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Electrohydrodynamic drying of multiple food products: Evaluating the potential of emitter-collector electrode configurations for upscaling

Thijs Defraeye[a,b,c,*], A. Martynenko[d]

[a] Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, 9014, St. Gallen, Switzerland
[b] Empa, Swiss Federal Laboratories for Materials Science and Technology, Multiscale Studies in Building Physics, Überlandstrasse 129, 8600, Dübendorf, Switzerland
[c] Chair of Building Physics, ETH Zurich, Stefano-Franscini-Platz 5, 8093, Zürich, Switzerland
[d] Department of Engineering, Dalhousie University, Agricultural Campus, PO Box 550, Truro, Canada

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ABSTRACT

Electrohydrodynamic (EHD) drying is a promising, non-thermal drying technology, based on ionic wind generation between an emitter and a collector electrode. This simulation-based study evaluates impact of various emitter-collector configurations for EHD drying in order to assess their potential towards industrial upscaling. The conventional wire-to-plate configuration, which creates impinging flow, is found not to be an optimal solution for EHD drying of multiple food products in a fast and uniform way. With a single wire (emitter), it is found that the products placed more downstream dry slower due to the progressive loading of the air with water vapor. With multiple emitters, up to a threefold increase in drying time of the food products is found, compared to a single wire. This increase is caused by the recirculation of most air. To avoid water vapor accumulation in the drying zone, a wire-to-mesh configuration is proposed. The mesh collector minimizes interference of neighboring airflows and avoids recirculation of moist air in the drying zone. As such, the wire-to mesh configuration provides more uniform drying between adjacent products, but also within a product, as it can dry from all its surfaces. An increase in emitter density for the wire-to-mesh configuration leads to an overall increase in air speed, but, surprisingly, not to increased product drying rates. The reason is that the high-speed EHD airflow is always generated very locally in the vicinity of the emitter and collector. Thereby the convective drying process is not affected so much by the emitter density.

1. Introduction

Electrohydrodynamic (EHD) drying is a non-thermal technology where ionic wind is created in order to improve the dehydration of heat-sensitive materials, predominantly food products (Bai et al., 2013; Martynenko and Zheng, 2016; Pirnazari et al., 2016; Singh et al., 2015; Taghian Dinani and Havet, 2015). A high voltage in the kilovolt range is imposed between an emitter and collector electrode, which induces corona discharge, so local ionization of the air, at the emitter. The movement of the ions towards the collector and their resulting collisions with air molecules lead to a net air movement. EHD drying is reported to reduce drying time and product shrinkage, to enhance rehydration capacity, to improve texture and to better preserve color, flavor and nutritional value (Bai et al., 2013; Ding et al., 2015; Esehaghbeygi et al., 2014; Esehaghbeygi and Basiry, 2011; Taghian Dinani et al., 2015, 2014; Yang and Ding, 2016). This promising alternative drying technology has been investigated for almost three decades, including by laboratory-scale tests (Barthakur, 1990; Chen et al., 1994; Hashinaga et al., 1999; Isobe et al., 1999), and working small-scale prototypes have been built (Lai, 2010). Nevertheless, EHD dryers are not commercially available yet, to our best knowledge.

The step towards industrial upscaling is hindered, amongst others, by the fact that most of the aforementioned studies focused on EHD drying of a single sample, using a wire/needle-to-plate configuration (Defraeye and Martynenko, 2018b). This sample was a single product or several small products (e.g. berries) spaced together to form one entity. Only rarely, multiple individual products were dried together (Taghian Dinani and Havet, 2015). In this case, effects of product spacing and heterogeneity on the drying rate have not been investigated. Industrial processes however require the simultaneous drying of large amounts of products. When using the wire/needle-to-plate configuration for this purpose, upscaling problems can occur (Defraeye and Martynenko,

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* Corresponding author. Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, 9014, St. Gallen, Switzerland.

E-mail address: thijs.defraeye@empa.ch (T. Defraeye).

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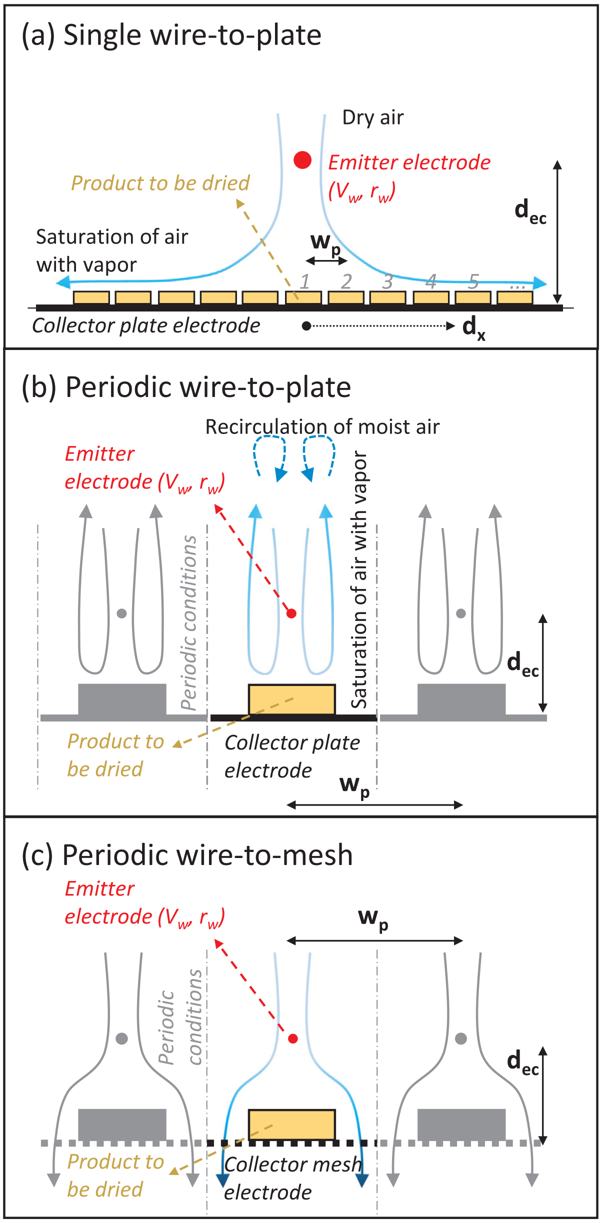

Fig. 1. Types of configurations for EHD drying of multiple products: (a) impinging flow for a single wire-to-plate configuration, (b) impinging flow for a periodic wire-to-plate configuration, (c) flow around the products for a periodic wire-to-mesh configuration. (emitter = red, collector = black; periodic conditions indicate that multiple products are placed sideways; not to scale).

2018b). For a single wire-to-plate configuration (Fig. 1a), it is probably difficult to achieve a uniform drying rate for multiple food products, located at different distances from the emitter. An EHD-driven air jet is directed towards the plate and is then diverted to the sides over the products. When air passes over successive products, partial saturation of the air with vapor will occur. This will likely reduce the drying rate of products more downstream, but this effect was not quantified yet. For a multiple wire-to-plate configuration (Fig. 1b), another problem arises due to the multiple air jets that bounce back from the product: partial saturation of the recirculating air with vapor will occur, which can also slow down the drying rate.

A better insight in the impact of the emitter-collector electrode configuration and spacing between multiple products on their drying rate and heterogeneity is required to enable further industrial upscaling. As a step towards drying large amounts of products faster and more uniform by means of EHD, this simulation-based study evaluates several configurations (Fig. 1). These include the conventional wire-to-plate configuration and the alternative wire-to-mesh configuration.

2. Materials and methods

The computational model, boundary conditions and simulation parameters are presented in detail in a previous study (Defraeye and Martynenko, 2018a), and therefore only the main features are highlighted here. The 2D continuum, finite-element model calculates convective EHD drying of rectangular apple fruit slices (L x H = 10 × 5 mm). Airflow is generated by placing a high voltage difference between a cylindrical wire ($V_w = 20$ kV, with radius $r_w = 250$ µm), i.e. the emitter electrode, and a grounded collector electrode, spaced at a distance $d_{ec} = 20$ mm. Under this electrostatic action, airflow is generated, which draws air at a temperature (T_{ref}) of 20 °C and a relative humidity (RH_{ref}) of 30% from the inlet towards the fruit to be dried. Multiple food products are spaced at a distance w_p. Three configurations of emitter-collector electrodes are evaluated for EHD drying (Fig. 1):

- (a) Impinging flow for a single wire-to-plate configuration, so where a single EHD air jet is generated. This case is evaluated for $w_p = 1.5$ L, 3L, 4.5L, 6L. As the size of the zone where the products are placed in is 30L, in total 19, 9, 7 and 5 products are included in the model, respectively. The width of the domain is extended to 60L to avoid an impact of the lateral boundaries on the drying process.
- (b) Impinging flow for a periodic wire-to-plate configuration, where an EHD air jet is generated above each individual fruit. This case is evaluated for $w_p = 4$L, 6L, 8L, 10L, 15L, 20L, 25L, 30L.
- (c) Flow around the products for a periodic wire-to-mesh configuration, where an EHD air jet is generated above each individual fruit. This case is evaluated for following $w_p = 4$L, 6L, 8L, 10L, 15L, 20L, 25L, 30L.

Note that for the two last cases, periodic boundary conditions are used, so only a single product needed to be explicitly modelled.

The computational model solves for (1) the electrostatic potential field, (2) the associated charge transport due to ion drift, caused by the corona discharge, (3) the resulting airflow generation due to ion movement and collision with neutral air molecules, (4) heat and mass transport in the fruit tissue due to convective, EHD-generated, airflow, which leads to dehydration. Airflow is coupled to the electrostatic field by a volumetric source term in the Navier-Stokes equations for turbulent flow, namely the Coulomb force. Out of the airflow calculation, the convective heat and mass transfer coefficients (CHTC and CMTC) are determined. These convective transfer coefficients are imposed afterwards on the product surface in order to calculate the impact of the airflow field on the fruit dehydration process. This model is implemented in COMSOL Multiphysics (version 5.2a), which is a finite-element based commercial software. The computational grid, time step, tolerances for convergence and other solver settings are determined from a sensitivity analysis. The electrical potential and space charge density are solved using linear shape functions together with a fully-coupled direct solver, relying on the MUMPS (MUltifrontal Massively Parallel sparse direct Solver) solver scheme. Turbulent airflow is solved using a segregated solver, relying on the PARDISO (PARallel DIrect sparse SOlver Interface) solver scheme. The drying process is solved using quadratic shape functions, together with a fully coupled direct solver, relying on the MUMPS solver scheme.

To compare drying efficiencies, the critical drying time (t_{crit}) is used (Defraeye and Verboven, 2017). It is the time needed for the sample to reach the critical moisture content (w_{crit}). The latter is defined as the (volume-)averaged moisture content in the sample that corresponds, via the sorption isotherm, to an equilibrium water activity $a_{w,crit} = 0.6$, below which no spoilage occurs. For the present study, w_{crit} is

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