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Electrohydrodynamic drying of apple slices: Energy and quality aspects

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ABSTRACT

In this study, EHD was applied for apple slices drying through a multiple needle-to-plate electrode with a fixed 25 mm gap, using different combinations of voltage and air velocity at room temperature. Effects of EHD on drying kinetics, color degradation, and energy consumption were studied. High voltage significantly increased drying rate by 1.5–4 times at high (5 m/s) and low (1 m/s) air velocity, respectively. Combined EHD-convective drying was more efficient for moisture removal than sole EHD drying. The most significant effect of EHD on drying rate was observed at the highest voltage and low air velocity. 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.

1. Introduction

Apple production is a major contributor to Canadian horticultural sector, which has 270 million kg of marketed fruit across Canada (AAFC, 2013). Canada is a great potential market for dried apple slices in consideration of a growing consumers demand for crispy dried fruits of premium quality and texture (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 and Elicin, 2006; Figiel, 2007; Pakowski and Adamski, 2012; Zarein et al., 2013) in the range of temperatures from 40 to 90 °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 and Lewicki, 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 electrohydrodynamic (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). Preliminary results of EHD apple drying showed acceleration of drying rates of apple slices, indicating the potential of bulk drying capacity of EHD (Hashinaga et al., 1999). In this research authors proved significant effects of electric field strength, electrode gap, number of needles and needle shape, using alternating current (AC) voltages in the range from 3.0 to 5.5 kV/cm. However, recent research showed advantages of use of direct current (DC) over alternating current. 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).

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

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Nomenclature

$X(t)$	instantaneous moisture content, g/g db	t	time, h
X_0	initial moisture content, g/g db	L^*	lightness
$m(t)$	instantaneous mass, g	a^*	redness
m_s	solid mass, g	b^*	yellowness
MR	moisture ratio	ΔE	color change
k	drying rate constant, h^{-1}		

(Xue et al., 1999). It should be noted, that EHD effect could be observed only above corona initiation voltage and below breakdown voltage (Goodenough 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 10 kV/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 and Esehaghbeygi, 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 and Barthakur, 1994), whereas a multiple-needle electrode accelerated drying rate of apple slices by almost 4.5 times (Hashinaga et al., 1999). They reported electric field strength 4.4–4.7 kV/cm and 1.3 cm gap as optimal conditions of EHD drying, which required only 7 h at 18 °C to reach moisture ratio of 0.2. 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 300 g agar gel samples with 98% of water, it was demonstrated that efficiency of EHD drying significantly depended on air velocity (Ahmedou et al., 2009).

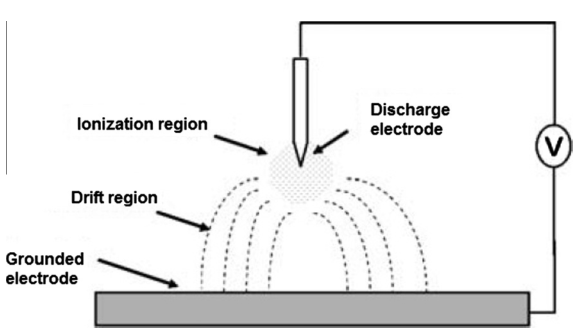

Fig. 1. Corona discharge between pin and plate.

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 (Dalvand 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 from 20 °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 and Hashinaga, 2001a, 2001b; Bajgai et al., 2006; Palanimuthu et al., 2009; Basiry and Esehaghbeygi, 2010; Esehaghbeygi and Basiry, 2011; Esehaghbeygi, 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 (Bajgai and Hashinaga, 2001a), Japanese radish (Bajgai and Hashinaga, 2001b), emblic fruit (Bajgai et al., 2006), tomato slices (Esehaghbeygi and Basiry, 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 (Esehaghbeygi and Basiry, 2011), mushrooms (Dutta et al., 2012), sea cucumber (Bai et al., 2013). The general consensus is that EHD provides less 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 efficiency of 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; Balcer and Lai, 2004; Wong and Lai, 2004; Lai and Sharma, 2005; Cao et al., 2004; Goodenough et al., 2007; Ahmedou et al., 2009; Esehaghbeygi and Basiry, 2011; Karami et al., 2012; Singh et al., 2012; Bai et al., 2012, 2013; Dinani et al., 2014; Dalvand et al., 2014). It was found that the most energy efficient was a single-needle electrode with positive DC voltage in the range