ANALYSIS OF THE ENERGETIC AND EXERGETIC EFFICIENCY OF THE ELECTROHYDRODYNAMIC DRYING PROCESS

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ABSTRACT

Drying is an energy intensive unit operation encountered in many industrial sectors, especially in the food industry. Still over 85% of industrial dryers are convective type. Electrohydrodynamic convective drying (EHD drying) is a novel drying method used to enhance forced convection drying by using electrodes to create an electrostatic field and generate an electric wind. This latter may alter the boundary layer and enhance the heat and mass transfer. In this study, experiments were performed to analyze the drying kinetics during EHD and forced convection (FC) drying experiments. Transient energy and exergy efficiencies expressions were discussed, proposed and computed for each experiment. With airflow of 0.3 m/s in the case of EHD configurations, similar drying rates than FC at 1.0 - 2.0 m/s can be achieved. Moreover, it leaded to greater energy efficiency (x5) and it was confirmed, using exergy efficiency concept, that EHD better used energy than FC.

Keywords: ElectroHydroDynamic, Drying, Convection, Energy, Exergy

1. INTRODUCTION

Drying is an energy intensive unit operation encountered in many industrial sectors, especially in the food industry. It offers many benefits including: extended shelf-life, reduced packaging, storage, handling and transportation costs. Several developed countries have reported that between 12 – 20% of their national industrial energy consumption is due to thermal dehydration operations (Mujumdar, 2014). Still, over 85% of industrial dryers are convective type with hot air or combustion gases as the heat transfer medium (Moses and Norton and Alagusundaram and Tiwari, 2014). Several innovations have been developed to improve product quality and energy efficiency. Forced convective drying (FC drying) uses high air velocity which leads to high energy consumption. One innovative approach to reducing this energy consumption is through ElectroHydroDynamic drying (EHD 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 focus on the influence of operating parameters on energy consumption (Ould Ahmedou and Rouaud and Havet, 2009, Bai and Hu and Li, 2011). Some studies have investigated the EHD drying effect on specific food products (Taghian Dinani and Havet, 2015) and pointed out its interest.

An effective drying process should account for the sustainability issue (Amantea and Fortes and Martins and Ferreira, 2011). Combining energy and exergy analysis is powerful for modeling and optimizing food drying. In a pioneering work, the usefulness of exergy analysis in the thermodynamic assessment of drying processes was demonstrated (Dincer and Sahin, 2004). Based on this approach, an expression for exergetic efficiency was adapted to EHD Drying (Bardy and Hamdi and Havet and Rouaud, 2015). In this work, both energy and exergy analysis are performed on a EHD drying process and the influence of operating parameters is discussed.

2. EXPERIMENTAL PROCEDURE

2.1. Experimental set-up

The set-up (Figure 1) consisted of a rectangular airflow channel (15 cm x 19 cm x 200 cm) used to perform drying experiments by means of forced convection with and without an electrostatic field (i.e. EHD and FC drying).

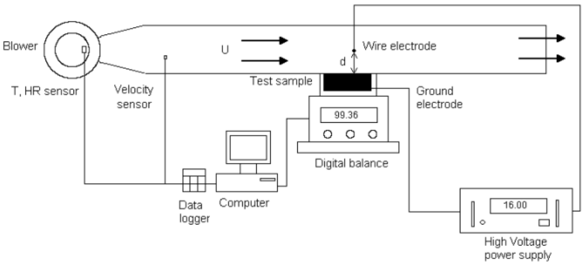

Figure 1: Experimental set-up

The mass loss was measured during drying using a weight scale (Radwag, PS600, Germany). The channel was connected to an air handling unit (ML180, Munters, France) used to control the psychrometric conditions, and the flow rate of the air entering the channel. The averaged temperature and relative humidity at the inlet of the airflow channel were T_i=28.9±0.5 °C and RH_i=16.8±0.7%. A wire-electrode(s) (diameter = 150 µm) suspended above the test specimen was connected to a high voltage generator (GLHT2260R2, Sefelec, France) in order to produce an electrostatic field. Details on this set-up and the methods are available (Bardy and Hamdi and Havet and Rouaud, 2015). From a preliminary experimental work on convective heat transfer enhancement (Hamdi 2014), a total of three different wire-electrode configurations were used for EHD drying in this study:

- 1 wire-electrode aligned perpendicular to airflow (Perp.),
- 1 wire-electrode aligned parallel to airflow (Paral. 1),
- 2 wire-electrodes arranged parallel to each other and aligned parallel to airflow (Paral. 2).

For each configuration, an applied voltage V=16 kV and an airflow velocity of 0.3 m/s were considered. The evolution of the electric current I was recorded over the drying experience. The wire-electrodes were placed according to the positions that resulted in the greatest increase in heat transfer (Hamdi 2014). Table 1 shows the exact arrangement of each configuration. For Forced Convection cases (FC drying), the airflow velocity were 1 and 2 m.s^{-1}.

Table 1: Dimensional placement of wire-electrodes for EHD drying experiments

Electrode arrangement	Perpendi - cular	Parallel	Parallel
Number of electrodes	1	1	2
Gap between electrode and surface (cm)	6	4	4

For this study, methylcellulose gel was chosen to be used as a test specimen because its thermophysical properties are close to those of meat it and can be controlled to a specific moisture content. Dimensions of test specimens were 15 x 15 x 1 cm and the moisture content was fixed at 80% (i.e. moisture content on dry basis: X_{db}= 4 kg w/kg dm). Average test specimen mass was 231.33 g ± 8.82 g.

2.2. Drying kinetics

The evolution of mass of the product m_p over time was used to compute the moisture content on dry basis over time as well as the drying kinetics (1) and (2).

$$X_{db}(t) = \frac{m_p(t)}{m_{dc}} - 1 \qquad (1)$$

$$\frac{dX_{db}}{dt}(t) = \frac{X_{db}(t_i) - X_{db}(t_{i-1})}{t_i - t_{i-1}} \qquad (2)$$

3. ENERGY AND EXERGY EFFICIENCIES

As the moisture in the the drying product is assumed to be in a saturated liquid water state at the drying product temperature (i.e. product temperature, T_p), 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_i). It is further assumed that $T_p = T_i$. Mass, energy and exergy balances for the system (Figure2) were performed by Hamdi (2014).

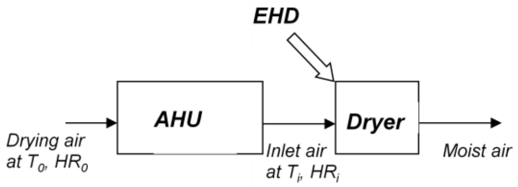

Figure 2: Sketch of Air Handling Unit and Dryer

3.1. Energy efficiency

Since the previous assumption, the energy use rate to evaporate moisture from the drying product is trivial (3). When computing energy efficiency, large differences may occur due to the dependence with the type of process used for conditioning the air. To avoid this effect, some author (Kudra 2012) calculated the energy performance by considering the energy used to heat/dry the air. It is possible to calculate this specific energy consumption by the difference between the enthalpy available in the drying air and a reference state (Amantea and Fortes and Martins and Ferreira, 2011). Nevertheless, this approach overestimates the energy efficiency because it completely makes abstraction of technology constraints. We propose in this study to calculate a realistic energy for the AHU based on the minimal energy required to deliver air from the standard conditions (T_0, RH_0, ω_0) to the measured inlet conditions in the dryer (T_i, RH_i, ω_i). We theoretically calculate that air should be dehumidified from the standard conditions (T_0, ω_0) to an intermediate stage (T_0, ω_i) and then heated to the inlet conditions (T_i, ω_i). The energy required to treat the drying air is then broken in two terms (4). This method minimizes the energy consumption in the Air Handling Unit because the dehumidification would require a higher cooling power. Using the energy use rate to evaporate moisture (3), the energy supplied by the AHU (4) and the energy supplied by the EHD sytem (5) we calculated a transient energetic efficiency (6).

$$\dot{Q}_{vap} = \dot{m}_w L_v \qquad (3)$$

$$\dot{Q}_{air} = \dot{m}_{da} \left| h_{interm} - h_0 \right| + \dot{m}_{da} \left(h_i - h_{interm} \right) \qquad (4)$$

$$with\ h = h_{da} + \omega\, h_v$$

$$\dot{Q}_{EHD} = VI \qquad (5)$$

$$\dot{\eta}_{en}(t) = \frac{\dot{Q}_{vap}}{\dot{Q}_{air}+\dot{Q}_{EHD}} \tag{6}$$

3.2. Exergy efficiency

An expression for exergetic efficiency as a function of time (i.e., 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 (7). The exergy use rate to evaporate moisture from the drying product ($\dot{\psi}_{use}$) is shown in equation (8). The exergy supply rate due to the air (the state difference between the air at the inlet of the drying tunnel and the dead state ($\dot{\psi}_{air}$), is shown in equation (9). It is broken down into three components: thermal, mechanical and chemical. Contrary to the definition of the energy supply rate for air, this definition is shared by the energy community. The exergy supply due to the EHD effect ($\dot{\psi}_{EHD}$) is shown in equation (10).

$$\dot{\eta}_{ex}(t) = \frac{\dot{\psi}_{use}}{\dot{\psi}_{air}+\dot{\psi}_{EHD}} \tag{7}$$

$$\dot{\psi}_{use} = \left(1 - \frac{T_0}{T_p}\right)\dot{Q}_{vap} \tag{8}$$

$$\dot{\psi}_{air} = \dot{m}_{air}\begin{bmatrix} (C_{p,a} + \omega_i C_{p,v})\left(T_i - T_0 - T_0 \ln\left(\frac{T_i}{T_0}\right)\right) \\ +T_0(R_a + \omega_i R_v)\ln\left(\frac{P_i}{P_0}\right) \\ +T_0\begin{Bmatrix} (R_a + \omega_{in}R_v)\ln\left(\frac{1+1.6078\omega_0}{1+1.6078\omega_i}\right) \\ +1.6078\omega_i R_a \ln\left(\frac{\omega_i}{\omega_0}\right) \end{Bmatrix} \end{bmatrix} \tag{9}$$

$$\dot{\psi}_{EHD} = VI \tag{10}$$

For each case, the dead state was assumed to be T_0 = 20 ºC, P_0 = 101.3 kPa, and RH_0 = 50% (standard conditions as stated by ISO 5011). It should be noticed that the overall energetic and exergetic efficiencies, can be determined by integrating equations (3) to (10).

4. RESULTS AND DISCUSSION

4.1. Drying kinetics

Figure 3 presents the variation of the moisture content X_{db} of the drying product as a function of time. As expected, the moisture content decreased over time for each experiment. It can be seen that the EHD cases are between the FC drying at 1 m/s and the FC drying at 2 m/s. This latter provides the greatest decrease. For the EHD cases, one wire-electrode parallel to airflow had a greater moisture loss over time than other cases and a moisture loss equivalent to that of FC at 2.0 m/s. It corresponds to the best case also found by Hamdi (2014) who look at the convective heat transfer enhancement. It is noted that the moisture content of all cases would converge if drying continued towards the point of equilibrium moisture content.

It is also interesting to compare the drying kinetics using the evolution of the drying rate (2) according to the moisture content (figure 3). This type of representation is known as Krischer curve. From the initial moisture content to a value of 3.5 g w/g dm, there was a fluctuation in drying rate with an initial decrease in drying rate followed by an increase. The drying rate then decreased steadily for the remainder of the experiment. FC at 2.0 m/s resulted in the greatest initial fluctuation in drying rate. This initial decrease and then increase was also present for EHD cases although not as pronounced. This initial decrease of the drying rate is attributed to the formation of a thin crust during the gel preparation. The water diffusion across this layer is reduced. The increase is more conventional, it corresponds to a thermal effect. As the product was colder than air, the surface temperature increased to the air wet-bulb temperature and provokes an enhancement of diffusion phenomena. The maximum values of the drying rate correspond to the period when the heat transfer by convection is used to evaporate water at the surface. As drying continues, moisture, entrapped within the product, diffuses towards the surface. This diffusion effect becomes more significant as time progresses and causes the drying rate to decrease. As previously, one can distinguish that the one wire-electrode parallel to airflow is equivalent to that of FC at 2.0 m/s and quite higher than other cases. A deeper analysis of drying phenomena may be performed by measuring shrinkage phenomena and quality attributes. Nevertheless, at this stage, it is important to consider that similar drying were obtained by convection with an airflow velocity at 0.3 m/s assisted by EHD and by forced convection at 2 m/s. The benefit of EHD drying should be discussed from an energetic point of view.

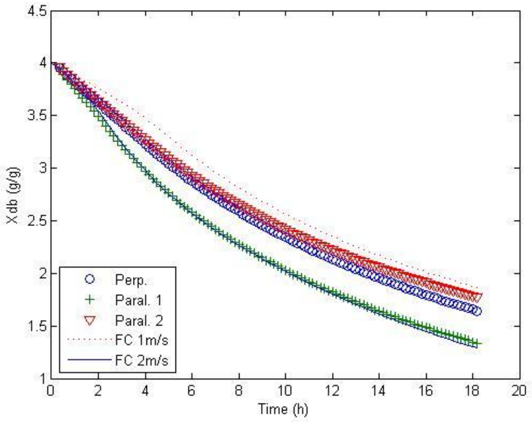

Figure 3: Moisture content as a function of time for each EHD and 2 FC drying cases

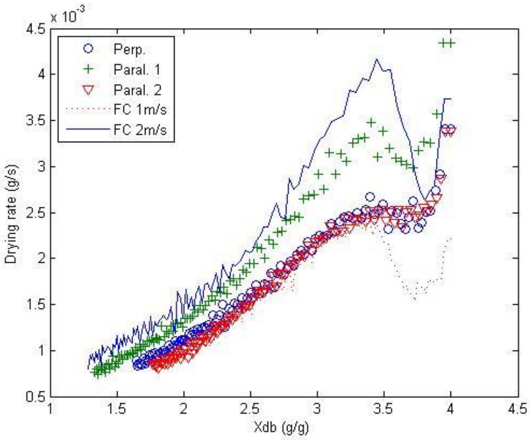

Figure 4: Drying rate as a function of Moisture Content for each EHD and 2 FC drying cases

4.2. Energy and exergy efficiencies

The evolution of the energetic efficiency during the time is depicted on figure 5. It should be firstly mentioned that the maximum energy efficiency is only close to 5%. This value could be considered as extremely low compared to results from literature (Amantea and Fortes and Martins and Ferreira, 2011, Kudra 2012, Hamdi 2014). It is firstly merely due to the definition of the energy supply for air treatment. Considering another definition would increase the energy efficiency but it would not affect the comparison of each case. Moreover, the surface of the specimen was relatively small (15 x 15 cm) compared to the airflow rate and the specific humidity of air did not evolve a lot inside the channel.

It clearly appears that FC cases have very low energy efficiencies compared to EHD case. EHD is 4 to 5 times more efficient. This great difference is due to airflow rate because the velocity is only 0.3 m/s in EHD case whereas it is up to 2 m/s for FC drying. In the first hours, we observe fluctuations due to the evolution of the drying rates but after 5 hours drying, all EHD cases reach similar values of energy efficiency. This values decrease from 3 to 1 % during the drying time.

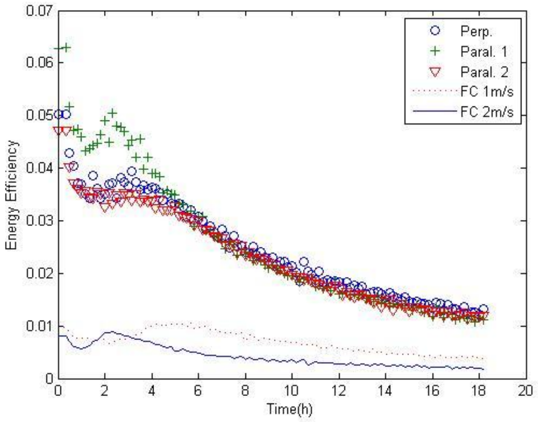

Figure 5: Energetic efficiency as a function of time for each EHD and 2 FC drying cases

The evolution of the exergetic efficiency during the time is depicted on figure 6. It is amazing to see that the values are quite similar to that of energy efficiency. They are in a classical order of magnitude found in literature with values lower than 10% (Dincer and Sahin 2004, Amantea and Fortes and Martins and Ferreira, 2011). The differences in exergetic efficiency between the EHD and FC cases can be attributed to the airflow velocity since the psychrometric inlet conditions of the primary airflow were held constant. The same dead state conditions were assumed for all experimental runs. It is noted that variations in the dead state assumption would lead to variations in computed exergetic efficiencies, but only in scale. For FC cases, exergetic efficiencies are still extremely low and increasing the air velocity reduces the efficiency. It is due to water diffusion that becomes the dominant mode and increasing convection is not relevant at all.

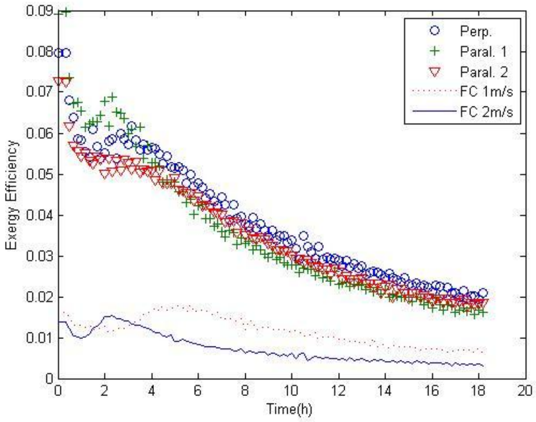

Figure 6: Exergetic efficiency as a function of time for each EHD and FC drying case

5. CONCLUSION

Expressions for the transient energetic and exergetic efficiencies of EHD drying were presented. The energy efficiency considered a minimum energy required to deliver air. The exergy efficiency took into account the power consumed by the EHD effect. The drying experiments indicated, that in the case of the EHD configurations, the same drying rate for FC at 1.0 - 2.0 m/s can be achieved with an airflow of only 0.3 m/s, leading to greater energy and exergy efficiencies. It should also be mentioned that these promising results could possibly be optimized by working with a higher applied voltage. This is a major finding that will also contribute to the design of low energy consumption process for air conditioning.

All EHD drying configurations had significantly higher energetic and exergetic efficiencies than FC drying, especially at the beginning of the drying. The higher exergetic efficiencies were due to the lower airflow velocity associated with EHD drying.

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AUTHORS BIOGRAPHY

Michel Havet received the PhD degree in Fluid Mechanics and Thermal Engineering at the University of Poitiers in 1995. He works since this date at ONIRIS, a public institute of higher education and research affiliated to the French Ministry of Agriculture. He is professor since 2008 and is currently assistant Director of the Joint Unit Research GEPEA 'Laboratoire Génie des Procédés Environnement Agroalimentaire', (UMR GEPEA 6144) and Head of the Research team 'Energy Engineering' in this laboratory. His main research interests concerns the enhancement of heat and mass transfer in convective food processes. He already supervised 8 PhD students and is actually supervising 2 PhD students. He wrote more than 50 scientific articles and 5 book chapters. He previously collaborated to 3 European projects. He is member of national scientific association and of the commission C2 'Food science & engineering' of the International Institute of Refrigeration since 2012.

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