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Novel drying technologies using electric and electromagnetic fields

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Abstract

Drying is a very old process designed to remove water from food products to extend their self-life, among many benefits. Because convective drying is a very energy-intensive process, novel drying technologies have to be studied to give rise to more efficient and economical dryers. Based on recent experimental and numerical studies, combining electric or electromagnetic fields with conventional air drying can reduce the drying time and increase the quality of dried products, whereas limiting the energy consumption. The principles of hybrid technologies such as microwave-assisted drying, radio-frequency drying and electro-hydrodynamic drying are presented in this chapter. Multi-physical models have finally to be developed to help engineers in the design and the optimization of such innovative drying processes.

Introduction

Drying is an operation aimed at removing water impregnating a solid or a liquid. It is mainly performed at atmospheric pressure by evaporation or at a pressure below the triple point of water by sublimation (freeze-drying). In these processes, heat is the driving mechanism for water removal whereas other technologies are based on osmotic dehydration. Drying is a very old process and one of the main methods for preserving agricultural and food products, such as fruits, vegetables and spices or other products with high water content. The process is also involved in food industries as a separate stage of processing, simply because the following processing steps and/or the final products require dried solids. Drying offers many benefits including extended shelf life, off-season availability, reduced packaging, storage, handling and transportation costs (Moses et al., 2014). According to (Mujumdar, 2014), between 12% and 20% of the national industrial energy consumption of many industrialized countries is due to the thermal dehydration operations. Indeed, even today, more than 85% of the dryers found in industries are convection dryers that use hot air or gas as the drying medium (Moses et al., 2014). Due to the high latent heat of vaporization and the energy consumed in heating and dehumidifying the air blown at high flow rates, convective drying is inherently inefficient and consequently a very energy-intensive process. In a world where the population continuously increases, with shortage of food and limited energy resources, it becomes crucial to find more efficient and economical drying methods able to preserve the sanitary, nutritional and organoleptic quality of food. Food industries are therefore interested in any solution that might accelerate the process, consume less energy and optimize the quality of dried product, the safety in operation and the controllability of the dryer.

Figure 1 shows a typical drying curve for a food product and drying takes place in three/four periods. The first phase, often short or even absent if the product is already at high temperature, corresponds to the time during which sensible heat is transferred to the product. The rate of evaporation increases considerably during this period because most of the free moisture is removed. The second phase is the constant rate period, in which a film of water is always present on the product surface. During this phase, the product temperature increases gradually but very slowly due to the effects of evaporative cooling. The drying rate is high because water is still available on the surface. The third and fourth phases, or falling rate periods (1st and 2nd falling rate periods in Figure 1), are phases during which the

migration of moisture from the internal interstices to the external surface becomes the limiting factor, resulting in a decrease in the drying rate. When the surface of the product is completely dry, the second falling rate period can be distinguished in most cases. Since the physical structure of the food product being dried is subject to change during drying (shrinkage, changes in porosity, etc.), the water transfer mechanisms may also change during the drying time.

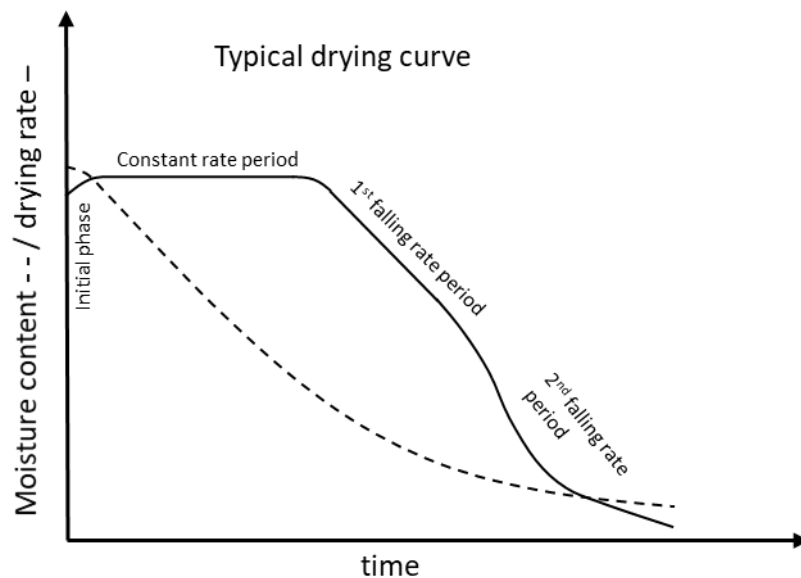


Figure 1. Representation of moisture content and drying rate as a function of time for conventional drying processes.

In most cases, the drying time of the first falling rate period is directly dependent on the drying conditions achieved during the constant rate period. Usually, if products are dried quickly when they have a high moisture content, they can continue to dry quite quickly in the low moisture range. This can be attributed to the formation of a more porous structure that promotes faster diffusion during the falling rate period and increases the exposed surface area of the material. Nevertheless, in some cases, especially for thick materials dried at high drying rates, the outer surface may dry much faster than the core and enter in a glassy state, leading to the case hardening phenomenon commonly observed during drying processes (Gulati & Datta, 2015). The resulting formation of a thin and dry shell on the outside can prevent moisture transfer and consequently reduce the drying rate. In the case of convective drying, increasing the drying medium temperature, and therefore decreasing its relative humidity, or the air flow rate during the constant rate period could reduce the drying time. However, since high air temperature can be detrimental to heat sensitive products, it may be preferable to increase the heat and mass transfer coefficient. Improving the falling rate periods of drying without acting on the constant rate period is more difficult because it requires an enhancement of heat and mass transfer through the material itself. This can be done through the introduction of other technologies in dryers such as microwave or ultrasound, but when these improvements are implemented, they can lead to a change in product quality (Nazir & Azaz Ahmad Azad, 2019). Thus, the poor quality of the final dried product and the low efficiency of convective dryers have led scientists to combine several techniques and energy sources. In recent decades, attention has been focused on several hybrid drying technologies using electromagnetic and/or electric fields, such as microwave-assisted drying, radio-frequency drying and more recently electro-hydrodynamic drying.

Microwave and Radiofrequency Drying

Electromagnetic waves can be used to enhance the drying efficiency of food products. Whereas Infrared radiation is limited to surface heating due to a low penetration depth, Microwaves (MW) and Radiofrequencies (RF) have the ability to heat up volumetrically the liquid to be vaporized (i.e. water). The heat transfer resistance is virtually removed in the material and the transport of moisture out through the food can be increased due to the higher mobility of water at higher temperatures. Moreover the transport of vapour due to the internal pressure gradient toward the material surface is improved. Because dielectric heating has the unique capacity to generate heat within the food, microwave and radiofrequency drying is suitable for products with a relatively small surface-to-volume ratio.

The frequencies used for industrial MW and RF heating applications are regulated to avoid the risk of interference with radio communications and radar. Therefore, a number of frequencies have been reserved for such radiation drying and the most frequently used are 13.56 and 27.12·MHz for RF and 915 and 2450·MHz for MW. RF and MW heating can be applied to most food products because these ones are dielectric materials that are characterised by poor electrical conduction properties.

The dipole orientation and the ionic orientation are the two main mechanisms that describe the coupling between electromagnetic field and dielectric materials. Polar molecules in food products, such as water, align themselves to the electrical field because their positive and negative charges centres do not coincide. If the electrical field is alternating, the polarization leads to dipole rotation and the resulting friction with adjacent molecules generates heat. Unlike polar molecules, dissociative ions of food are free to move towards regions of opposite charges. In case of alternating electromagnetic field, the ionic migration can cause friction between molecules, resulting in heat generation. Due to the difference in frequency range, the ionic orientation is generally more important in RF drying than in MW heating where both ionic conduction and dipole relaxation can be dominant heating mechanism.

The power dissipated per unit volume of dielectric material (P_v , W/m³) can be expressed as follows:

$$P_v = 2\pi f \epsilon_0 \epsilon'' |E|^2 \quad (1)$$

Where f is the frequency (Hz), E , the electric field strength in food load (V/m) and ϵ_0 the dielectric constant in vacuum (8.854×10^{-12} F/m). The parameter ϵ'' (loss factor) is the imaginary part of the relative complex permittivity ϵ^* ($\epsilon^* = \epsilon' - j\epsilon''$) that governs the interaction between dielectric materials and MW or RF energy. The real part ϵ' , termed as dielectric constant, describes the ability of dielectric products to store energy. Because dielectric properties ϵ' and ϵ'' of a food product vary with frequency, water content, temperature, porosity and composition, they are key factors in considering the relevance of dielectric drying. For most food, the dielectric properties increase with increasing temperatures but they always decrease during drying due to the decreasing water content. Control of dielectric drying has to include the competition between the increasing trend of loss factor giving rise to larger temperature differences inside the material ('thermal runaway') and the moisture content dependent-loss factor contributing to uniform drying.

According to Eq.(1), the heating power is proportional to the frequency. In case of loss factors of the same magnitude at any frequency, the usual way to compensate the low frequencies is to operate RF drying with higher electrical field strengths, which must, however, remain below 30 000 V/m to avoid voltage breakdown of air (arcing). Conversely, the penetration depth of the wave is inversely proportional to the frequency, as shown in Eq.(2).

$$d_p = \frac{c}{2\pi f \sqrt{2\epsilon' \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right]}} \quad (2)$$

where c is the velocity of the light in free space (3×10^{-12} m/s). Assuming an exponential decay of the electromagnetic power, the distance d_p theoretically defines the depth where the intensity of power falls to $1/e$ of the incident power at the food surface. Thus, RF heating may be preferred if the food load is very large and MW heating can be used for food in the centimetre or millimetre range. The parameter d_p is very useful to select appropriate size of food to ensure uniform heating in RF and MW applications. Sosa- Morales et al. (Sosa-Morales et al., 2010) indicate that the penetration depth of microwaves in food with high moisture content at room temperature is between 0.3 and 7 cm, depending on the salt content and frequency. The penetration of RF energy can be more to 10 times greater.

Because dielectric heating is more powerful than conventional heating, they have often to be used in combination with conventional drying techniques to overcome some drawbacks such as excessive temperature along the corner or edges of food products, a non-uniform heating and sometimes textural damages. Several comprehensive reviews on the contribution of electromagnetic field for drying processes can be found in (Chandrasekaran et al., 2013; Kumar & Karim, 2019; Zhou & Wang, 2019). Common applications of dielectric heating include RF and MW assisted hot air drying, MW vacuum drying and MW freeze-drying. MW and RF can also be combined with spouted bed drying and osmotic drying.

Post-baking drying for crackers and cookies was the first commercial application using RF in the food industry (Piyasena et al., 2003). Usually, the production capacity is improved and factory floor space reduced because treatments are shorter and RF is not detrimental to the product quality. More recently, a RF system combined with a hot-air system was successfully used for drying in-shell nuts. In such a process hot air carries away moisture from the nut and lowers its surface temperature whereas RF energy is used to heat the nuts above the air temperature. Zhou and Wang (Zhou & Wang, 2019) mention an approximately 52% reduction of hot air drying time by combining RF energy. However, despite the great potential of RF-related combination drying for improving heating uniformity and energy efficiency, commercial RF drying applications are currently predominantly limited to the wood, textile and bakery industries.

MW was successfully combined with hot air for drying of high moisture fruits and vegetables, especially during the falling rate period where the diffusion is rate-limiting. Substantial reduction in the drying time has been achieved in MW drying with hot air when compared with conventional drying. The saving in drying time is often greater than 25% and the reduction can reach a factor of two for apple and up to a factor of ten for *Penne* short cut pasta (Chandrasekaran et al., 2013). Applying MW energy in a pulsed manner is more advantageous than continuous application as it can overcome the problems of overheating, uneven heating and too rapid transport of moisture which can lead to quality damage in the food texture by 'puffing'. Vacuum drying, usually used for highly perishable commodities and high heat sensitive products, can be combined with MW to improve the thermal efficiency and drying time. The loss of nutritional qualities of food is reduced due to the absence of air and the absence of heat. MW vacuum drying can improve the quality of dried snacks, such as the crispy texture (Zielinska et al., 2019). Freeze-drying is also considered a gentle dehydration technique for heat sensitive food but is very time consuming because of low drying rates. Experimental studies of MW freeze-drying have shown that the assistance of MW could provide a 50-75% reduction in drying time in comparison with conventional freeze-drying methods (Khaing Hnin et al., 2019).

In summary combinations of MW with other drying techniques are almost unlimited and they can reduce energy consumption and improve product qualities. Thus MW-assisted drying methods may become the future trend in the development of drying technologies. To fulfil the potential for novel combined RF and MW-assisted drying methods, future research has to concern industrial equipment, process parameters, the combination orders between different heat sources, the properties of materials being dried, the influence of pre-treatments and the energy aspects.

Electrohydrodynamic (EHD) Drying

One of the obvious ways to intensify drying rates in convective drying is to increase the convective heat and mass transfer rate. The evaporation rate can be significantly enhanced when using impinging flow configurations rather than a flow parallel to the surface to be dried. The main advantage of Electrohydrodynamic (EHD) drying is precisely to generate a secondary flow directly to the product. Generally speaking, EHD investigates the flow of electrically charged fluids. A gas flow may be generated through a corona discharge which is obtained when a high voltage is applied between two electrodes whose radii of curvature are significantly different. The EHD drying device usually consists of a vertically movable electrode (sharply needle or thin wire) suspended above a fixed grounded electrode on which the food to be dried is placed (Figure 2). From a threshold voltage, usually of the order of kV up to 10 kV, the high electric field at the vicinity of the discharge electrode causes ionization of gas around the electrode. While the process is rather complex the effect of ionization is that ions of the same polarity drift to the grounded electrode. A space charge is formed and a very low electric current of the order of μA flows between both electrodes. The gas motion is generated by the ions that collide with the neutral molecules of gas. This secondary flow termed ionic wind perturbs the boundary layer created on the food surface and consequently enhances the heat and mass transfer coefficient.

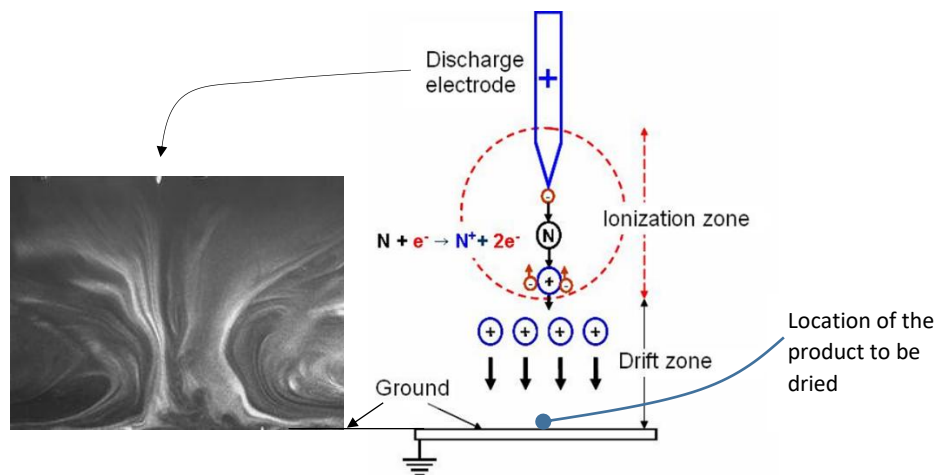


Figure 2. Example of EHD drying configuration in case of positive corona discharge: flow visualization by Particle Image Velocimetry (PIV) and physical sketch (ionization zone not on scale).

Contrary to dielectric drying for which the electromagnetic field generates heat inside the food, the electric field in EHD drying has an effect on charge transport in gas media. The concept of volume force can be introduced to describe the additional movement of air and the force F_v below is included in the Navier-Stokes equation (Martynenko & Kudra, 2016).

$$F_v = \rho_c E - \frac{\epsilon_0}{2} |\mathbf{E}|^2 \nabla \epsilon_r + \frac{\epsilon_0}{2} \nabla \left(|\mathbf{E}|^2 \rho \frac{\partial \epsilon_r}{\partial \rho} \right) \quad (3)$$

where ϵ_r is the relative dielectric permittivity of gas, ρ_c the charge density (C/m^3) and ρ the density of gas (kg/m^3). In case of air with constant temperature, the second term of the equation, representing the dielectroforetic force, and the third term called electrostriction can be neglected. Thus the Coulomb force, which is the product of the charge density and the electric field, is the main force generating ionic wind. Its mean velocity can be evaluated from Eq (4) (Robinson, 1961):

$$u = k \sqrt{\frac{j}{\rho b}} \quad (4)$$

where j is the current density at the grounded electrode (A/m^2), k a parameter depending on the geometry of electrodes and b the ion mobility in gas ($m^2/(s.V)$). Velocities of the order of 5 m/s can be reached in EHD drying.

Because of the non-generation of heat, EHD drying is considered as a novel non-thermal processing method particularly suitable for heat-sensitive materials. The process has received considerable attention in recent years because it ensures high product quality preservation and promises a reduction of the energy consumption. Because of low temperature drying, less shrinkage is usually obtained in EHD drying compared with conventional drying (Alemrajabi et al., 2012). Moreover, experimental investigations have shown that less color degradation of vegetables and fruits resulted from EHD drying (Martynenko et al., 2019). EHD drying can also have favourable effects on the shelf life of food materials. Several studies have reported that the respiration rates of lettuce, spinach and some fruits such as pear, plum, banana and cranberries were reduced following EHD treatment (Singh et al., 2012).

Drying kinetics with EHD is similar to the kinetics of convective drying, suggesting that EHD drying effects are essentially convective (Bardy et al., 2016). Cross-flow of air, parallel to the food to be dried, is often necessary, to evacuate moisture from the material. It was clearly shown that a cross-flow with too high velocity can suppress the positive effect of ionic wind (Ould Ahmedou et al., 2009). In addition to its negative effect, additional airflow implies increasing of energy consumption (due to blower and temperature and humidity control).

Numerous publications refer to energy advantages of EHD drying. Based on the energy calculated from current and applied voltage and the energy associated with primary air blower (Bardy et al., 2015) have shown, through an exergy analysis, that EHD improved efficiency of forced convection especially at the beginning of the process with an eightfold greater efficiency. However, as mentioned by (Kudra & Martynenko, 2015), the energy calculated in most papers does not include the energy efficiency of high voltage converter which can range between 0.01 and 0.17. The real energy consumed for EHD drying remains certainly lower than the one for air drying but the savings effect might be less than the one observed in several studies. This does not, however, call into question the interest of using EHD for heat-sensitive products.

EHD drying has been basically investigated by laboratory-scale tests and working small scales prototypes are scarce (Lai, 2010). Process parameters, such as voltage settings, electrode geometries and configurations, gap between electrodes and cross air-flow velocity, have to be optimised to develop EHD industrial units. For example, the drying rate increases with the increase of electric field strength through either the decrease of the electrode gap or the increase of voltage. If some results are more or less consensual, the influence of some parameters need to be further investigated. For example, multiple needles/wires configuration seems to be necessary in case of industrialisation but

the number of electrodes per dried surface area remains under debate. Because food can be dried more uniformly, (Defraeye and Martynenko 2019) have shown that the wire-to-mesh configuration shows better potential than conventional wire to plate, but more configurations have to be studied. Finally, some important parameters, such as air humidity, which clearly influences the onset of ionization, has never been extensively considered.

In conclusion, the lack of knowledge on the influence of process parameters and the uncertainty concerning the real energetic gain are the main reasons why commercial dryers with EHD enhancement are not yet available. Thus, efforts remain to be done to deploy this technology with huge potential.

Conclusions and perspectives

EHD drying and dielectric drying and more generally drying with the help of electromagnetic and/or electric fields have a great potential of innovation and application, especially for preserving organoleptic quality of foods and enhancing energy efficiency of the drying process. Several studies remain to be carried out to examine the application of MW, RF and EHD for the enhancement of evaporation processes and to fill the gap between laboratory scales and industrial scales, especially for EHD drying, which is still under development. Besides additional experimental studies, numerical simulation is a very promising way to enhance the knowledge of physical phenomena involved in such new drying processes (Defraeye & Martynenko, 2018; Malekjani & Jafari, 2018; Ould Ahmedou et al., 2009; Shi et al., 2017). The development and the optimization of new drying technologies can favorably benefit from numerical models able to predict fluid flow and heat and mass transfer. The design and the performance assessment of the innovative drying process as well as its dynamic control should also include the detailed and simultaneous analysis of food quality/energy efficiency issues. Such an integrated modelling approach requires the development of more comprehensive multi-physical models.

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