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Electrohydrodynamic (EHD) drying: fundamentals and applications

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Abstract

Following background to the phenomenon of electrohydrodynamics with concise review of basic features like shorter drying time, lower energy consumption and better product quality, the selected key factors affecting EHD drying are examined. These include the geometry of discharge electrodes, effects of air humidity on drying rate, depression of material temperature, and cooling effect of ionic wind.

Examples are given for: (i) prototype EHD dryers of multi-belt types, and (ii) pilot-scale multi-belt EHD dryer in vertical arrangement that can be aggregated into one unit of higher capacity, and vertical cylindrical EHD dryer with vibrated shelves.

Keywords: *ionic wind; corona discharge; drying; energy; quality.*

1. Introduction

Electrohydrodynamic (EHD) drying appears to be a viable technology alternative to conventional thermal drying for certain thermally-labile 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.).[1-4]

The benefits of EHD compared to hot air drying on food quality include lesser shrinkage [15, 16], higher rehydration ratio [15], preserved content of ascorbic acid (vitamin C) [17] and no discernible color degradation [16-20], though Li et al· [21] reported distinctive browning of okara cake just under the needle electrode. The quality-related benefits can be attributed to increased drying rate respectively by 1.5 to 4 times at high (5 ms^{-1}) and low (1 ms^{-1}) cross-flow air velocity, which translates into shorter drying time [22, 23] Although the sole ionic wind can favorably affect mass transfer, the combinations of EHD with low-temperature air drying[4-6], vacuum freeze drying[7] and auxiliary contact heating [8] have also been reported.

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 no heat lost with exhaust air. However, the favorable low energy consumption given in published papers is based on the "net" energy calculated from the applied voltage and current. Even though the real energy consumption by EHD and peripheral equipment ranges from 90 to 5000 $kJkg^{-1}$ [2] it is still attractive for end used of EHD dryers. The energy-related issues in EHD drying have been reviewed by Kudra and Martynenko.[23]

Aside from purely experimental research on EHD drying of apples, carrot, potato, tomato, mushrooms, spinach, rapeseed, grapes blueberry, cranberry, etc., as well as model materials such as water, paper tissue, agar gel, wet sand and glass, theoretical studies on EHD drying are focused on determination of the ionic wind characteristics, such as space charge and corona current distributions [9, 10] or numerical solution of the mathematical model with experimental validation through drying experiments.[11-14]

Electrohydrodynamic (EHD) drying relies on the so-called corona (electric or ionic wind), originating from a sharp electroconductive needle or horizontal fine wire under high AC or DC voltage.[24] As a result, ions leaving discharge electrode impinge the surface of the drying material located on the metallic and electrically grounded plate-type electrode. The partially ionized gas molecules along with residual non-charged molecules create a jet-type gas flow between the discharge (needle or wire) electrode and the collecting (solid or perforated plate) electrode. Since some factors affecting EHD drying (e.g., voltage, current, temperature) are well presented in topical literature [25], this paper is focused on less elaborated factors, such as desirable geometry of electrodes and air humidity on EHD drying. Examples of large-scale dryers are also given.

2. Key factors in EHD drying

2.1. Geometry of discharge electrode

The fundamental studies on EHD drying were performed mostly with a single pin or wire, and only few of them used multi-pin electrodes, yet placed arbitrarily regarding geometrical arrangement (e.g., rectangular or triangular) and spacing between pins. However, because of conical form of the ionic wind [26], the impact surface of the wind from a single pin electrode on the plate electrode is circular unless disturbed by the air cross-flow, for example. Referring to multi-pin electrode it is intuitive to expect that the minimum distance between pins at a definite pin-to-material gap should result in a series of circular areas on the material surface which almost touch each other.[22]

It should be noted that the gaseous jet of ionic wind impinging the material under drying rebounds from the material surface along with the stream of evaporated moisture, which affects the aerodynamics of neighboring jets emitted from a multi-needle or multi-wire electrode. It means that the optimum spacing of pins is larger than theoretically predicted. This conclusion is supported by our own research [26] and literature data which indicate that single-pin electrode performs better that the multi-pin electrode.[27] The same effect is expected for multi-wire discharge electrode.

2.2. Effect of air humidity

Even though the air humidity plays significant role in the process of drying, its effect on the EHD performance has rarely been studied. Air humidity was measured in several studies by Lai[28] to calculate the Sherwood number but no explicit relationship for relative humidity was given. Bai et al.[29] presented results of vacuum freeze drying, which revealed better performance of EHD drying at ambient temperature 18ºC and relative humidity of 45% versus vacuum freeze drying (conditions were not specified, however).

To fill this gap in the knowledge we performed targeted research on EHD drying of sliced white champignons at various humidity levels controlled by dehumidifier.[30] The results show that high air humidity is detrimental for the performance of EHD drying. Decreasing air humidity from 70 to 30% significantly increased drying rate (drying rate constant increased more than threefold from 0.12-0.13 to 0.45-0.5 h^{-1}). These experiments confirmed that low air humidity is definitely desirable in EHD drying.

2.3. Depression of material temperature

Among various electrically-induced phenomena in EHD drying[2, 25] is a noticeable temperature drop in the boundary layer at the liquid-gas interface[31, 32], which was identified as large as 8 K per 100 micrometers.[33] Usually temperature depression of wet material is a result of water evaporation, which depends on the gradient of water vapor pressure at the liquid-gas interface. The maximum value of temperature depression could be calculated through absolute air humidity Y (kg H_2O) (kg^{-1} dry air)

$$T_{DB} - T_{WB} = \frac{\Delta H_{WB}}{c_H}(Y_{sWBT} - Y) \qquad (1)$$

where T_{DB}, T_{WB} denote respectively the dry- and wet-bulb temperatures (K), ΔH_{WB} is the latent heat of evaporation at wet bulb temperature (kJ kg^{-1}), c_H quantifies the humid heat (kJ kg^{-1} K^{-1}), and Y_{sWBT} stands for the absolute air humidity at wet bulb temperature.[34] Our own research aimed at measuring temperature of the wet paper towel with thermal imaging camera revealed noticeably difference between air/material temperatures during EHD drying under controlled humidity of 11% and different air velocities.[35]

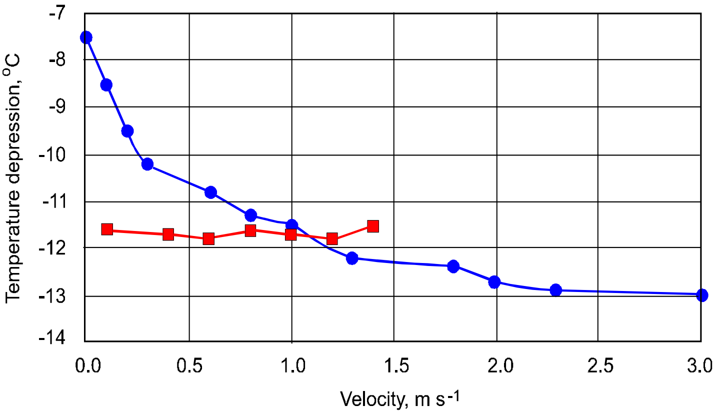

Fig. 1 Magnitude of temperature depression for paper towel exposed to forced air flow at 21.6°C (blue points) and ionic wind (red points) generated at 9.5-15 kV.

It is evident that the temperature drop in humid air reflects typical psychrometric curve leveling off at high air velocity (above 6 ms^{-1}). Thus, the cooling effect of air flow is directly related to air velocity. In contrast, temperature drop due to ionic wind demonstrated completely different behavior. The range of ionic wind velocities below 1.0 ms^{-1} corresponded to electric field strength 3-4 $kVcm^{-1}$ (9.5-12 kV), whereas ionic wind velocity above 1.0 ms^{-1} was induced by electric field above 4 $kVcm^{-1}$ (13-15 kV). Interestingly, temperature drop due to ionic wind is larger than the effect of similar air flow at the range of low velocities, while is smaller for the velocity above 1.0 ms^{-1}. However, it should be noted that EHD-induced temperature of the material surface never attains the wet bulb temperature at convective air flow, which in this case is 13°C at RH=11%. Interestingly, the cooling effect of EHD was found practically independent of ionic wind velocity up to 1.5 ms^{-1} above which the breakdown occurred because of excessively high electric field intensity.

2. Large-Scale EHD dryers

2.1. Prototype EHD dryers

It appears that the first prototype EHD dryer has been designed in Ukraine, in 1989 and tested for sliced apples.[36] The dryer has been built as a three-band conveyor unit fed with wet material at the upper band and discharged from the lower band. Although the dryer operates continuously with respect to material flow down from band-to-band the air in the dryer is basically stagnant. It means that moisture released from wet material builds-up air humidity and concentrations of volatile compounds and ionization products such as ozone. Therefore, after certain period the feeder is stopped and the empty dryer is blown with fresh ambient by a draft fan. The drying cycle is then repeated with the new batch of a drying material. The bands 0.8 × 0.3 m are driven at controlled velocity from 0.1 to 1 m/min. The needles in discharge electrodes with optimum packing density of 500 needles per 1 m^2 are made from molybdenum and powered with 10 to 30 kV AC at 50 Hz. The density of current about 0.01 A m^{-2} and power of 100 W m^{-2} results in apple temperature by 20 deg higher than the ambient temperature. Energy consumption for drying apple slices from 85 to 20% wb is on the order of 0.95-1.1 kWh per kg of evaporated water.

Another prototype of EHD continuous dryer is based on two belt conveyors 0.3 m wide and 3 m overall length with inter-stage mixing of the material.[37] Belts tilted at 11.5º are driven at fixed velocity of 0.33 ms^{-1}. Wire-type discharge electrode is made from stainless steel wire 0.5 mm in diameter with 5 cm spacing between neighboring wires. The wires arranged in parallel through a cable bus are connected to reversible polarity DC power supply with regulated voltage from 1 to 50 kV and current from 0 to 0.3 mA.

Tests with wet sand at 8-12 % wb in a 2-cm layer with 2.52 cm gap between discharge electrode and the material surface revealed drying enhancement by 1.35 at 12 kV and throughput of 3.1 kg of evaporated water per 1 hour. This dryer can be used for processing of granular materials in size up to 10 mm such as sand, gravel, preformed (extruded) pastes as well as sliced or diced fruits and vegetables.

2.2. Pilot-scale EHD dryers

As of year 2018 there is no information on commercially available EHD dryers. However, large EHD dryers of various designs have been custom-made in China for research purpose[38]. These dryers are basically of two types: (i) multi-band dryer in vertical arrangement (GXJ-2) that can be aggregated into one unit (GXJ-16), and (ii) vertical cylindrical dryer (GTJ-1.7) with vibrated shelves (Fig. 2).

The overall size is 1.6×1.7× 2.4 m (for GXJ-2) and 5.2×3.5× 3.1 m for GXJ-16 where numbers in the model signify drying area in m^2. Depending on the material, drying rate is over 3 kg of water per m^2h at corona power of 0.4 and 3.2 kW, respectively. The dryer is equipped with dehumidifier with power 0.37 and 5.5 kW, respectively. The dryer GTJ-1.7 is 1.7 m in diameter with 5 shelves with drying area of 10 m^2 vibrated with amplitude 0-4 mm. Drying rate is over 5 kg of evaporated water per m^2h at corona power 2.2 kW. These dryers were used to dehydrate various whole and cut fruits and vegetables including specific plants used in Chinese medicine.

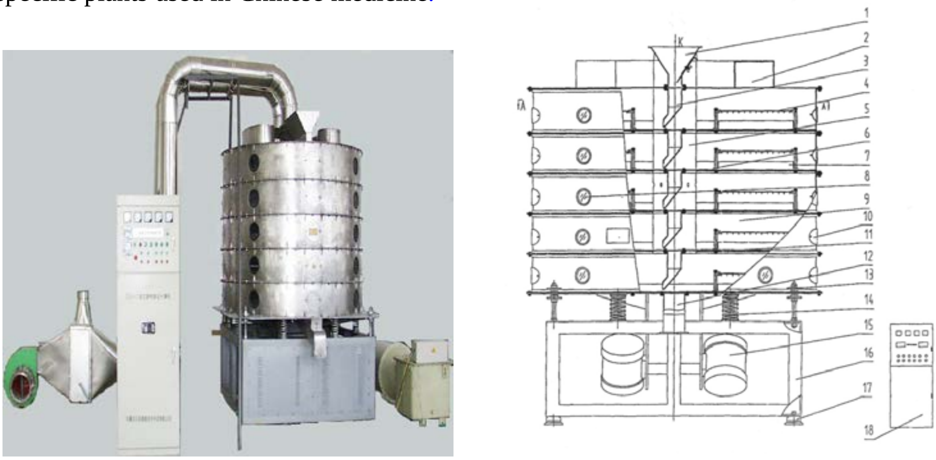

Fig. 2 The picture and schematics of the EHD dryer model GTJ-1.7. [38]

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