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Transient exergetic efficiency and moisture loss analysis of forced convection drying with and without electrohydrodynamic enhancement

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A B S T R A C T

EHD drying (Electrohydrodynamic convective drying) is a novel drying method used to enhance FC drying (forced convection drying) by using a wire-electrode to create an electrostatic field. In this work we studied the dehydration of a food product by means of FC verses EHD drying using three different wire-electrode configurations determined by a prior study. Airflow velocity was set to 1.0–3.0 m/s for FC drying, and 0.3 m/s for EHD drying (applied voltage of 16 kV) at a temperature and relative humidity of 30 °C and 17%, respectively. Drying rates were analyzed as well as the overall and time dependent (transient) exergetic efficiency by means of a specific model. It was found that EHD drying yielded approximately the same drying rate and used exergy as FC drying with airflow velocities of 1.0–2.0 m/s. Both overall and transient exergetic efficiencies were found to be significantly higher for EHD drying compared to FC drying. This was attributed to the lower velocity associate with EHD drying. It was therefore concluded that EHD drying, using the three wire-electrode configurations analyzed in this study, can yield the same drying rate as FC drying, but with significantly lower airflow velocities, and therefore higher exergetic efficiencies.

1. Introduction

Drying is an energy intensive unit operation encountered in many industrial sectors. The process is mainly used for lowering the amount of water mass in foods such as fruits, vegetables, spices and other products with high moisture content (>80%) [1]. Drying offers many benefits including: extended shelf-life, reduced packaging, storage, handling and transportation costs along with out-of-season availability [1]. Several developed countries have reported that between 12 and 20% of their national industrial energy consumption is due to thermal dehydration operations [2]. Several innovations have been developed that attempt to improve product quality and energy efficiency such as, but not limited to, microwave-assisted drying [3,4], superheated steam drying [5,6], infrared drying [7], heat pump drying [8–10] and solar convective dryers [11]. Still, over 85% of industrial dryers are convective type with hot air or combustion gases as the heat transfer medium [1,12]. Forced convective drying (FC drying) in particular uses high air velocity which leads to high energy consumption [13] and low efficiency [14].

One innovative approach to reducing this high energy consumption, and thereby increase efficiency, is through electrohydrodynamic drying (EHD (Electrohydrodynamic) drying). The main principle behind EHD drying is to generate a corona discharge by one or more electrodes placed in an air stream in order to disrupt the primary airflow. The ionic air stream significantly alters the boundary layer, and intensifies convective heat transfer between the air and the drying product for low primary airflow velocities. Recent work demonstrates the benefits of such a process, especially that the electric forces involved are effective with low air speed in the drying tunnel [15–17]. The application of the electrostatic field results in an increased drying rate [18], and an overall reduction in energy consumption [16,19–22]. Many studies have investigated the EHD drying effect on specific food products such as, but not limited to rapeseed (Brassica napus L) by Basiry and Esehaghbeygi [18], okara cake by Li et al. [17], wheat by Cao et al. [19], banana slices by Pirnazari et al. [23], mushroom slices by Dinani et al. [24,25], cooked beef by Ding et al.[26] and Spanish mackerel by Bai et al. [27].

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Other studies have investigated the process itself. For example, Ould Ahmedou et al. [13] used a numerical analysis to study heat transfer enhancement by the EHD effect; Singh et al. [21] evaluated and discussed, from the literature, experimental investigations carried out to explain the effect of operating parameters on the drying rate and specific energy consumption (kJ/kg water) of the EHD process. Bajgai et al. [22] reviewed the prospect of EHD drying for non-thermal processing of biological materials. Dinani and Havet [28] varied primary airflow velocity and applied wire-electrode voltage to study the effects of drying kinetics, drying rate, final moisture content and specific energy consumption of mushroom slices.

Some investigators have worked on improving the performance of EHD drying by varying electrode configurations. Lai [29] investigated the effect of a multiple-needle electrode on the EHD drying of wetted glass beads and found, in terms of energy per mass, that a single electrode was more effective than multiple electrodes. Goodenough et al. [30] commented, in a study on the efficiency of corona wind on paper towels and biscuits, that “the arrangements of the electrodes is crucial for effective operation.” A recent study by Hamdi et al. [31], which was similar in principle to Lai [29], investigated the direct heat transfer enhancement associated with EHD flow due to varying wire-electrode arrangements. In that particular study, a horizontal airflow channel was used to study three different wire-electrode arrangements (i.e. one wire-electrode arranged parallel to airflow, one wire-electrode arranged perpendicular to airflow, and two parallel wire-electrodes arranged parallel to airflow). For each configuration, parameters such as the wire-electrode to plate distance, applied voltage, and airflow velocity were varied. Airflow was controlled at a fixed temperature and relative humidity. The convective heat transfer coefficients were determined by directly measuring the temperature at the surface of a heated plate by means of thermal imaging. It was found that a maximum applied voltage of 16–20 kV at an airflow velocity of 0.3 m/s resulted in the greatest increases in the convective heat transfer coefficient as compared to pure forced convection. More specifically, when comparing all three wire-electrode configurations for an applied voltage of 16 kV, one wire-electrode arranged parallel to airflow resulted in the greatest increase in heat transfer. Hamdi et al. [31] therefore demonstrated a direct increase in convective heat transfer due to EHD flow when compared to pure force convection, although no direct measure of drying rate or efficiency was measured for any specific food product.

In order to quantify how EHD drying improves upon conventional FC drying on a food product, it is important, first, to choose a model that appropriately quantifies the efficiency in terms of food product drying rate, and energy consumption in conditioning the air. This can be done by an energy or exergy analysis. When computing efficiency for FC drying in terms of an energy analysis (i.e. the first law of thermodynamics), there would be large differences in efficiency depending on the type of process used for conditioning the air (e.g. saturated cooling for dehumidification vs. using a desiccant dehumidification wheel). A model for computing a first law, or energy efficiency, on a particular FC drying process would need to take this into account. For example, in a study by Kudra [32] on the energy performance of convective dryers, energy efficiency was computed by only considering the energy used to heat/dry the air. If another process were used to treat the air, that would change the “perceived” energy efficiency. In an exergy analysis (i.e. the second law of thermodynamics), on the other hand, the “availability” of the flowing air can be expressed in terms of the state difference between the condition of the air used for drying and the dead state. Prommas et al. [33,34] used both energy and exergy to analyze the performance and efficiency of convective drying on porous media. Erbay and Icier [35] used both energy and exergetic efficiency to analyze the effects of drying temperature and air velocity on the drying of olive leaves. In another study, Aviara et al. [36] performed an energy and exergy analysis on native cassava drying in a tray dryer. A study by Dincer and Sahin [37] demonstrated the usefulness of exergy analysis in the thermodynamic assessment of drying processes by presenting expressions for exergetic efficiency. These expressions were derived based on modeling the drying process as an open system with a steady-state input and output of moist products to be dried. This did not take into account, however, transient effects on drying parameters. As noted in a study by Amantea et al. [38] on the drying of cereal grains, the energy and exergy used to evaporate the water depend directly on both the spatial and temporal values of the product temperature and moisture content. In addition, any exergetic efficiency model for EHD drying would have to take into account the exergy rate due to the applied voltage.

The purpose of this study was to use the wire-electrode configurations determined by Hamdi et al. [31] to compare the drying performance of EHD drying compared to FC drying. Drying performance was quantified in terms of drying rate and transient and overall exergetic efficiency by means of a proposed model [39]. Results were compared to FC drying to determine which primary airflow velocities would result in the same drying rate as EHD drying. In addition, results were also used to determine if the wire-electrode configuration (determined by Hamdi et al. [31]) that resulted in the greatest heat transfer enchancement also correlated to the greatest moisture loss.

2. Modeling transient exergetic efficiency

For this study, an expression for exergetic efficiency as a function of time (i.e., transient exergetic efficiency) was proposed by modifying a model presented by Dincer and Sahin [37]. The modified model accounts for the changing drying rate over time of a drying product located inside the control volume. In addition, the moisture in the drying product is assumed to be in a saturated liquid water state at the drying product temperature (i.e. drying specimen temperature, $T_{specimen}$). The liquid water is then evaporated to a saturated vapor state at the temperature of the air at the inlet of the airflow channel (T_{in}). It is further assumed that $T_{specimen} = T_{in}$. A preliminary version of this expression was presented by Bardy et al. [39].

A transient exergetic efficiency was defined as the ratio of the exergy use rate to evaporate moisture from the drying product ($\dot{\psi}_{use}$) over the exergy supply rate ($\dot{\psi}_{supply}$) as shown in equation (1). The exergy use rate to evaporate moisture from the drying product ($\dot{\psi}_{use}$) is shown in equation (2). The exergy supply rate ($\dot{\psi}_{supply}$) is shown in equation (3), and is defined for both FC and EHD drying. For FC drying, the exergy supply rate was due only to the air (the state difference between the air at the inlet of the drying tunnel and the dead state, $\dot{\psi}_{air}$). The exergy supply rate of the air ($\dot{\psi}_{air}$) is shown in equation (4), and is broken down into three components: thermal, mechanical and chemical, as defined according to a study by Ren et al.[40]. It is assumed that $P_{in} = P_0$. For EHD drying, the exergy supply rate also took into account the exergy supply due to the EHD effect ($\dot{\psi}_{EHD}$), shown in equation (5).

It is also noted that the overall exergetic efficiency, as well as the overall exergy used for evaporation, exergy supplied of the air, and exergy supplied by the EHD effect can be determined by integrating equations (1), (2), (4) and (5), respectively.

$$\dot{\eta} = \frac{\dot{\psi}_{use}}{\dot{\psi}_{supply}} \tag{1}$$