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Electrically-induced mass transport in a multiple pin-plate electrohydrodynamic (EHD) dryer

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ABSTRACT

A theoretical approach to quantify the electric field intensity, space charge density and mass transport in a multiple pin-plate electrohydrodynamic dryer has been developed. It was found that: (i) the corona onset voltage depends largely on the electrode geometry, decreasing for smaller gaps and larger spacing between pins, (ii) the charge flow rate (convection current) depends on voltage, gap and electrode geometry, and (iii) airflow mass flux generated by multiple-pin electrode is proportional to the voltage and square root of electric current. The theoretical model of electrically-induced airflow predicts velocity profile and occurrence of aerodynamic vortices in a single channel of flowing air. The model has been experimentally validated in drying experiments with wet paper tissue. Drying with 2 × 2 cm electrode showed good correlation between model-predicted air mass flux and water transport from the wet material. Smaller spacing between pins (1 × 1 cm) significantly affected charge distribution, aerodynamics of airflow and mass transfer.

1. Introduction

Besides freezing, drying is another commonly used technology for long-term preservation of perishable foods. The natural drying is known from an early history of humanity, but industrial drying requires special techniques to intensify water removal through evaporation (Mujumdar, 2015). Contact, radiant heating and convective drying are the most used techniques, accelerating mass transport from wet food materials. Contact heating is efficient but energy consuming and may lead to food degradation due to overheating (Bonazzi and Dumoulin, 2011). Thin-layer convective drying seems to be the most economical option, since exposing of the material surface to air flow would require a very small pressure difference and relatively low thermal energy (Talbot et al., 2016). Recently developed electrohydrodynamic (EHD) drying exploits the effect of electrically-induced convective drying. Due to low-temperature operation, EHD drying is particularly suitable for heat-sensitive materials, such as foods (e.g., vegetables, mushrooms, berries, fruits, tofu, fish), medicinal plants, and biomaterials (e.g., probiotics, nutraceuticals, enzymes). EHD-dried products are characterized by lower shrinkage (Bajgai and Hashinaga, 2001a; Alemrajabi et al., 2012), better color (Bajgai and Hashinaga, 2001a; Esehaghbeygi and Basiry, 2011), higher rehydration ratio (Bajgai and Hashinaga, 2001a) and preserved vitamin content (Bajgai and Hashinaga, 2001b; Yang and Ding, 2016).

The electrohydrodynamic (EHD) flow results from electrical discharge between two electrodes with substantially different radii of curvature (Chang et al., 1995). This electric field is much stronger near the sharper (discharge) electrode, causing local air ionization. A thickness of the ionization zone is usually in the order of a fraction of a millimeter, but the whole air gap is filled with low-energy ions accelerated by electric field. Moving ions frequently collide with neutral air molecules, dragging them towards the collecting electrode. This electrically-induced airflow, consisting of ionized and neutral molecules, is called the ionic wind or EHD flow. It is commonly accepted that ionic wind is a key factor of EHD drying, intensifying water mass transfer from the surface of the wet material. Water is picked-up by airflow, rebounding from the material surface. The interaction between electric field, space charge and electrically-induced airflow is usually examined through the set of Poisson and Navier-Stokes equations. However, numerical simulation of

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spatial distribution of electric field and space charge requires significant computational power and specialized software (Sattari et al., 2010; Adamiak, 2013).

Another alternative is the application of simplified equations, accounting for average effect of voltage and current on ionic wind velocity. For example, equation proposed by Barthakur and Al-Kanani (1989) establishes direct relationship between ionic wind u_e and electric field intensity E:

$$u_e = \sqrt{\frac{\varepsilon_0}{\rho}}E \tag{1}$$

where ε_0 is dielectric constant equal to 8.85 pF/m and ρ is the gas density (kg/m^3). The underlying assumption is that gas density is constant and electric field is uniform in the gap between electrodes. However, electric field of corona discharge is highly non-homogeneous (Warburg, 1899), which creates non-homogeneous distribution of ionic wind at the material surface (Rickards et al., 2006). To account for this effect, Robinson (1961) proposed the relationship between ionic wind velocity u_e and electric current density:

$$u_e = \sqrt{\frac{jd}{\rho b}} \tag{2}$$

where j is current density (A/m^2) at the surface of the material, b is the ion mobility (m^2/(V·s)), and d represents the gap between electrodes (m).

Equation (2) has been experimentally verified for the single pin-plate (Rickard et al., 2006; Kawamoto et al., 2006) and single wire-plate configurations (Zhao and Adamiak, 2005; Moreau et al., 2013). However, accurate simulation of electrically induced airflow in a multiple pin/wire discharge system is extremely complicated because of: (i) interactions between neighboring jets of ionic wind; and (ii) interference of the impinging streams of ionic wind and evaporated water leaving the material surface.

Our recent literature review (Martynenko and Kudra, 2016) revealed that most of published studies on the EHD enhancement of mass transfer are constrained to simple configurations, such as a single-pin/wire discharge electrode. However, the single-pin/wire system has no potential for industrial application (Kudra and Martynenko, 2015). Several experimental studies have, however, been carried out to study the effect of multi-pin/wire electrode on drying performance (Dalvand et al., 2013, 2014; Balcer and Lai, 2004; Lai and Sharma, 2005; Bai et al., 2011). Surprisingly, local evaporation rate of single-pin electrode was found higher than for multi-pin configuration (Lai and Sharma, 2005; Dalvand et al., 2013). Similar results for multi-wire discharge electrode were reported (Bardy et al., 2015). Obviously, to maximize total drying rate, optimal spacing between pins/wires should exist (Bai et al., 2011; Yang and Ding, 2016).

Non-uniform exposure of the material surface to EHD flow remains the critical issue for industrial application of EHD technology (Chen and Mujumdar, 2002). To the authors' best knowledge, the pattern of electrically-induced airflow in a multiple pin-plate geometry has yet not been investigated. Therefore, the objective of this study was numerical and experimental investigation of airflow and associated drying rate in a multiple-pin EHD dryer. Simulation and justification of multiple pin-plate discharge systems is extremely important for the industrial scaling and practical applications of EHD drying technology.

2. Materials and methods

2.1. Theoretical model

The numerical model for the corona discharge in a pin-plate configuration developed previously (Adamiak and Atten, 2004) has now been extended to quantify the effects of voltage, current, gap and spacing between pins. All simulations were based on the COMSOL (Comsol Inc, MA, USA) commercial software package based on the Finite Element Method (FEM). Although it may be less accurate than the numerical algorithms based on the hybrid FEM-Method of Characteristics, it runs much faster and is applicable for 3D geometries (Adamiak, 2013).

2.1.1. Assumptions

Material:

1. Free water evaporation takes place from the material surface.
2. Moisture and temperature gradients within the material are negligible.
3. Diffusion of liquid water within the material is negligible as compared to capillary flow.

Fluid:

4. The humidity of EHD flow impinging and rebounding from the material is constant.
5. Air mass flow in the channel constraining the stream of ionic wind is unidirectional.
6. No aerodynamic interaction exists between convective airflows in neighboring channels.
7. Charge convection due to forced airflow does not exist.

Corona:

8. Varying air humidity and elevated temperature do not affect the corona discharge.
9. Reactions in ionization zone, leading to generation of numerous ions species, are neglected.
10. Drift zone is considered as filled with only one kind of ions.

2.1.2. Geometry

In the theoretical model, it is assumed that pins form a uniform infinite array with identical discharge cells. Each pin is a cylinder of given length and radius, ended with a conical section having hemispherical tip. The pin length, pin-to-pin spacing and air gap between the discharge and collecting electrodes were considered as the model variables. Given the symmetry of the pins placing geometry, only a triangular prism zone of a single pin electrode was analyzed. Fig. 1 shows how 10 × 10 mm triangular prism with the single pin was adopted to analyze infinite pin matrix with 20 × 20 mm cells. The origin of the x, y and z coordinate system coincided with the pin tip.

2.1.3. Simulation of the ionized electric field and EHD flow

The complete numerical model of the EHD flow generated by corona discharge is highly complex (Sattari et al., 2010). However, a simplified model, based on the so-called single-species approximation, is usually sufficiently accurate in engineering applications (Adamiak and Atten, 2004). This simplified approach is based on the assumption that outside the ionization region, called the drift zone, there is just one ionic species having the same polarity as the polarity of voltage applied to the discharge electrode. In this case, the following charge transport equation governs the ion density