Electrically enhanced drying of white champignons

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Abstract

Electrohydrodynamic (EHD) drying is a novel non-thermal dewatering technology using electric discharge in air to enhance dehydration of heat-sensitive biomaterials. Low energy consumption and high product quality make it attractive for industry. In this study, the mushrooms slices have been dried under sole EHD with 12, 14, and 16 kV DC, and EHD in combination with air cross-flow at 1 m s⁻¹ and different relative humidity (RH) from 30 to 70 %. It was found that drying kinetics was exponential over initial moisture contents from 3.3 to 14.1 g·g⁻¹ (db). The equilibrium moisture content ranged from 0.15 to 0.1 g g⁻¹ depending on RH. Decrease of RH or air cross-flow significantly improved efficiency of EHD drying.

Keywords: mushrooms; electrohydrodynamic; ionic wind; air humidity; equilibrium moisture content.

1. Introduction

Electrohydrodynamic (EHD) drying is regarded as a non-thermal dewatering technology, suitable for drying of heat-sensitive materials because of high product quality and low energy consumption.[1] Hence, it is excellent alternative as compared to hot-air convective drying of mushrooms with extremely short shelf life, which should be consumed or processed within hours after harvest.[2]

Commonly accepted hypothesis is that EHD drying occurs due to ionic wind. The effect of ionic wind on shiitake mushrooms drying was first investigated by Xue et al.[3] under 6, 8, 10, 12 kV AC (electric field strength from 3 to 6 kV cm^{-1}), concurrent airflow at 45ºC and 40% RH. The results showed that electro-convective drying for 10-14 hours was faster by 1.1 to 1.6 times compared to control. The effect of ionic wind increased with increasing voltage and decreased with increasing airflow rate. However, slight browning of the dried shiitake gills under the effect of ionic wind was noticed. Dutta et al.[4] showed that pre-treatment of mushroom slices with AC electric field 4.3 kV cm^{-1} accelerated subsequent convective or freeze drying. They also reported that the EHD pre-treatment improved quality of dry mushrooms, in particular lesser shrinkage, higher rehydration ratio and enhanced color as compared to control. Dinani et al.[5, 6] investigated the effect of EHD in combination with hot air drying at 60ºC and 10% RH for voltages 17, 19 and 21 kV DC, and gaps between electrodes 5, 6 and 7 cm. Electric field accelerated drying rate by 1.38, 1.41, and 1.43 times for voltages, and by 1.52, 1.36, and 1.33 times for gaps, so one can conclude that increasing of electric field strength significantly increased water diffusion in mushrooms. These experiments were done under conditions of natural convection. Similar experiments with EHD in combination with hot-air drying at 45ºC under conditions of forced convection [7-9] showed significant effect of air velocity. The enhancement of the drying rate due to EHD was as high as 1.40, 1.56, and 1.78 times at 0.4 m s^{-1}, while at 2.2 m s^{-1} these were 1.08, 1.03, and 0.97 times (no significant effect of EHD). These results confirmed previous conclusions of Xue et al.[3] that EHD is efficient only under low air velocities, while increase of air velocity above certain threshold results in purely convective drying. Unfortunately, all these experiments with mushrooms were conducted for combination of EHD with hot air drying with temperature as the dominant drying factor. These settings hindered the role of EHD in drying, making difficult interpretation of sole EHD effect on drying kinetics and product quality.

Promising experiments on EHD mushroom drying confirmed the importance of industrial scaling of the EHD technology. This research was initiated on the request of industry partner Jantex Ltd (Poland) to improve efficiency and quality of white champignons drying because of high sensitivity of product color to drying temperature. The main objective of this paper is to present preliminary results of EHD drying of sliced white champignons, including the effects of relative humidity, air cross-flow, initial moisture content, electric

field strength and configuration of discharge electrode, which are instrumental for industrial scaling of EHD technology.

2. Materials and methods

White champignons (Highline, Leamington, Canada) purchased from a local grocery were cut perpendicularly to the head into 5-mm slices and then spread uniformly in a single layer on the collecting electrode. Initial mass of sliced champignons varied from 30 to 34 g. Initial moisture content was in the range 3.3 to 14.1 kg kg^{-1} (db).

Experimental apparatus is shown in Figure 1. The drying chamber (1) was made of Plexiglas (40×20×20 cm) with two openings 10 cm in diameter. Discharge electrode (2) was built from 143 needles arranged into 11×13 rows giving 1×1 cm needles packing density or 42 needles arranged into 6×7 rows giving 2×2 cm needles packing density. Discharge electrode was connected to the positive pole of a DC high voltage source, while aluminum plate (3) with the size (20×10 cm) was used as a grounded electrode. Both electrodes were placed in the drying chamber. The room air humidity was maintained at 20% by the air conditioning system. Airflow velocity was maintained at 1.0 m s^{-1} by a 1.5 W fan (5) and measured with the hot wire anemometer HD300 (Extech Instruments, USA). High voltage (6) was supplied by DC power supply BAL-32-5 (Voltronics, USA). Voltage and current were recorded continuously using the LabView2012 (National Instruments, USA) data acquisition system with USB-6120 interface and desktop computer (7). The weight of mushrooms was determined with a digital scale (4) (model HCB 1002, Adam Equipment, Oxford, CT, USA).
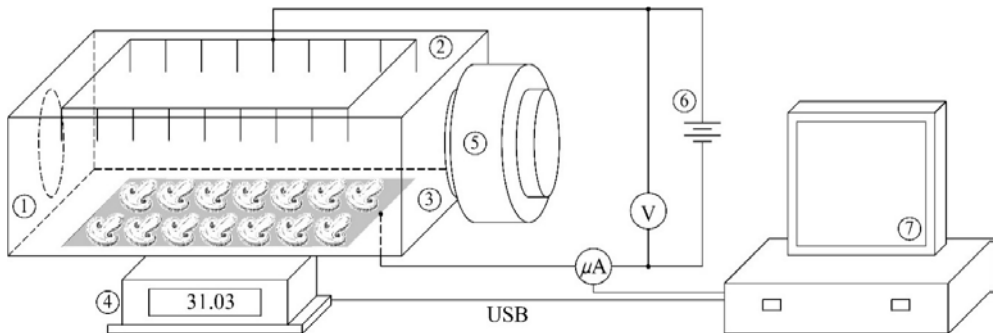

Fig. 1 EHD experimental setup.

Experiments for determination of equilibrium moisture content were carried out for sole EHD at 12, 14, and 16 kV with a gap 3.0 cm between electrodes, or EHD combined with air cross flow of 1.0 m s^{-1}. The effect of initial moisture content on EHD drying rate was measured for fresh slices and for slices after storage in the cooler from one to three days. The effects of EHD (1) and EHD + air cross-flow (2) were compared with sole air cross-

flow (control 1) or natural convection (control 2) for the same batch of slices. Drying rate for each treatment was calculated for 30 min using four-steps drying protocol. For these experiments the RH was kept constant at 20±2% and room temperature of 20±0.5ºC.

3. Results and discussions

The effect of discharge electrode geometry and air humidity on drying kinetics is shown in Figure 2. The effect of 1×1 and 2×2 cm needle packing density was studied at 15 kV, 3.5 cm gap, RH 70-80% and air cross-flow 0.4 m s⁻¹ (Fig. 2A). Drying kinetics showed the difference between effects of two electrodes. In particular, 1×1 electrode initiated linear drying kinetics (constant drying rate), which indicates convection-limited conditions. In contrast, 2×2 electrode initiated exponential drying kinetics (falling drying rate), which indicates diffusion-limited drying. Both cases have been reported in literature,[5,10] however the reason for the difference in drying behaviour has not been discussed.

Better results of EHD drying, obtained with 2×2 electrode, determined preferable use of such electrode in further experiments. The effect of 30, 50, and 70% relative humidity on the drying kinetics was studied with 2×2 electrode at 22 kV, 3.5 cm gap (electric field 6.3 kV cm⁻¹) and superficial velocity of air cross-flow 1.0 m s⁻¹ (Fig. 2B).
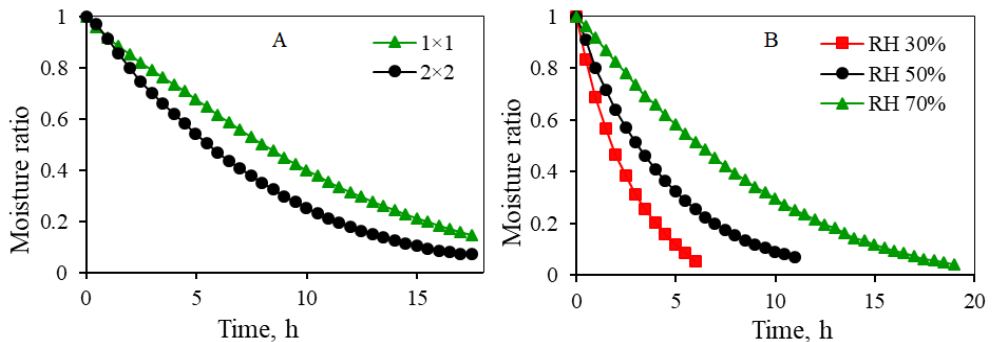

Fig. 2 Moisture kinetics for different discharge electrodes (A) and relative humidity (B).

Drying time was in the range from 7 to 20 hours, depending on relative humidity. The equilibrium moisture content at the end of drying was in the range from 0.1 to 0.15 g g⁻¹. This moisture content for white champignons corresponds to the range of water activities a_w from 0.3 to 0.35[11], which is considered as safe for shelf-life stability.[12] These data demonstrate how important is to maintain low air relative humidity in the EHD drying.

Effect of sole EHD and EHD combined with convective air cross-flow on drying kinetics is presented in Figure 3. It follows that drying rate increases with voltage, which corresponds to results reported earlier.[8, 9] Drying time to reach 0.2 g g⁻¹ of moisture content (dashed line) significantly decreased from 25 h at 4.0 kV cm⁻¹ to 12 h at 5.3 kV cm⁻¹. Effect of combined air cross-flow and ionic wind was significant at 12 and 14 kV, however at 16 kV

the drying effect of sole ionic wind was higher. This result is difficult to explain within existing theories of EHD drying. Therefore, the phenomenon of interaction between ionic wind and air cross-flow requires additional research.
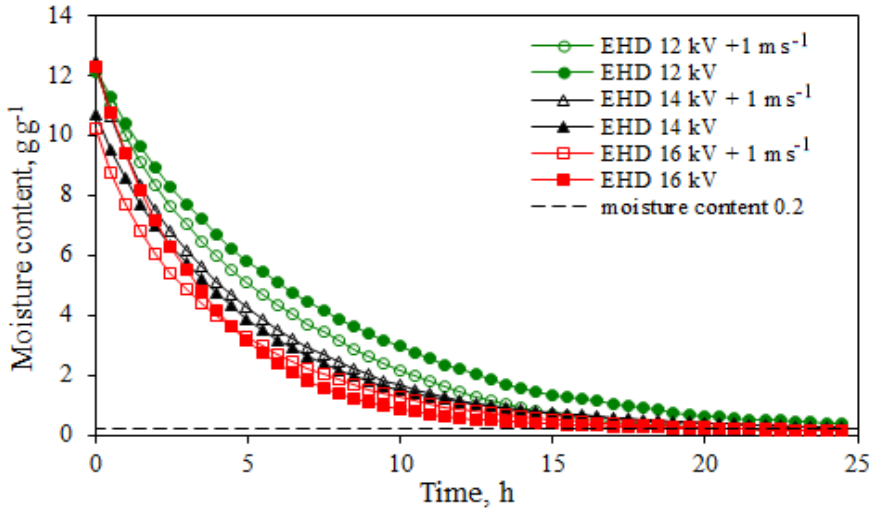

Fig. 3 Effect of EHD drying and combined EHD with convective cross-flow drying (1.0 ms⁻¹) under different voltages on drying time (3 cm gap, 20% RH).

The effective moisture diffusivity (D_{eff}) can be calculated from the following equation:

$$D_{eff} = \ln\left(\frac{\pi^2}{8} MR\right) \cdot \left(\frac{4L^2}{\pi^2 t}\right) = (-0.0851 - 0.4053 \ln MR) \cdot \frac{L^2}{t} \qquad (1)$$

Based on equation (1) it is possible to estimate instantaneous diffusion coefficient from experimentally determined parameter k:

$$D_{eff} = (-0.0851 \cdot \frac{1}{t} + 0.4053 k) \cdot L^2 \qquad (2)$$

Results of experimental evaluation of k for different modes of EHD drying are presented in Figure 4. Parameter k was stable over drying period from 0 to 14 hours in the wide range of voltages with/without forced convection, which indicates a suitability of the exponential model for approximation of drying kinetics in EHD drying. Based on the average value of parameter k, the effective moisture diffusivity coefficient has been calculated (Table 1):

Table 1. Effective moisture diffusivity coefficient, $D_{eff} \cdot 10^{-10}\ m^2\,s^{-1}$

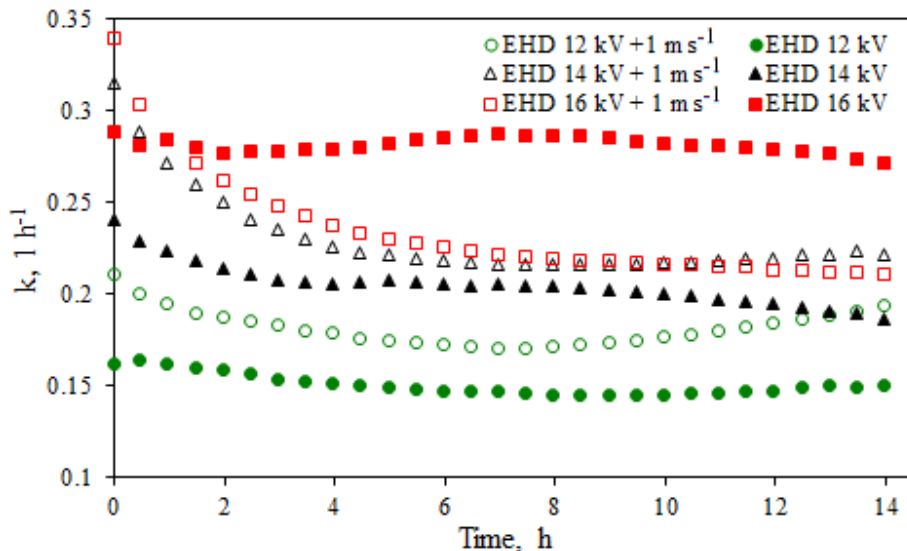| Drying	12 kV	14 kV	16 kV
EHD	3.29 ± 0.31	4.84 ± 0.11	6.42 ± 0.30
EHD + 1.0 m s⁻¹	3.78 ± 0.23	5.09 ± 0.14	5.39± 0.20

Fig. 4 Velocity of EHD drying and EHD + convective cross-flow drying (1.0 m s⁻¹) under different voltages on drying time.
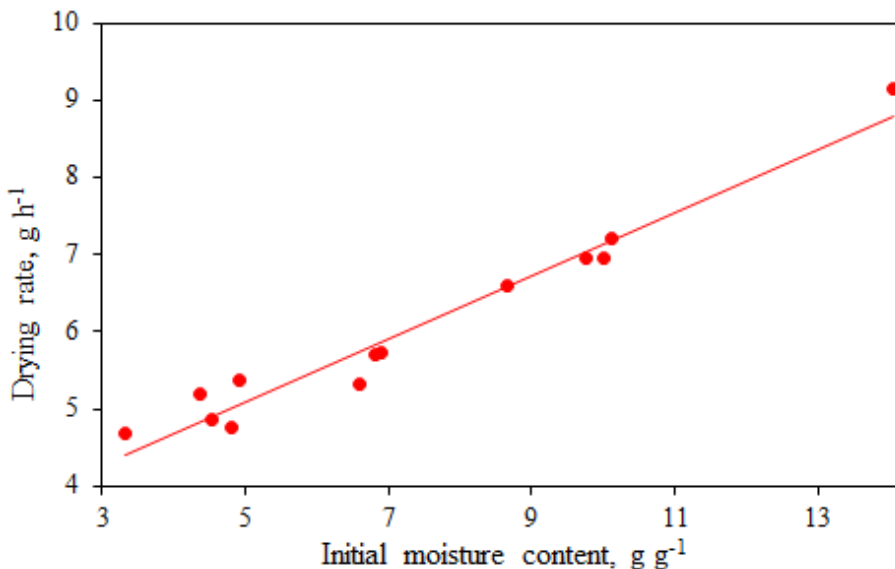

Fig. 5 Dependence of drying rate (DR) on initial moisture content (X_o) at EHD 14 kV and RH 20% (fitted linear regression DR = 3.056 + 0.4087 X_o with R^2 = 0.962)

From these results it is clear that drying rate is proportional to moisture content, which validates initial assumption, underlying simplified diffusion model. To study interactions between forced air cross-flow and electro-convection, the four-step experimental protocol

was designed, exploring three cases in various combinations: (1) Sole EHD, (2) air cross-flow, and (3) EHD with simultaneous air cross-flow (Fig. 6).
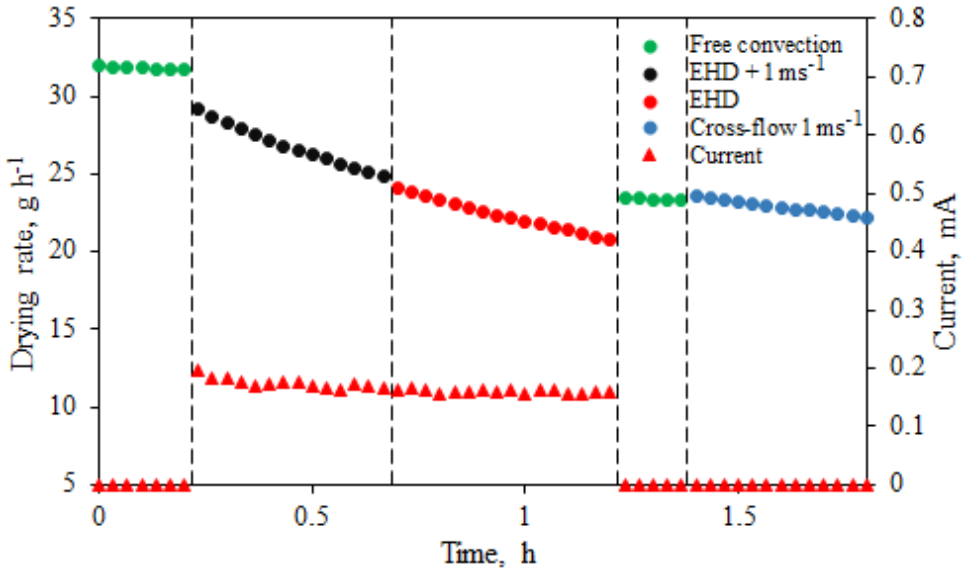

Fig. 6 An interactions between forced air cross-flow (1 m s⁻¹) and electro-convection (18 kV) at 3.5 cm gap, 20±2% RH.

The case # 3 was found to be the most efficient. The enhancement ratio was: EHD/Free convection = 6.66/1.4 = 4.757, EHD/Cross-flow = 6.66/3.36 = 1.982, EHD+Cross-flow/Free convection = 10.04/1.4 = 7.171, EHD+Cross-flow/Cross-flow = 10.04/3.36 = 2.988. It follows that EHD effect was always positive, resulting in enhancement of drying rate in the range from 1.98 to 7.17 times.

4. Conclusions

1. EHD drying kinetics typically followed the exponential curve, hence it is diffusion-limited and could be described by Fick's equation.
2. Drying rate of white champignons is proportional to initial moisture content, increases with electric field strength and with decrease of relative humidity.
3. The effect of needle packing density on drying rate of white champignons was significant.
4. The effect of 1.0 m s⁻¹ cross-flow air on EHD drying was found significant at 12 and 14 kV, while at 16 kV the drying rate was higher than EHD without air cross-flow.
5. Effect of electric field on effective moisture diffusion was much more pronounced in the case of sole EHD: from $3.38 \cdot 10^{-10}$ m^2 s^{-1} (12 kV) to $7.22 \cdot 10^{-10}$ m^2 s^{-1} (16 kV).

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