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Driving forces for mass transfer in electrohydrodynamic (EHD) drying

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ABSTRACT

Electrohydrodynamic (EHD) drying is considered as energy efficient non-thermal technology suitable for dewatering of heat-sensitive materials, including food products. A factorial experimental design was used to identify significant factors affecting mass transfer in EHD drying. The experiment revealed significant effects of voltage, distance (gap) between electrodes, configuration of discharge electrode, air cross-flow and the characteristics of material surface on mass transfer. Strong coupling between mass and charge transfer was found for all voltages, gaps and configurations of discharge electrode. The effect of air cross-flow at 1.0 m/s on mass transfer was additive to the effect of ionic wind, consistently increasing total mass transfer by 5.0–5.1 g/h in all experimental conditions. These results led to the conclusion that the effect of EHD is convective in nature, enhancing mass transfer due to ionic wind. The effect of material surface characteristics was attributed to different hydrodynamic conditions of air boundary layer.

Industrial relevance: This research is focused on better understanding of the factors that play a significant role in EHD drying, and therefore it is important for industry to facilitate practical applications of EHD in bioprocessing and food engineering.

1. Introduction

Electrohydrodynamic (EHD) drying is regarded as emerging, non-thermal dewatering technology, which appears to be a viable alternative to conventional thermal drying for certain heat-sensitive materials, such as high-value bioactive components of fruits and medicinal plants (polyphenols, flavonoids, dietary fiber, etc.), living cells (bacteria, yeasts and viruses), and non-living substances of biological origin (blood plasma, serum, hormones, antibiotics, probiotics, nutraceuticals, etc.) (Alemrajabi, Rezaee, Mirhosseini, & Esehaghbeygi, 2012; Bajgai, Raghavan, Hashinaga, & Ngadi, 2006; Singh, Orsat, & Raghavan, 2012; Zhang, Chen, Mujumdar, Zhong, & Sun, 2015). The positive effect of EHD on mass transfer was also reported for combination with other drying techniques, such as EHD-assisted hot air drying (Alemrajabi et al., 2012; Dinani, Havet, Hamdami, & Shahedi, 2014b; Singh et al., 2017), EHD-assisted vacuum freeze drying (Bai, Yang, & Huang, 2012), or EHD with auxiliary contact heating (Lai & Wang, 2009). Energy consumption in EHD drying is much lower than that in hot air drying, likely because of targeted supply of energy for moisture evaporation and practically there is no heat lost with exhaust air. The energy-related issues in EHD drying have been reviewed by Kudra and Martynenko (2015). The reported benefits of EHD compared to hot air drying on food quality include lesser shrinkage (Alemrajabi et al., 2012; Bajgai & Hashinaga, 2001a), higher rehydration ratio (Bajgai & Hashinaga, 2001b), preserved color (Alemrajabi et al., 2012; Bajgai & Hashinaga, 2001a; Esehaghbeygi & Basiry, 2011; Hashinaga, Bajgai, Isobe, & Barthakur, 1999; Xue, Barthakur, & Alli, 1999), and higher vitamin C content (Bajgai & Hashinaga, 2001b).

The principle behind EHD drying is the phenomenon of charge transfer (corona discharge) from a high-voltage electrode. The corona appears when a high voltage is applied to two electrodes with substantially different radii of curvature, such as a sharp vertical pin or fine horizontal wire and a flat surface, giving respectively point-to-plate or wire-to-plate configurations (Kulacki, 1982). The discharge electrode with larger curvature generates ionic wind due to corona discharge, which impinges the surface of wet material deposited on the collecting (grounded) electrode (Fig. 1).

EHD drying is the most efficient under conditions of stable "glow discharge" from low-energy ions, dragged by electric force (Goldman, Goldman, & Sigmond, 1985). The space charge in the drift region is the major factor of drying, determining current density distribution and mass transfer from the surface of the wet material. The space charge density in the drift region depends on the gap between electrodes, expansion of ionization region and thickness of the material under drying. The limit of ionization region (α') is determined by electric field strength.

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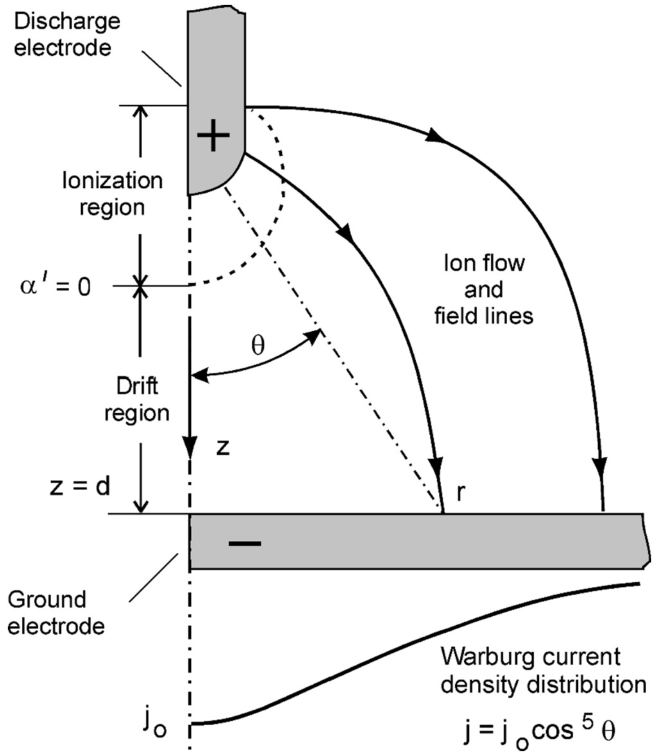

Fig. 1. A typical pin-to-plane corona geometry.
(Adopted from Goldman et al., 1985).

1.1. Existing theories of electrically-induced mass transfer

Mass transfer in EHD drying could be attributed to various physical phenomena. Some of them, such as ionic wind, impingement of material surface, gradient of surface tension, polarization, space charge and electrocapillarity are briefly discussed in the topical literature (Rounsley, 1985). Early research on EHD considered the ion-drag force (ionic wind) as a major driving force for mass transfer (Kulacki, 1982; Robinson, 1961). This force, resulting from exposure of a unit volume of charged gas to electric field with strength E, is represented as a pressure gradient ∇P

$$\nabla P = \rho_c E \tag{1}$$

where ρ_c is the space charge density, C/m^3.

The ionic wind velocity from the electric field force at the surface of the collecting electrode can be estimated from the momentum conservation law (Robinson, 1961)

$$\frac{\rho {u_e}^2}{2} = \int_0^d \rho_c E dz \tag{2}$$

where d is the gap between discharge and collecting electrodes (m), ρ stands for air density (kg/m^3), and u_e represents ionic wind velocity (m/s). Taking air density ρ as constant and independent of both the water vapor density and electric charge density, Barthakur and Al-Kanani (1989) derived the linear relationship between ionic wind velocity u_e and electric field strength E

$$u_e = \sqrt{\frac{\varepsilon_o}{\rho}} E \tag{3}$$

where ε_o represents dielectric permittivity of vacuum (8.85 pF/m).

This equation considers uniform electric field at the surface of the collecting electrode. However, according to Warburg law (Warburg, 1927), discharge from the sharp pin or thin wire causes highly non-uniform distribution of electric current density, and therefore non-homogeneous electric field at the plane surface (see Fig. 1). The relationship between ionic wind velocity and current density j (A/m^2) at the surface of collecting electrode has been derived by Robinson (1961) as

$$u_e = \sqrt{\frac{jd}{\rho b}} \tag{4}$$

with

$$j = j_o \cos^5 \theta \tag{5}$$

where b is the ionic mobility (m^2/(s V)), j_o is the maximum current density just underneath of a pin, and θ is the Warburg angle, determined from the geometry of electrode (see Fig. 1).

Eqs. (4) and (5) predict non-uniform ionic wind velocity over the surface of the material, which then was confirmed experimentally (Kawamoto, Yasuda, & Umezu, 2006; Rickard, Dunn-Rankin, Weinberg, & Carleton, 2006). These results correspond well to early experimental findings of Isobe, Barthakur, Yoshino, Okushima, and Sase (1999), who reported Warburg distribution (Eq. (5)) of mass transfer, initiated by the pin electrode at the surface of agar gel.

It is important to note that the estimate of ionic wind velocity from Eq. (4) is about one third of than the one given by Eq. (3). This fact could be attributed to the averaging the profile of ionic wind velocity over the surface area. The maximum ionic wind velocity, calculated from Eq. (3), is usually on the order of several meters per second, which definitely entails the aerodynamic effect, disturbing the boundary layer at the material's surface.

The surface action of EHD was confirmed in the experiments with water evaporation (Kamkari & Alemrajabi, 2010; Li, Li, & Tatsumi, 2000; Wolny & Kaniuk, 1996), wetted solid and perforated glass beads (Ramachandran & Lai, 2010), sand (Singh et al., 2017), apple slices in the first 5 h of drying (Hashinaga et al., 1999), tomato slices in the first 3 h of drying (Esehaghbeygi & Basiry, 2011), carrots and miscanthus in the first 1.4 h of drying (Pogorzelski, Zander, Zander, & Wrotniak, 2013). These experiments demonstrated constant drying rate, which is typical for convective mass transfer. It corresponds to Type 1 (Dirichlet) boundary condition, when liquid mass transfer is controlled only by the gas properties, such as temperature, density, humidity and superficial velocity.

In contrast, EHD drying of biomaterials, such as rapeseed (Basiry & Esehaghbeygi, 2010), tomato slices after 3 h of drying (Esehaghbeygi & Basiry, 2011), kiwi fruits (Dalvand, Mohtasebi, & Rafiee, 2013), apple slices (Martynenko & Zheng, 2016), mushrooms (Dinani, Hamdami, Shahedi, & Havet, 2014a) and carrot slices (Ding, Lu, & Song, 2015), demonstrated exponential decay of moisture content or falling drying rate, which is typical for the diffusion-limited mass transfer. The diffusion could be constrained either because of low internal diffusivity of the biomaterial (Ding et al., 2015), or due to the receding evaporation front with solid-gas interface below the material surface (Alem-Rajabi & Lai, 2005; Pogorzelski et al., 2013). This case corresponds to Type 3 boundary condition (Robin), linking water diffusion towards the material surface and convection from the material surface

$$\frac{dm}{dt} = D\frac{\Delta m}{\Delta x} = h_m(m - m_\infty) \tag{6}$$

where D is the water diffusivity (m^2/s) in the material with thickness x (m), $\Delta m = m - m_\infty$ stands for the concentration gradient or difference in water vapor concentration between the sample surface and ambient gas (kg/m^3) and h_m denotes the mass transfer coefficient (m/s).

It was found that mass transfer increases with voltage and decreases with the gap between electrodes (Lai & Lai, 2002). However, it is still unclear, whether mass transfer is driven by voltage or by electric field strength. Moreover, the effect of electrode configuration on charge density and mass transfer has never been studied.

The effect of air cross-flow on mass transfer was thoroughly examined by Lai and Lai (2002) and Lai and Sharma (2005). Whereas