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RESEARCH ARTICLE

A STUDY ON ADVANTAGES AND LIMITATIONS OF EHD DRYING OF FOOD MATERIALS

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ABSTRACT

Energy consumption index is one of the most important criteria for judging about new, and emerging drying technologies. Electrohydrodynamic (EHD) drying is a novel method of non-thermal processing. The drying can be carried out using either AC or DC high voltages. The thermodynamic considerations regarding the lowering of temperature under EHD drying include rapid rates of evaporation and exothermic interaction of the electric field with a dielectric material. Multi-point and plate electrode systems are efficient in accelerating drying of agricultural materials. Compared to hot air (convective) drying systems, EHD drying systems offer lower food production costs along with superior quality in terms of physiochemical properties such as color, shrinkage, flavor, and nutrient content. This paper presents briefly the nature of ElectroHydroDynamic (EHD) phenomena, and details on the mechanisms of moisture movement inside the solid and its evaporation at the exposed solid surface during drying of solids. Choosing the data presented in literature, a critical discussion is presented on the advantages and limitations of EHD drying of food materials.

INTRODUCTION

Drying involves removal of water from a solid with the application of thermal, mechanical or electrical energy. Conventional drying processes are based on conductive, convective and radiative heat transfer, using air, superheated steam, microwave, electrohydrodynamic (EHD) phenomena and freeze drying. Drying is a common method of food preservation. Thermal drying, if carried out at high temperatures, produces undesirable changes in the physical, chemical and biological properties of food. Freeze drying gives the highest quality food product, obtainable by any drying method; however, it is expensive because of slow drying rate and the use of vacuum. Mechanical drying is cheaper than thermal or freeze drying; the product however loses its texture. EHD drying is surface drying; it is convective without the involvement of heat and hence is energy-efficient. Microwave drying is volumetric drying, it requires shortest drying time, it is however highly energy-intensive (Esehaghbeygi *et al.,* 2014).

ElectroHydroDynamic (EHD) Phenomena (Aaron *et al.,* 2013; Fylladitakis *et al.,* 2014)

EHD is a phenomenathat involves the direct conversion of electrical energy into kinetic energy through coupling of an electric field with the fluid field in a dielectric medium. When a DC or an AC high-voltage low-current electric field is applied in the dry electric fluid medium flowing between a charged electrode (emitter) and a receiving (grounded) electrode, an electrophoretic force sets in and induces fluid motion called 'Corona Wind'. A corona will occur when the potential gradient of the electric field is high enough to form a conductive region; the corona discharge is the electrical discharge brought on by the ionisation of the fluid surrounding the emitter. Ions generated by the corona discharge get accelerated by the applied electric field and drift toward the collector electrode; this zone is termed 'drift zone'. In the drift zone, momentum is transferred by collision from the ions through the neutral dielectric fluid medium. The ions have the same polarity as that of the emitter (for air, primarily H_3O^+, NO^+, NO^{2+} from positive corona, and CO^{3-}, O^{3-}, HCO^{3-} for negative corona). The spatial distribution of the electric force depends on the frequency of the applied field. At low frequencies, it extends throughout the inter-electrode region while at high frequencies it gets localised near the tip of the emitter, with ions being consumed by ion-ion recombination within the inter-electrode region[1]. The ionic wind velocity is given by (Kiousis *et al.,* 2015; OuldAhmedou *et al.,* 2009)

$$v = \left(\frac{\varepsilon_0}{\rho}\right)^{0.5} E \qquad \text{...} (1)$$

EHD requires low energy input (high-voltage:10-15kV, low-current:1.5-5μA), low air velocity (0.5-1.0ms^{-1}), low air temperature (20°C-25°C), average humidity (20-25 RH), can dry solids of high moisture content (>90%) to low moisture content (5-6%) and does not alter colour, texture or nutrients in the food product. The critical factors in EHD drying are inter-electrode gap (<20mm), thin slices of food material (<3-4mm) and laminar flow for ambient air.

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In chemical engineering EHD finds wide application in controlling boundary layer dynamics, in the enhancement of heat and mass transfer in confined spaces, in modifying surface properties, in removing atmospheric pollutants etc.

EHD drying of food materials

Several investigators reported EHD drying of food materials like slices of tomato, potato, banana, carrot, apple, kiwi or agricultural products like wheat, rice etc. covering a wide range in applied voltage (0-30kV), air velocity (0-5ms^{-1}), and inter-electrode distance (10-200mm). The following conclusions may be drawn from the reported results in the literature.

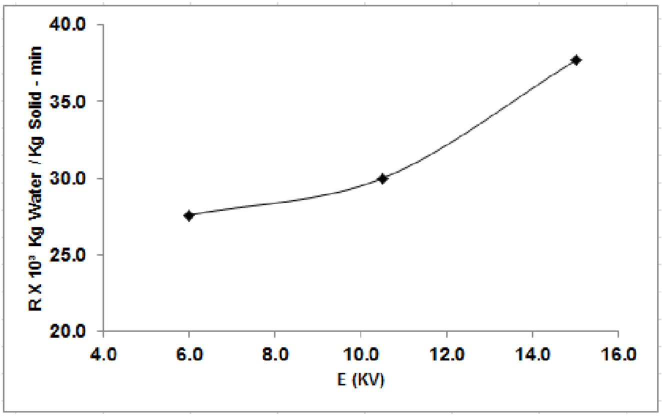

Figure 1. Variation of drying rate[5], R with applied Voltage: Field strength – 4.5 KV/cm

EHD drying is energy-efficient compared to conventional air drying or microwave drying (Esehaghbeygi *et al.,* 2014). Drying rate increases as the applied voltage increases (Dalvand *et al.,* 2012; Dalvand *et al.,* 2013). This is shown in Fig. 1 using data reported in literature (Dalvand *et al.,* 2012) for drying of kiwi fruit. The drying time decreases with increase in electric field strength (Esehaghbeygi *et al.,* 2014), the optimal value was reported to lie between 3KV/cm to 6KV/cm[6]. A minimum voltage was needed to initiate the ionic wind; this was reported to be 9KV for drying of agar gel (OuldAhmedou *et al.,* 2009). EHD enhancement in drying is best realised at low air velocities (Reynolds number <2000) and when the corona is at radial position to the drying medium (OuldAhmedou *et al.,* 2009). The inter-electrode distance is the key parameter; the smaller the distance, the better is the performance (OuldAhmedou *et al.,* 2009). Constant drying period was not reported for EHD drying (Esehaghbeygi *et al.,* 2014), prompting some authors to represent the experimental data as Page model (Changjiang Ding *et al.,* 2004) or Lewis model (Abdul KadirYagcioglu *et al.,* 2007) and evaluating the effective diffusivities for the different experimental conditions.

Mechanism of solids drying (Perry and Chilton, 1973)

Drying of solids proceeds by diffusion of vapour from the exposed saturated surface of the solid across a stagnant air-film into the drying medium. The movement of moisture within the solid is rapid enough to maintain a continuous film of water over the solid surface, and the rate of drying is controlled by the rate of heat transfer to the evaporating water film over the solid surface. Under the conditions, the temperature of the solid surface approximated to the wet bulb temperature. This is the constant drying rate period and its extent depends on (i) the heat or mass transfer coefficient (ii) the solid surface area exposed to the drying medium and (III) the temperature gradient or humidity between the drying medium and the wet surface of the solid. The falling drying rate period begins when the constant drying rate period ends at the critical moisture content characterised by discontinuities in the continuous liquid film over the slid surface. The falling drying rate period is divided into (a) the zone of unsaturated surface dying and (b) the zone where internal moisture movement controls. As drying proceeds below the critical moisture content, the exposed wet surface area of the solid decreases, decreasing the drying rate which is expressed based on the total surface area. During this period, the drying rate is a linear function of the moisture content of the solid. During this period, the mechanism of drying does not appreciably differ from that during constant drying rate period. As drying proceeds, at low moisture content of the solid, the drying rate Vs moisture content becomes non-linear characteristic of total unsaturated exposed surface of the solid due to inadequate internal movement of moisture to the surface to match the evaporation rate from the exposed surface. This zone is termed ‘Second falling drying rate period’, wherein the moisture content of the solid decreases very slowly as drying proceeds and the plane of evaporation moves into the solid. The drying rate is governed by internal resistance and the influence of external variables diminishes.

The mechanism of movement of moisture inside the solid material is either by diffusion or by capillarity. In practice, it can be assumed that both the mechanisms contribute to the moisture movement at all times, though one may be the dominating contributor at any given time. In drying of porous solids, moisture moves from regions of high concentration to those of low concentration through the capillaries due to the mechanism of surface tension. In fibrous or food materials, the pores are of varying sizes and are inter-connected[13]. As drying proceeds, the surface moisture evaporates, a meniscus of liquid forms across each pore setting up capillary forces by the interfacial tension between the water and the solid. These forces provide the driving force for the movement of water through the pores to the surface. Small pores develop greater forces than do large pores (ChainarongChaktranond and PhadungsakRattanadecho, 2010). As driving proceeds beyond critical moisture content, the surface layer of water recedes below the surface. Air starts filling the pores. As the water is continuously removed, continuous film across the pores cannot be maintained due to insufficient water, resulting in decreasing the drying rate which marks the beginning of second falling rate period. Here, the rate of diffusion of water vapour through the pores and the rate of conduction of heat in the solid are the controlling factors. The drying rate is very low and the driving curve is concave upwards.

Analysis of drying data

It is generally assumed that Fick’s second law is applicable when diffusion is thought of controlling the moisture movement through the pores of the solid. The drying rate and drying time are given by (for long drying times) (Perry and Chilton, 1973)

$$\frac{dx}{dt} = -\frac{\pi^2 D_e}{4l^2}(X_c - X_e) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

$$t = \frac{4l^2}{D_e \pi^2} \ln \frac{X_c - X_e}{X - X_e} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The capillary theory assumes the solid as a packed bed of non-porous spheres with interstitial spaces to develop an equation for the drying rate starting with a modified Poiseuille's equation. The drying rate and drying time are given by (Perry and Chilton, 1973)

$$\frac{dx}{dt} = -\frac{h(T - T_W)(X - X_e)}{\rho_S \lambda l (X_c - X_e)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$t = \frac{\rho_S l \lambda (X_c - X_e)}{h(T - T_W)} \ln\left(\frac{X_c - X_e}{X - X_e}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Food materials shrink during drying causing the material to warp and change in structure, or even may form hard layer on the surface causing additional resistance during drying. Constant drying rate period is rarely observed in drying of food materials. Food materials show different size pores. For example, it was reported that apple, potato, cabbage exhibited two peaks at 3.6 µm and 5.8 µm while carrots showed three peaks at 20 µm, 1 µm and 0.2 -0.4 µm. Further the pore sizes do change during drying; some open up while some get closed due to warping of the material (Karathanos *et al.,* 1996; Wanga and Brennen, 1995).

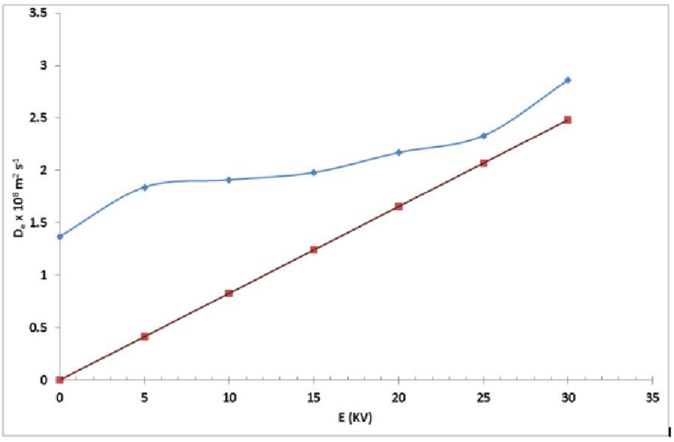

Figure 2. Variation of effective diffusivity[4], D_e and ionic wind velocity, v with applied voltage E

Diffusion coefficients are obtained from the experimental moisture Vs. time data by plotting [(X – Xe) / (Xc – Xe)] Vs. drying time on semi-log coordinates and evaluating D_e from the slope of the line. D_e thus estimated for EHD drying of food materials and reported in literature was found to increase marginally with increase in applied voltage, increase with increase in drying temperature and decrease with decrease in moisture content[14]. D_e ranged from 10^{-8} to 10^{-10} m^2s^{-1} depending on the material and experimental condition[4]. Fig. 2 shows the variation of effective diffusivity, D_e with the variation of applied voltage, E reported in literature[4] for EHD drying of carrot slices. The ionic wind velocity, v shown in Fig. 2 is estimated using Eq1). It is noted from the figure that D_e varies marginally with E in the recommended range of 6 to 15 KV. This suggests that EHD phenomena has less influence on drying of solids during the falling rate period. A plausible explanation for the sharp increase in D_e with E beyond 20 KV could be due to the movement of drying zone into the solid at very high ionic wind velocities, enhancing the diffusion of moisture especially from small pores.

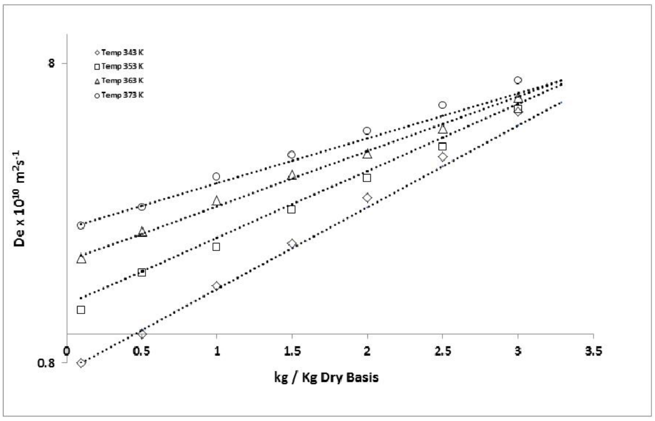

Figure 3. Variation of effective diffusivity, D_e with the moisture content of the solid, X and the temperature of the drying medium, T. (points refer to the experimental data[14] and the lines refer to prediction using Eq. 6)

Fig. 3 shows the variation of effective diffusivity, D_e with the variation in moisture content and the temperature of the medium, reported in literature[14] for air drying of banana slices. It is seen that D_e decreases with decrease in the moisture content of the solid and increases with increase in the temperature of the medium. The linear relationship between $D_e$vs X at any given temperature of the medium suggests the first order kinetics for air drying during the falling rate period. The lines for different temperatures tend to merge at high moisture content corresponding to the critical moisture content of the solid; they span as the moisture content decreases suggesting that the temperature influences as the moisture decreases. The effective diffusivity, D_e is related to the moisture content, X and the temperature T as

$$D_e * 10^{10} = pe^{qX} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where, p and q are related to temperature as

$$p = (0.05T - 16.4)$$
$$q = 600e^{-0.02T}$$

The predicted values of D_e are shown as continuous lines in Fig. 3 to compare with the experimental data points. The D_e values are of the order of 10^{-8} m^2/s for EHD drying of carrot slices, and are of order 10^{-10} m^2/s for air drying of banana slices. Though it is difficult, in the absence of pore size distribution and porosity of the materials, to ascribe the advantages of either method of drying, the low values of D_e suggest that moisture as liquid water diffuses from the interior to the exposed surface of the material during the first falling rate period. Thus is expected because of the high initial moisture content of the food materials such as tomato, kiwi fruit, banana, potato etc. EHD corona wind enhances the heat transfer coefficient by reducing essentially the external resistance through turbulence in the fluid film; its effect, if any, on internal resistance is negligible. For example, OuldAhmedou *et al.* (2009) reported that experiments for drying of Agar gel of 20mm thick were conducted at air velocity of 0.5 ms^{-1}, when the weight loss was 43g after 450 min, which was four times higher than with EHD drying. The authors observed that to achieve equivalent performance of EHD drying, the air velocity should be more than 4.2 ms^{-1}. Noting that,

$$h=0.0204G^{0.8} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

For parallel flow of air, as G increases from 0.5 to 4.2 ms^{-1}, the increase in h is 5.5 times which corresponds to the figure reported by the author. Changjiang Ding *et at.* (2015) compared air drying at 70 ^{0}C with EHD drying at 35 KV and 40^{0}C of 5mm thick carrot slices of 91 % initial moisture to 6 % final moisture. The drying time for air drying was 430 min and EHD drying 280 min, i.e. 1.5 times more for air drying. It was shown earlier that the drying time depends on the thickness of the material. For diffusion controlling, it is directly proportional to the square of the material thickness while for capillarity controlling, drying time is proportional to the thickness of the material. This is applicable for both air drying and EHD drying. Since EHD drying influences only the external resistance, its advantage in drying of materials is limited to thin slices. Further since the ambient air temperature is low in EHD drying, the temperature gradient is small and it takes longer duration for the drying zone to reach the inner depths of the pores and evaporate the water at low moisture concentration corresponding to second falling drying rate period.

Conclusion

In summary, EHD drying, being effective in reducing the external film resistance is advantageous to dry thin slices of food materials and to dry non porous materials before further processing. Compared to other drying techniques, EHD drying systems, given their simpler design and lesser energy consumption, show great potential for bulk and industrial drying applications. The energy efficiency and other advantages, such as low implementation and maintenance costs make EHD an interesting alternative to conventional drying processes

Nomenclature:

D_eDiffusion Coefficient (m^2 s^{-1})
E Applied voltage (KV)
G mass velocity (kg m^{-2} hr^{-1})
hheat transfer coefficient (W m^{-2} K^{-1})
lmaterial thickness (m)
R drying rate (kg water (kg solid. min)$^{-1}$)
T temperature (K)
t drying time (s)
v ionic wind velocity (m/s)
X moisture content (kg hr^{-1} kgdrysolid^{-1})
λ latent heat of vaporisation (kcal/kg)
ρgas density (kg m^{-3})
ϱ_s solid density (kg m^{-3})
ε_0 permittivity of free space (F/m)
subscripts:
ccritical
eequilibrium

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