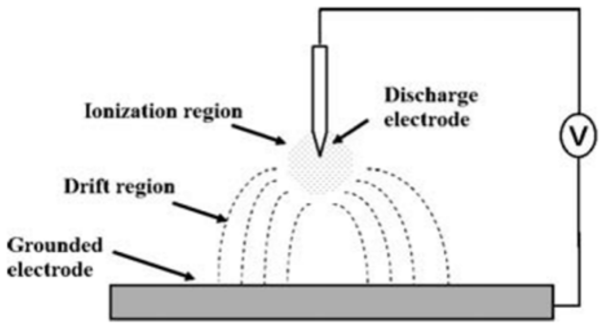

Fig. 1. Corona discharge between pin and plate.

The high electric field strength at the vicinity of the discharge (corona) electrode causes gas ionization and drifting air ions to the opposite (grounded) electrode, contributing to the formation of a space charge and an electric current flow between both electrodes (Gourdine, 1968). This current, called sometimes “corona wind”, “ionic wind” or “low-density plasma” creates dipole polarization and electrophoretic forces in the material (Allen and Karayiannis, 1995). Effect of polarization in electric field was observed for both water (Isobe et al., 1999) and protein molecules (Xue et al., 1999).It should be noted, that EHD effect could be observed only above corona initiation voltage and below breakdown voltage (Good enough et al., 2007).

Despite of various hypotheses about mechanisms of EHD drying, there is a consensus that major driving force is electric field strength in kV/cm, calculated as voltage (kV) divided by the distance between electrodes (Ahmedou et al., 2009). It was found that the drying rate increased with the increase of electric field strength through either increased voltage or decreased gap (Dalvand et al., 2014). For example, wheat drying with multiple-needle electrode showed enhancement of drying rate by 1.7, 2.0 and 2.1

at 5, 7.5 and 10kV/cm, respectively (Cao et al., 2004). Another example is rapeseeds drying, where multiple-needle electrode revealed enhanced drying rate by 1.78, 2.11 and 2.47 times at 4, 4.5 and 5 kV/cm, respectively (Basiry et al., 2010).It should be noted that the maximum field strength in EHD is limited by air conductance.

There are numerous evidences on the effect of electrode geometry on EHD performance. A comparison of electrode shapes showed that a sharp tip of the sewing needle electrode was more effective than thick copper wire with a blunt point (Hashinaga et al., 1999). A single-needle electrode enhanced drying rate of potato slabs rate by 2.1-2.5 times (Chen et al., 1994), whereas a multiple-needle electrode accelerated drying rate of apple slices by almost 4.5 times (Hashinaga et al., 1999). Similar conclusion about positive effect of multiple-needle as compared to one-needle electrode was reported by Lai and Sharma (2005). With respect to optimal number of needles, interesting results were reported by Bajgai and Hashinaga (2001a). Number of needles had no effect on drying of spinach at constant rate period; however, the effect became significant ($p<0.01$) when moisture content decreased below 80% (wb). In contrast, Dalvand et al. (2013) found that increasing of needle number from 1 to 17 consistently decreased drying rate. These contradictory findings require further experimental research.

The effect of drying conditions, in particular air temperature and velocity on drying rate was studied by Cao et al. (2004) and Ahmedou et al. (2009). In experiments with 300g agar gel samples with 98% of water, it was demonstrated that efficiency of EHD drying significantly depended on air velocity (Ahmedou et al., 2009). To maximize efficiency of EHD drying at a small electrode gap they suggested low air velocity, while at a large electrode gap high air velocity was recommended. The conclusion about negative effect of forced convection on EHD performance is in good agreement with results, obtained by other researchers (Dalv and et al., 2014;Balcer and Lai, 2004).Airflow significantly decreased energy efficiency of EHD drying because of at least two reasons: (i) concurrent effect of airflow on ionic wind, resulting in partial or full suppressing the electrohydrodynamic effect; (ii) increased energy consumption by air blower. Combined effect of temperature and electric field characteristics was studied by Cao et al. (2004). Experimental results showed consistent drop of EHD performance with increasing of temperature from20°C to 50°C (Cao et al., 2004). Decrease in EHD efficiency with temperature might be related to non-Fickian mechanism of drying with negligible effect of thermodiffusion. This hypothesis is supported by the fact that temperature can enhance EHD drying if the gradient of heat flux coincides with the gradient of electric field (Wong and Lai, 2004).

The effect of EHD drying on the food quality attributes was studied by several researchers (Xue et al., 1999; Hashinaga et al., 1999; Bajgai et al., 2001a, 2001b, 2006; Palanimuthu et al., 2009; Basiry et al., 2010; Esehaghbeigy et al., 2011, 2012; Dutta et al., 2012; Bai et al., 2012, 2013; Singh et al., 2013). It was found that EHD drying resulted in lesser color degradation of apples (Hashinaga et al., 1999), spinach (Bajgaiand Hashinaga, 2001a), Japanese radish (Bajgaiand Hashinaga, 2001b), emblic fruit (Bajgai et al., 2006), tomato slices (Esehaghbeigy et al., 2011), mushrooms (Dutta et al., 2012), as compared to oven or ambient air drying. The EHD effect on shrinkage was documented for apple slices (Hashinaga et al., 1999), Japanese radish (Bajgai and Hashinaga, 2001b), tomato slices (Esehaghbeigy et al., 2011), mushrooms (Dutta et al., 2012), sea cucumber (Bai et al., 2013). The general consensus is that EHD providesless shrinkage as compared to oven or ambient air drying. Specific effect of EHD on shrinkage is related to low-temperature drying, which results in less structural stresses. No curling, bending of slices or case hardening in EHD drying was observed. Superior hardness, reported by Esehaghbeygi (2012); Dutta et al. (2012); Singh et al. (2013) along with better rehydration ability (Bajgai and Hashinaga, 2001b; Dutta et al., 2012) could be explained by minimal effect of EHD drying on food microstructure.

Energy efficiencyof EHD drying remains the most controversial issue, because it depends on multiple-design parameters and energy consumption record. Usually, energy efficiency is estimated through specific energy consumption, which refers to energy used for evaporation of kg of water (kJ/kg) (Kudra, 2004).Most of researchers claim lower energy consumption of EHD as compared to ambient or hot air drying (Lai and Lai, 2002; Lai and Wong, 2003; Balcerand Lai, 2004; Wong and Lai, 2004; Lai and Sharma, 2005; Cao et al., 2004; Goodenoughet al., 2007; Ahmedou et al, 2009; Esehaghbeygi et al., 2011; Bai et al., 2011; Karami et al., 2012;Singh et al., 2012; Bai et al, 2012; Bai et al., 2013; Dinani et al., 2014; Dalvand, 2014). It was found that the most energy efficient was a single-needle electrode with positive DC voltage in the range 9-11 kV (Lai and Wong, 2003). Increasing of voltage resulted in progressive increasing of current, which was proportional to the squared voltage (Goodenough et al., 2007). Although high current accelerated drying rate, it decreased energy efficiency of EHD drying (Lai and Sharma, 2005).These authors pointed on at least three factors, which could negatively affect energy efficiency: multiple-needle electrode configuration, negative polarity and high voltage (Lai and Sharma, 2005). Effects of other factors, such as temperature, air pressure, humidity and modified atmosphere, require careful examination.

While the basic corona effects and their applications have been discussed for more than two decades, the whole process of EHD drying of biomaterials is rather complex and thus far from complete understanding.

This research aimed to study effects of EHD on apple drying rate, color degradation and energy efficiency with the goal of further optimization for the industrial scaling.

Materials and Methods.

Materials. Apple (*Malus Domestica*) variety McIntosh were purchased from a local farmer market in Truro, Canada, in August 2014 and stored in a cooler at 9°C. Three hours before each drying experiment, the required number of apples were removed from the cooler, kept under the room temperature and then cut into slices with 8±0.5 mm thickness and average 42±0.5 mm diameter. Initial moisture content of apple samples was in the range from 11.12 to 7.12 g/g (db).In each experiment we used three slices in a single layer touching each other, forming equilateral triangle with 73 mm side. This configuration allowed uniform exposure of all slices to ionic wind.

Experimental Apparatus

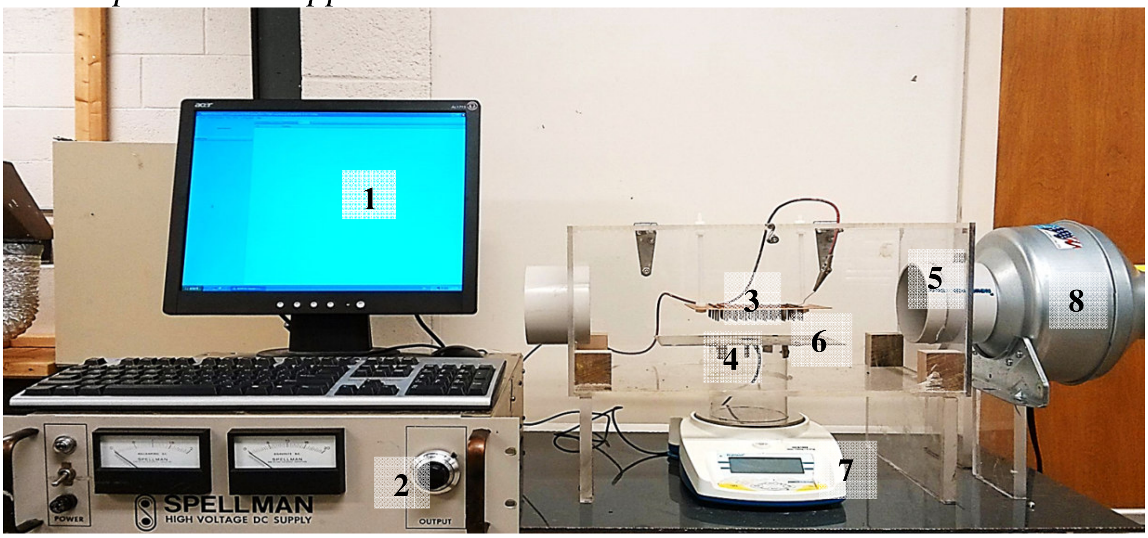

Fig. 2. Experimental setup

(1-desktop computer, 2-AC/DC high voltage converter, 3-electrode with multiple needles, 4-groundedplate-type electrode, 5-drying chamber, 6-sample place, 7-digital balance, 8-air blower)

A small-scale convective chamber for EHD drying (Fig. 2) consisted of a multiple points-to-plate electrode, real-time mass measurement system, an industrial blower (Fantech, Model K4, Canada), and a AC/DC high voltage converter (SPELLMAN, Model RHR20P10/FG/RC, USA). The 40×20×20 cm drying chamber was made from transparent plastic, leaving two air vents at 10.2 cm in diameter on both sides of the chamber. Air velocity was regulated by the blower. The multiple-point discharge electrode 10×9 cm was formed from 1.5 cm long sharp needles located in the nodes of the rectangular grid arranged in 10×9 rows with 1 cm square cells. This electrode was connected to positive pole of the high voltage converter. The grounded 20×10 cm aluminum plate electrode was connected to the ground of the high voltage power unit. The range of voltage was adjustable from 0 to 20 kV, forming the corona wind between these two electrodes. In all experiments the applied voltage was set below the electric breakdown to avoid avalanche ionization and arcing. Both the applied voltage and current between the electrodes were displayed on the control panel of the high voltage converter.

Drying Experiment. The effect of high voltage electric field on the apple's drying rate and color change were evaluated from drying experiments at temperature of 21±1 °C. The discharge gap between discharge and grounded electrodes was set constant at 2.5 cm. The initial mass of fresh apple slices (in the range from 11.50 to 14.65g) was measured before placing them in a single layer on the center of the aluminum plate. In our study we used the two factors factorial experimental design with repeated measurements. Voltage was set at four levels: 0, 5, 10 and 15kV. Superficial air velocity was set at three levels: 1.0, 3.0 and 5.0m/sas measured by a thermo-anemometer (Model HD300, Extech Instruments, USA). Each combination of voltage and air velocity was repeated three times. Duration of each experiment was 10 hours with air convection and 35 hours without convection. The pictures of dried apple samples were captured by a digital CCD camera (Model Oscar F-810C IRE, Canada) with light intensity of approximately 395 lux and recorded by imaging software(Vision Assistant 8.5, National Instruments, USA). Accuracy of color measurements was limited by quality of illumination and color rendering index of LEDs (Martynenko, 2006).Mass was measured by weighing on the digital balance HCB1002 (Adam Equipment, Danbury, CT, USA) with 0.01g resolution. Moisture content X was determined from mass measurements m_t as a mass ratio of water (variable) to dry solid, m_s

$$X = \frac{m_t - m_s}{m_s}. \quad (1)$$

Mass of dry solid m_s was determined for each slice by oven drying at 105°C for 24h. Moisture ratio *(MR)* was further calculated as a ratio between instantaneous (X_t) and initial (X_o) moisture content

$$MR = \frac{X_t - X_e}{X_o - X_e}. \quad (2)$$

where X_e is the equilibrium moisture content at thermal equilibrium at the end of drying. Moisture ratio as a function of time was expressed usingthe following exponential model:

$$MR = e^{-kt}, \quad (3)$$

$$\ln MR = -k \cdot t. \quad (4)$$

Parameter k in this model represents the drying rate constant, which was identified by linear approximation of (lnMR) vs. (time) over the entire period of drying. Drying rate constants for each combination of factors were used to calculate activation energy in the process of drying.

Ionic Wind. Ionic wind velocity u_e is directly proportional to the electric field strength *E* and can be calculated from the following relationship (Chen and Barthakur, 1994)

$$u_e = E\sqrt{\frac{\varepsilon_0}{\rho}}. \tag{5}$$

where ε_o - is the dielectric permittivity of air ($8.85\cdot10^{-12}$ F/m);

ρ - is the air density (1.204 kg/m^3 at 20^{o}C and 0.1 MPa atmospheric pressure).

The silent assumption incorporated in this formula is that air density ρ is independent of water vapor and electric charge density.

Interaction between ionic and convective wind was quantified by dimensionless EHD number, which represents the ratio between ionic wind velocity u_e and cross-flow air velocity u (Lai and Lai, 2004)

$$N_{END} = \frac{u_e}{u} \tag{6}$$

The EHD number reflects interaction of two orthogonal forces: electric force of ionic wind F_e and inertial force of air cross-flow *F*.

Color Measurements. A color measurement procedure was developed on LabVIEW2013 (National Instruments, USA) to determine the color with RGB color space output, which was further converted into CIE 1976 (*L**, *a**, *b**) color space, using standard conversion matrix (Weeks, 1996). In the CIELAB coordinate system, color values expressed as *L**, ranging from 0 (darkness) to +100 (whiteness or brightness), *a**(redness to greenness), and *b** (yellowness to blueness) were determined for each sample. Color changes *ΔE* were then calculated, using the following equation (Chen and Martynenko, 2013)

$$\Delta E = \left[\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b_0 - b_0^*\right)^2\right]^{1/2}, \tag{7}$$

where L_o^*, a_o^*, and b_o^* - are the initial values of fresh apple sample.

Energy Efficiency. Energy efficiency of drying was calculated as specific energy consumption, or amount of energy needed to evaporate unit mass of water in kJ/kg (Kudra, 2004). The index, further termed as energy efficiency, was determined from two measurable variables, namely the supplied electric power (kW) and the drying rate (kg/s)

$$\eta = \frac{V * I}{\Delta m}\Delta t. \tag{8}$$

In our experiments energy efficiency was calculated for the first 5 hours of drying.

Statistical Analysis. Measurements were carried out triplicate and results were expressed as mean ± standard deviation. Changes in drying rate were analyzed using one-way analysis of variance (ANOVA).Model assumptions (normality and constant variance) were verified by examining the residuals as described in Montgomery (2013). All statistical procedures were completed using Minitab 15.0 software (Minitab Inc., USA).Statistical significance was determined using least significant difference (LSD) t-tests and accepted at $p < 0.05$.

Results and Discussion.

Kinetics of EHD-activated mass transfer. Typical kinetics of EHD drying at different voltages and air velocities is shown in Fig. 3. In all cases drying followed first-order kinetics without constant rate period. Exponential shape of drying curves indicated diffusion-controlled drying. Fig.3a shows EHD drying in the absence of convective air flow (0m/s). At low voltages (0-10 kV) it was no significant difference between EHD and natural convective drying (k=0.053±0.005 h^{-1}). However, at 15 kV significant acceleration of drying rate was observed. Approximation of this curve with the exponential model (equation 4) showed noticeable acceleration of drying rate within first 5 hours (k=0.155±0.005h^{-1}), which decreased to 0.07±0.01 h^{-1} in the next 20 hours. This could be explained by the fact of decreasing EHD efficiency with the receding evaporation front (Alem-Rajabiand Lai, 2005). It follows that low voltage or low moisture content makes EHD drying non-efficient.

Drying kinetics for combined EHD-convective drying is shown in Fig. 3(b-d). Increase of electric field strength resulted in increased drying rate, which was expected for EHD drying (Dalvand et al., 2014). The most significant effect of EHD on drying rate was observed at the highest voltage and lowest air velocity in the range from 0 to 1 m/s. With the increasing of air velocity from 1 to 5 m/s, the EHD effect on drying rate was gradually decreasing. At 5 m/s the difference between EHD-aided drying and sole convective became non-significant. The possible reason could be that with increase of air velocity, convective drying tends to be the major factor, governing moisture transfer. Our results are in agreement with simulation study, which showed EHD activation of mass transfer only within a limited range of cross-flow velocities (Ahmedou et al., 2009).

Intensity of mass transfer was characterized with the drying rate constant k (h^{-1}). The values of drying rate constants, approximated from equation (4), are presented in Fig.4 as functions of air velocity (Fig. 4a) and voltage (Fig. 4b).

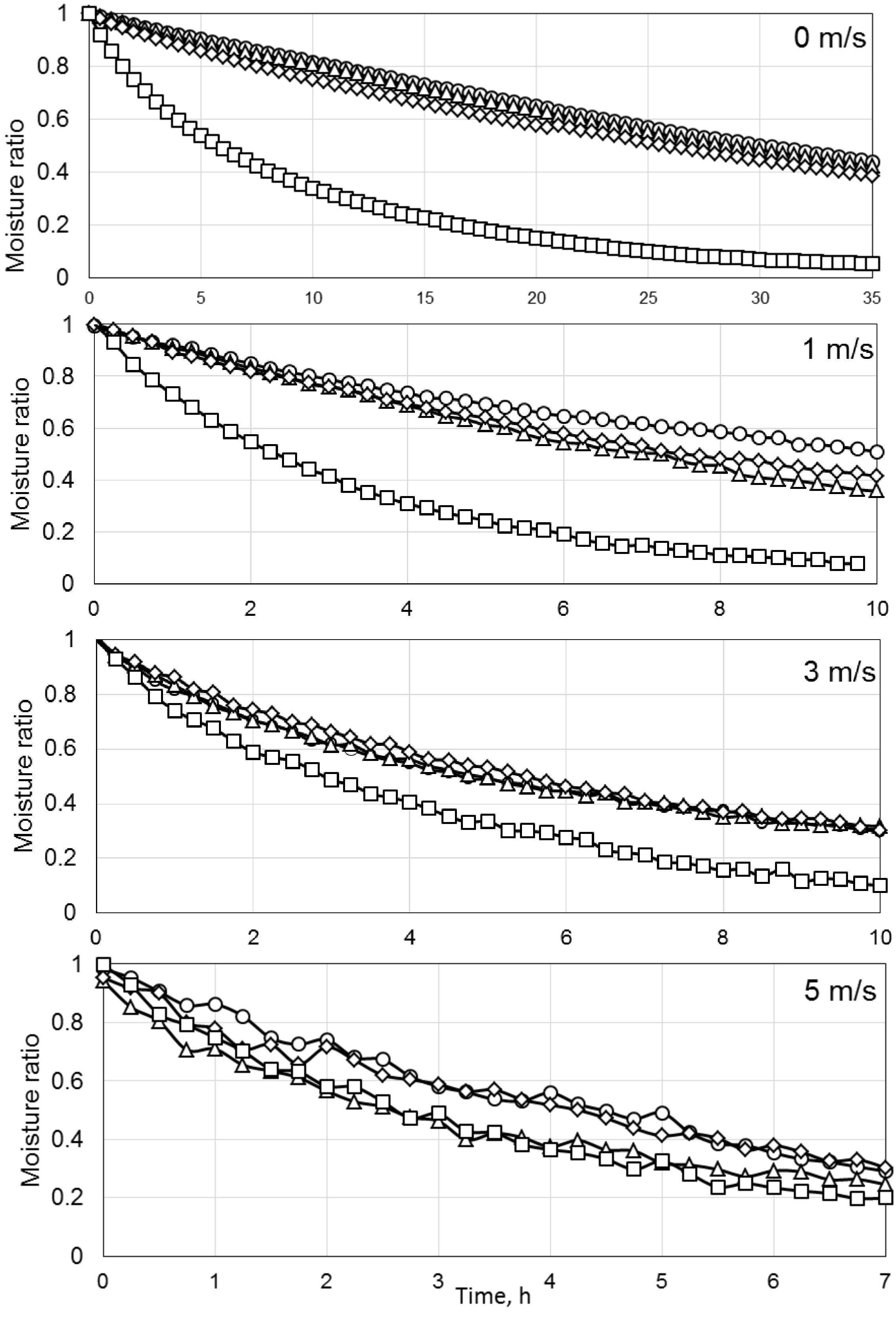

Fig. 3. Drying kinetics for combined EHD-convective drying.

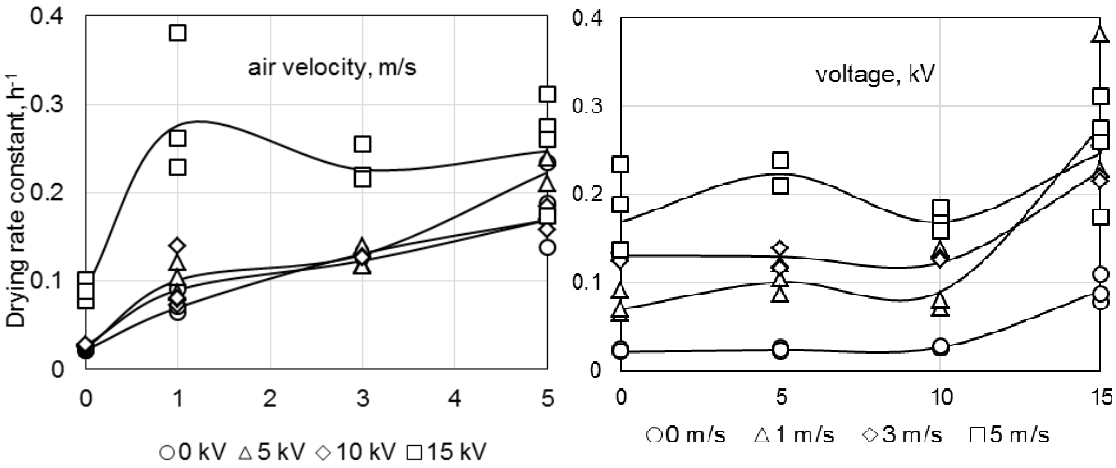

Fig.4. Drying rate constants

Fig 4 a shows that increase of air velocity accelerated mass transfer, which was expected from the theory of convective drying. There was no significant difference between effects of EHD at 0, 5 and 10 kV. However, effect of high electric field (15 kV) on the mass transfer was significant. It is important to mention that this effect was not monotonic, depending on air velocity. In particular, in the range of low air velocities from 0 to 1.0 m/s, the sharp increase of drying rate was noted, but in the range from 1.0 to 5 m/s drying rate became independent of air velocity. This behaviour could be explained by the complex nonlinear interaction between ionic wind and convective cross-flow (Ahmedou at al., 2009). Ionic wind velocity, calculated from equation (5), was 0.54 m/s at 5 kV, 1.0 m/s at 10 kV and 1.63 m/s at 15 kV, which was comparable with chosen range of cross-flow air velocities. It may create discord in aerodynamic interaction of ionic and convective flows on the surface of apple slices.

The sensitivity of mass transfer to electric field was evaluated from Fig 4b. Positive slope of drying rate constant as a function of voltage was consistently observed only in the range of high voltages from 10 to 15 kV. The mostly pronounced EHD effect was at low air velocity of 1.0m/s. It means that the main region of EHD effects is in the range of low air velocities from 0 to 1m/s and high voltages from 10 to 15 kV. However, 15 kV was very close to the breakdown voltage and was not always achievable under our experimental conditions. For example, at stagnant conditions (0m/s), the breakdown voltage was only 12.5-13 kV. Interestingly enough that increase of air velocity resulted in the increase of breakdown voltage and the current between electrodes. For example, increase of airflow from 0 to 5m/s at the voltage 13 kV resulted in increase of the current from 0.5 to 0.7mA. Hence, the effect of low breakdown voltage and low current at stagnant conditions could be attributed to the buildup of charged particles in the gap between electrodes.

To estimate interference between ionic and air convective flows, we calculated EHD numbers N_{EHD} from equation (6). Results of calculation for different combinations of voltages and air velocities ARE presented in Table 1.

Table 1. EHD numbers for different regimes of drying

Voltage, kV	Electric field strength (kV/m)	Air velocity, m/s		
		1.0	3.0	5.0
0	0	0	0	0
5	200	0.54	0.18	0.108
10	400	**1.08***	0.36	0.216
15	600	**1.63***	0.54	0.326

* EHD effect was significant

Table 1suggested that EHD number is an excellent indicator of EHD effect on drying. Regimes with EHD number above 1.0 (in bold) coincided with previously found region of significant EHD effect (voltage above 10 kV and air velocity below 1.0 m/s).Above 1.0 m/s convective cross-flow suppressed ionic wind, which is in agreement with Fig.4. Also, it is in agreement with results of Pogorzelski et al. (2013), where ionic wind, generated by the needle electrode (1.45 m/s at 527 kV/m)was much higher than the cross-flow air velocity of 0.1 m/s. These authors confirmed the findings by others that EHD effect is significant at$N_{EHD}>1$.

Effects of different combinations of voltage and air velocity on drying rate constants, presented separately in Fig.4, were summarized in the form of 3D response surface (Fig.5).

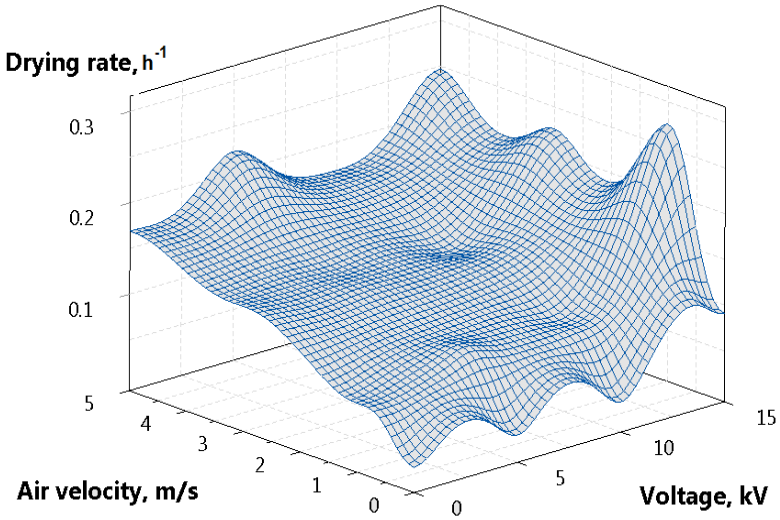

Fig. 5. Response surface for drying rate according to the air velocity and voltage

It follows that effect of convective air flow on drying rate, observed without electric field, was rather monotonic. In contrast, the effect of electric field on drying rate could be described as non-monotonic with periodical oscillations. These periodical oscillations, mostly pronounced at 0 m/s, depended on applied voltage with the cycle around 5 kV. The same cyclic changes of drying rate were observed for high voltage with the cycle around every 2 m/s. This unusual behavior could be associated with non-linear dependence of breakdown voltage from the gap length.

Color Changes. It is well known that time and temperatures determine color changes during drying. High temperatures or long time of drying could negatively affect food color because of enzymatic (Nicolas et al., 1994) or non-enzymatic (Manzocco et al., 2000) browning. In our low-temperature experiments we expected predominant effect of enzymatic browning. Following literature survey, initial hypothesis was that electric field could mitigate negative consequences of enzymatic browning.

Color changes were calculated for each drying regime, using equation (7). The total color degradation at various combinations of voltage and air velocity was presented in Table 2.

All drying combinations resulted in browning of apple slices at the end of drying. Color degradation was significantly stronger at stagnant air (0 m/s) for all electric treatments. Convective air flow slightly mitigated color degradation in all cases, except of 15 kV. High voltage of 15 kV facilitated color degradation for all air velocities. However, no significant effect of EHD on browning was observed at voltages 5 and 10 kV with respect to control (0 kV). Total color changes as a function of air velocity and voltage are presented in Fig.6.

Table 2 Total color change ΔE at different voltage and air velocity

Voltage, kV	Air velocity, m/s			
	0	1.0	3.0	5.0
0	27.66[a]	13.08[b]	11.57[b]	5.45[b]
5	28.36[a]	11.10[b]	11.33[b]	6.78[b]
10	20.45[a]	14.64[b]	14.08[b]	9.61[b]
15	23.84[a]	33.87[c]	20.35[a]	17.21[ab]

*Mean values, sharing the same letter, are nor statistically different

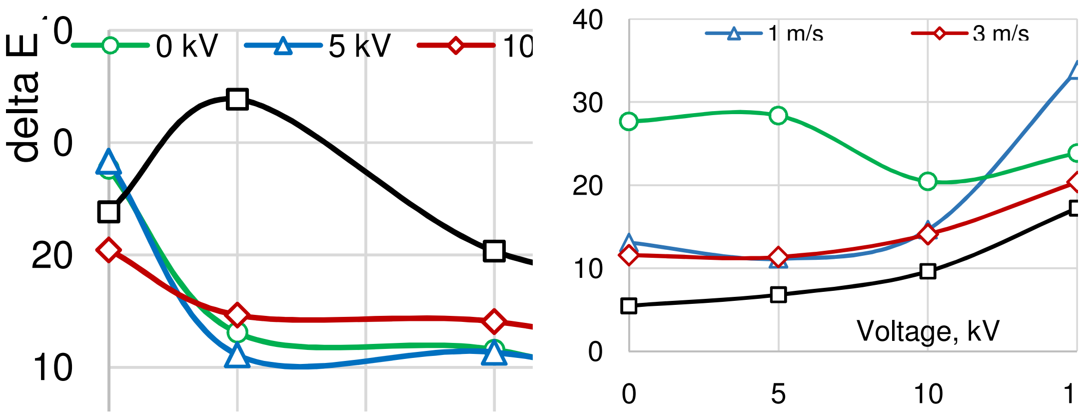

Fig. 6. Color changes at various combinations of voltage and air velocity

From Fig.6a it follows that 15 kV treatment negatively affected color. Apple slices were highly vulnerable to quality degradation in the range of air velocities from 0 to 1 m/s. Interestingly, air velocity of 5 m/s resulted in decrease of color degradation to ΔE=12±5. Diminishing of color degradation at high air velocities indicated positive effect of air convection on color preservation. It could also be related to decreased time of drying.

From Fig. 6b it follows that color degradation was definitely higher at stagnant air conditions (0 m/s), which could be associated with longer time of drying. With the increase of voltage, quality degradation slightly increased, passing through the inflection point at 10 kV. Based on our data, we could conclude that EHD at 10 and 15 kV slightly retarded color degradation, but in all other cases EHD increased color degradation, especially at 15 kV, 1.0 m/s.

Effects of different combinations of voltage and air velocities on color change, presented separately in Fig.6, were summarized in the form of 3D response surface (Fig.7).

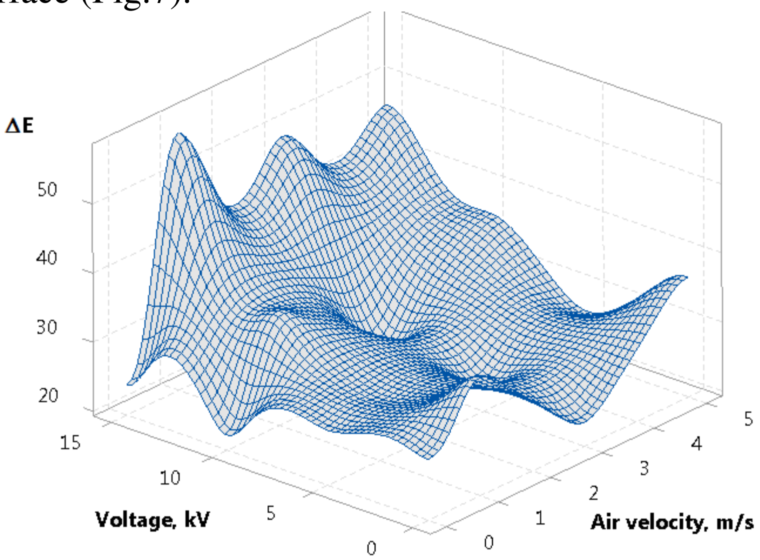

Fig. 7. Response surface for color changes Δ*E* at different voltage and air velocity.

It could be seen that in general EHD enhanced color degradation. However, from irregularities of the response surface shown in Fig 7, it follows that certain combinations of voltage and air velocity could potentially mitigate enzymatic browning.

In the absence of electric field, quality degradation significantly depended on the intensity of air flow, decreasing exponentially with the increase of air velocity. We could conclude about positive effect of convective air flow on reducing quality degradation initiated by high voltage.

Energy Consumption. Energy consumption was determined by the electric power of all used equipment, namely AC/DC high voltage converter and convective blower. Energy consumption of high voltage converter was calculated from direct measurements of voltage and current consumed by AC/DC converter and ranged from 55 to 75 W depending on high voltage output. This power could be translated into 900 to 1350 kJ of energy consumed in 5 hours. Energy, consumed by the AC convective blower was calculated from direct measurements of voltage and currents at different air velocities. The power was in the range from 4.95 to 13.72 W, being dependent on air velocity (Table 3).

Table 3. Energy consumption by convective blower

Air velocity, m/s	Voltage, V	Current, mA	Power, W	Energy consumed in 5 hours, kJ
1.0	120	45	4.95	89.1
3.0	120	87.5	9.63	173.3
5.0	120	124.7	13.72	247.0

It follows that energy consumed by convective blower is much less than energy consumed by AC/DC high voltage converter. At low air velocity the blower consumed 10 times less energy than the high-voltage generator. At high air velocity the blower consumed from 3.5 to 5.5 times less energy than the high-voltage generator with the same effect on drying rate. Energy consumption of electric equipment, used for EHD drying, is summarized in Table 4.

Table 4. Energy consumption at different drying regimes over 5 hours of drying, kJ

Voltage, kV	Air velocity, m/s			
	0	1	3	5
0	0	89.1	173.3	247.0
5	900	989.1	1162.4	1409.4
10	1150	1239.1	1412.4	1659.4
15	1350	1439.1	1612.4	1859.4

The amount of energy, factually used in EHD drying, was calculated from direct measurements of voltage and current of ionic wind. It was independent of air velocity, but dependent on applied voltage(Table 5).

Table 5. Energy used in EHD drying, kJ

Voltage, kV	Current, mA	Power, W	Energy consumed over 5 hours, kJ
5	0.025	0.125	2.25
10	0.05	0.5	9.0
15	0.05	0.75	13.5

From Fig.3 one could see that drying rate at 15 kV, 0 m/s (pure EHD drying) is compatible with the drying rate at 0 kV, 5 m/s (pure convective drying). If we compare energy used in EHD drying (13.5 kJ) with equivalent convective drying (247.0 kJ), it is obvious that EHD drying is at least 18 times more efficient. From the simple comparison of energy output (Table 5) with energy input (Table 4), it became clear that energy used in EHD drying is by two orders (65 to 100 times) lower than energy consumed by the AC/DC voltage converter. Hence, we could conclude about the extremely low (about 1 to 2%) energy efficiency of the AC/DC high voltage converter. This conclusion could explain common misconception that energy consumption in EHD drying is negligibly small (Lai et al., 2004, Dinani et al., 2014).

Energy Efficiency. Energy efficiency calculated from actual energy consumption (Table 4) and water evaporated over 5 hours under different drying regimes is presented in Table 6.

Table 6. Energy efficiency of EHD drying, kJ/kg

Voltage, kV	Air velocity, m/s			
	0	1	3	5
0	0	18000	24875.6	39710.6
5	242152.5	240461.9	191709.7	172228.1
10	229540.9	254784.1	232557.6	179913.3
15	124884.4	166819.9	180223.5	209785.6

From data presented in Table 6, it follows that the simple convective drying offers the best energy efficiency. Energy efficiency with EHD was almost independent of drying regime, because the vast majority of energy consumption was due to the power supply unit. This is in agreement with previous analysis of energy efficiency in EHD drying (Kudra et al., 2014). This efficiency increased with increasing of voltage applied, which is in agreement with Dalvand et al. (2014).

Practical applications.

In our experiments the EHD effect on drying was observed in the range of 10-15 kV and 0-1.0 m/s. This regime of drying resulted in the fastest mass transfer, but it is the most damaging for product quality. Hence, it is difficult to compromise both objectives of high efficiency and high quality of EHD drying. Further fine-tuning of drying parameters in order to find sufficient combination of high voltage and air velocity is required.

Also, the low efficiency of AC/DC high voltage converter as the major limiting factor in EHD drying has been identified. Unfortunately, current efficiency of AC/DC high voltage converters (1-2%) is too low for industrial acceptance of the EHD technology. Further engineering towards design of more efficient AC/DC high voltage converters is required.

Conclusions.

1. Positive effect of EHD on drying rate was significant at air velocities below 1m/s, increasing with voltage and decreasing with air velocity. For example, EHD enhancement of drying rate at 15 kV was 3.9 at 1.0 m/s, decreasing to 1.73 at 3.0 m/s and 1.46 at 5 m/s of air velocity. The EHD number could be an excellent indicator of EHD effect on drying.
2. Negative effect of EHD on color degradation was significant and increased with voltage, especially at low air velocity. However, high air velocity (mostly convective drying with low EHD number) resulted in lower color degradation as compared to low air velocity and high voltage (mostly EHD drying with high EHD number).
3. Energy consumption at different regimes of drying was mostly determined by the efficiency of AC/DC high voltage converter. Despite numerous statements that energy consumption in EHD drying is negligibly small, current efficiency of AC/DC high voltage converters (1-2%) is too low for industrial application of EHD drying.

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ЕЛЕКТРОГІДРОДИНАМІЧНЕ СУШІННЯ: ЯКІСТЬ ТА ЕНЕРГОВИТРАТИ

Мартиненко О. І.

Анотація **- електрогідродинамічне сушіння використовує феномен прискорення тепломасообміну в присутності сильного електричного поля. Енергетична ефективність цього нетермічного процесу значно перевищує ефективність конвективно-дифузійного сушіння. В цій роботі ми вивчали вплив електричного поля 5-10 кВ/см на питомі енерговитрати, інтенсивність і якість сушіння фруктів. Експериментально встановлено, що інтенсивність сушіння в присутності електричного поля зростала в 1.5...4 разів. Ефект був пропорційний напруженості електричного поля і обернено пропорційний швидкості конвекції. Електричне поле не впливало на якість сушіння при напруженості менше 5 кВ/см, але більша напруженість прискорювала біохімічну деградацію. Енерговитрати менші в 18 разів порівняно з конвективно-дифузійним сушінням.**

ЭЛЕКТРОГИДРОДИНАМИЧЕСКАЯ СУШКА: КАЧЕСТВО И ЭНЕРГОЗАТРАТЫ

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Аннотация **- электрогидродинамическая сушка использует феномен ускорения тепломассообмена в присутствии сильного электрического поля. Энергетическая эффективность этого нетермический процесса значительно превышает эффективность конвективно-диффузионного сушки. В этой работе мы изучали влияние электрического поля 5-10 кВ / см на удельные энергозатраты, интенсивность и качество сушки фруктов. Экспериментально установлено, что интенсивность сушки в присутствии электрического поля возросла в 1,5 ... 4 раза. Эффект был пропорционален напряженности электрического поля и обратно пропорционален скорости конвекции. Электрическое поле не влияло на качество сушки при напряженности менее 5 кВ / см, но большая напряженность ускоряла биохимическую деградацию. Энергозатраты меньшие в 18 раз по сравнению с конвективно-диффузной сушкой.**