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Innovative microwave technologies for food drying processes

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Abstract

It is well known that microwaves can assist food drying processes; Current knowledge of Solid-state technology permit to assess feedback from forward and reflected signal. This allows for easy measure and track the energy levels along the process, which can help to avoid most of current drying problems. Beside this option, advanced materials have been developed for transducing electromagnetic energy into heat, this being transferred to the drying air by using high contact surface structures. This paper presents the advantages offered by these two innovative microwave technologies: Solid-State Microwave Heating (S^2MH) technology and Advanced Materials for Microwaves based Heating (AM^2H).

Keywords: *microwaves; drying; Solid-State Microwave Heating; Advanced Materials.*

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1. Introduction

Food preservation aims at preventing the growth of bacteria, fungi and other microorganisms as well as retarding oxidation of fats to reduce rancidity, thus allowing it to be stored for longer periods. Water is the main food component involved in food spoilage reactions, thus the decrease of water activity by dehydration is one of the oldest and well-known preserving strategies[1]. Drying reduces weight and volume so foods can be carried easily and can be storage in low space needs. Besides this, any preservation method should ensure that the quality, edibility and the nutritive value of the food remain as intact as possible. For this purpose, different dehydration methods can be used depending on the type of product. Dehydration techniques can be divided in two main groups according to whether the water is eliminated in the liquid phase, as in the case of osmotic dehydration, or if the water is removed by surface evaporation[2]. In the case of osmotic methods, sugar or salt are used in syrup or brine form to dehydrate fruits, meat or fish products, while in evaporation methods, an air flow is needed to remove the water from the food surface; this is the case of bed dryers, fluidized bed dryers, shelf dryers, spray drying, etc.

It is well known that microwaves can assist most of food drying processes; but despite its benefits, microwave energy has not yet been exploited to its potential in the industrial applications. Some of the reasons are because available microwave technology (tubes and valves) cannot offer a homogeneous heating, causing hot/cold spots depending on product geometry and distribution in the chamber or tunnel [3]. Particularly in drying processes, when available water decreases, the efficiency of the process will decrease. If the microwave power is not adjusted at this point of the drying process, the electromagnetic field strength increases, and thermal runaway, arcing, or plasma formation can be created. Currently, the solid-state microwave heating (S^2MH) technology is considered one of the most promising options to avoid the ancient problems preserving the known advantages[4]. The new S^2MH features include frequency and phase variability and control, low input-voltage requirements, compactness and rigidity, reliability, and better compatibility with other electronic possibilities (Internet-of-Things). The first notable advantage is the S^2MH system ability to assess feedback from forward and reflected signal[4]. This allows the application to easily measure and track the energy levels being put into the load, which can avoid the mentioned final drying problems, together with many others related to monitoring needs. On the other hand, almost all energy consumption and CO_2 generation in drying processes correspond to air heating stage. To tackle this problem, Advanced Materials for Microwaves based Heating (AM^2H) have been developed for transducing electromagnetic energy into heat, which is transferred to air by using high contact surface ceramic structures. The aim of this work is to review Microwaves Assisted Drying Processes and to present the advantages offered by two

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innovative microwave technologies: Solid-State Microwave Heating (S^2MH) technology and Advanced Materials for Microwaves based Heating (AM^2H).

2. Microwave-assisted drying in Food Technology. Advantages and drawbacks

Microwave drying is a process based on the volumetric heating that involves heat generation and mass transfer. The heat is generated within the product because of dipolar induction and orientation when the electromagnetic field is alternated. During the process, electromagnetic energy is transformed into heat, and the corresponding vapor is then spread through internal pressure gradient; water is evaporated and transported toward the surface. However, microwaves alone cannot fully complete a drying process, so combined techniques are highly recommended, such as forced-air or vacuum-drying, in order to complete the drying and further improve the process efficiency[5]. Air and vacuum act then as carriers of evaporated moisture and contribute to a more homogeneous and faster drying. Utilization of microwaves combined to conventional drying processes have shown beneficial effects, mainly energy savings, reduced processing time and operational costs without mitigating the food quality[6]. During **Microwaves-assisted air-drying,** microwaves can be applied either at the beginning, when the drying rate begins to fall, or at the end of the process of falling rate [7]. Microwave-assisted air-drying acts as follows: on the one hand, the airflow favors the removal of outside moisture of the product, while the volumetric heating of the microwaves leads to an intensive moisture evaporation and transportation toward the food surface. This combined process has been extensively proven to reduce drying time, and thus, energy requirements, while improving product quality [7–9]. Thus, reductions of 55–85% of drying time were reported when microwaves assisted hot-air drying of apple and strawberry slices[8], and of osmotic pre-treated cherry tomatoes[9], compared to analogous air-dried products. Berteli and Marsaioli[10] observed a reduction of drying time by a factor of 10 times during pasta drying compared to conventional air drying. They also highlighted a decrease of 90% of the space required for drying when microwaves are applied. With regards to **Intermittent microwave-convective drying** (IMCD), which consists of microwave application at pulsed rates, has been widely used because of it results in more homogenous moisture and temperature distributions together with an enhanced quality of the dried foods[11]. For instance, Soysal et al.[12] reported a processing time reduction of 4.7-17.3 and better sensory qualities of oregano under IMCD conditions. **Microwave-assisted vacuum drying** has been widely studied in the recent years due to the advantages derived from combining the volumetric heat absorption provided by microwaves with an increase of drying kinetics at reduced pressure [6]. The absence of air prevents oxidation and thus, the color, flavor and texture are minimally affected. As vacuum drying requires less temperature, high vitamin contents are retained compared to convective drying. Some attempts have been also performed to evaluate the impact of microwaves during freeze-drying. In this sense, Duan et al.[13] reported an additional decrease of energy consuming and freeze-drying time when microwaves power is

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used to supply the heat of sublimation. Some studies have also paid attention to the **Microwave-assisted infrared drying**. Considering that the main limitation of infrared drying is the low penetrating power, microwave energy has been applied together to compensate this weakness. Notable time savings (from 55 to 98 %) were obtained in banana, kiwifruit, raspberry, green pepper and egg plants subjected to different conditions of microwave and infrared energies combinations[6].

Apart from the reduction of drying rates, the application of microvawes presents a positive impact on rehydration capacity of dried products and, in volume and bioactive compounds retention[14].

Despite of the remarkable benefits of microwave application in food drying, its implementation in the food industry remains still not common, even if some formerly successful applications has been listed[15] such as in pasta drying, snack drying and, in the finish drying of potato chips, biscuits and crackers. The major limitation for their industrial employment seems to be the loss of efficiency of the microwave process as long as dehydration of the food progresses. The reduction of available water causes an increase of the electromagnetic field strength (because of load mismatch) and the consequent lower microwaves absorption during drying, being necessary an adaptation of microwaves power at this point of the drying process, that is not easy. This adaptation would be also dependent on the dielectric properties, size and geometry of the product, and on the presence of other materials that also absorb the microwaves, and therefore modifies the local field strength[14]. Other additional problems that could appear are thermal runaway, arcing, or plasma generation because of a drastic increase of the electromagnetic field strength causing damages in both the equipment and the product. The homogenous distribution of microwaves power in the drying chamber remains also a challenge to be solved due to the undesirable occurrence of hot and cold spots in the product, causing reflections that can lead to overheating in central areas, edges or corners [3,16]. Some manufacturers tried to solve this lack of homogeneity by the incorporation of mode stirrers or a turntable (as in household microwave ovens), although appropriate homogeneity has not been achieved. In addition, the design of microwaves-assisted dryers to reach an optimal heat distribution is unique for a binomial process-product; thus, reducing the versatility of the drying process to be extended to other food products.

3. Solid-State Microwave Heating technology (S^{2}MH)

The solid-state technology allows producing microwaves with power enough to generate heat inside dielectric materials, using solid state transistors to amplify a specific signal instead of valves (which are power oscillators). At the beginning of this century, the laterally-diffused metal-oxide semiconductor (LDMOS) technology became mature and cost-effective, in particular for the market segment of cellular communication base-stations[4]. The first

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relevant use of a LDMOS amplifier for microwave heating purposes (~10cc samples) was presented in 2006 at IMPI-40 by Schwartz et al.[17]. Solid-State RF Amplifiers (LDMOS) efficiency has improved in recent years to performance levels compared to magnetron-based conventional microwave systems: from 50% efficiency and 180W in 2014 to 68.5% efficiency and 250W in 2017[18].

There are several differences in the design and performance between S^2MH and magnetron systems. Mainly, while valves systems generate powered waves in a given spectrum (inside a bandwidth from ISM), the systems based on LDMOS have more degrees of freedom, being able to vary frequency (inside a bandwidth and among them) and the power (in amplitude and phase) in real time. In addition, LDMOS are littler, more durable (4 vs. 20 years) and permit better compatibility with electronic circuitry (Internet-of-Things). Among these advantages, the most important it the capacity of the S^2MH system to evaluate the feedback from forward and reflected power levels (amplitude, phase), what favors the measurement and control of the energy levels present in the system. This feature could solve the load mismatching along the process, one of the main problems in drying applications. Moreover, the feedback system will detect and manage the problems of thermal runaway along the drying process, a big limitation of microwave-assisted drying. Different authors have developed new techniques to improve efficiency, with the aim of maximizing microwave absorption, by developing algorithms controlling frequency and phase[19]. Concretely, it has been developed a feedback scheme capable of associate the scatter parameters related to the dielectric properties to the load temperature changes in food. Furthermore, the system integrates the measurements of cavity power delivery into an oven. Detailed 'fingerprints' of the load can be sensed in this way, which provide feedback from the changing dielectric and structural properties of the food as heating proceeds[19]. In addition, the capability of the S^2MH to modify frequency bandwidth (among the permitted in ISM), and thus, the penetration depth, could minimize the problems of size and geometry refereed in magnetron based systems[3,16]. Recently, Tang et al.[20] have proposed a novel method (using a solid-state amplifier) to improve heating uniformity by selecting optimal frequencies. From the industrial point of view, only in microwave ovens capable to modify the frequency range will extend the variability of products (different sizes). Apart from the signal measurement and control, S^2MH modules offer excellent reliability (reduced "Mean Time Between Failures"), security (lower voltage), scalability, and design freedom (regarding form factor and system integration), which will allow a better industrial implementation[4].

4. Advanced ceramic materials to absorb microwave energy quickly and efficiently

Advanced Materials for Microwaves based Heating (AM^2H) have been recently developed by adding a ceramic matrix composite[21]. AM^2H can be performed adding high loss factor materials (SiC, zirconia) into low loss factor ceramic matrix (Al_2O_3, cordierite). These

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materials behave as localized susceptors into ceramic matrix and work as high energy source (due to microwave energy absorption). Beyond the materials applications, Microbiotech have patented a heating system (named MBT-01) that uses AM^2H as heat emission elements which are heated by means of microwave radiation distributed by planar technology[22]. The first stage was to optimize AM^2H to be used as heat emitter by achieving the non-reciprocal behavior that would lead to energy efficiency. The MBT-01, is the result of the research on the combination of different ceramic matrix with microwave susceptors integrated in it[23]. Once optimized, MBT-01 has been integrated in novel planar devices able to transduce wave energy (2.45 GHz) to heat with an efficiency better than 99%, both in microstrip (resonant) and stripline (wideband) variations[23]. Fig. 1 shows a transducer, and some thermographic images obtained along a heating of an integrated cell, applying 30W at 2.45 GHz per cell.

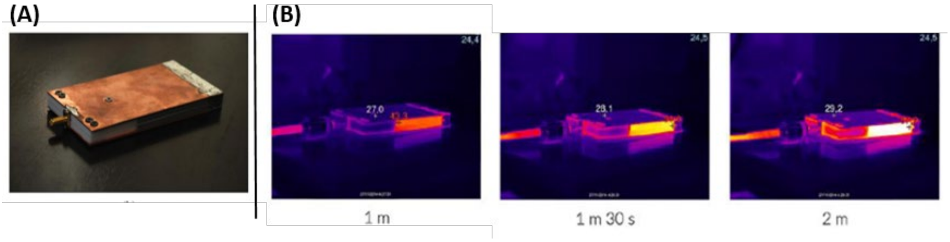

Fig. 1. Picture of stripline radiators (A) and, (Bb) Thermographies of a heating cycle, applying 30 W microwave power at 2.45 GHz per cell, on the right *[24]*.

The ability to increase 10ºC the ambient temperature with a 300 W prototype has been tested in controlled conditions; the high thermal inertia of the ceramic material to be heated with microwaves allow to save about 60% of energy as compared to current electric ceramic heaters. Savings in CO2 emissions with respect to electrical systems are about 70% (analysis performed with the energy certification program Ce3X). Fig. 2 shows the temperature variation of the surface, where the non-reciprocal behavior can be appreciated (heating rate (0.75 ± 0.03 °C/s) vs. cooling rate (0.05 ± 0.02 °C/s)[25].

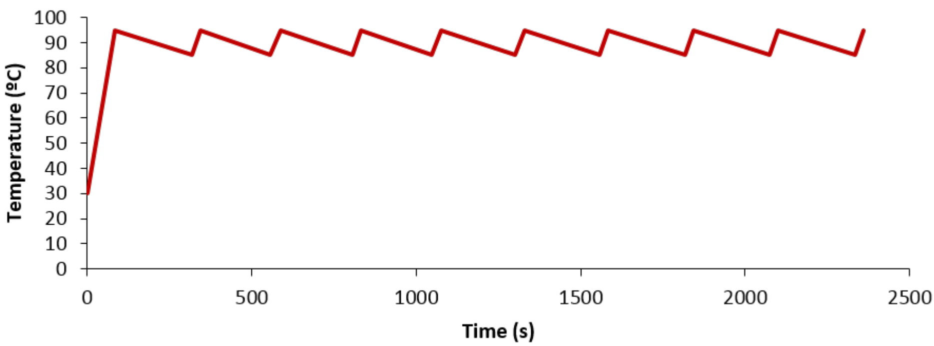

Fig. 2. Temperature variation of the surface of a 300 W prototype *[26]*.

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The capacity of AM^2H to heat fluids was also tested, obtaining high-energy efficiency using on-off cycles (efficiencies about 69.8% in water heating)[26].

5. Conclusions and future prospects

Microwave energy improves efficiency and quality of food drying processes; but the common use technology (tubes and valves) cannot offer a homogeneous heating, causing hot/cold spots depending on product geometry and distribution in the chamber or tunnel. S^2MH technology is considered one of the most promising options to avoid the ancient problems preserving the known advantages. Additionally, S^2MH offers several advantages over tubes and valves because admits more flexibility in energy application and control, has low input-voltage requirements, compactness, rigidity, reliability, durability and compatibility with other electronic possibilities. S^2MH allows the application to easily measure and track the energy levels being put into the load, which can avoid the mentioned final drying problems, as well as others related to monitoring needs. Moreover, the use of optimized AM^2H (quick and high-efficiency) can heat air and fluids. Future works will lead to AM^2H based microwave devices with optimized tridimensional structures to improve air heating.

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