NOVEL TECHNOLOGIES FOR THE THERMAL PROCESSING OF FOODS

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Keywords: ohmic heating, micro-waves, radio-frequency, induction, infrared

Abstract: Heating is probably the oldest means of processing foods and has been used by mankind for millennia. However, the technology used to heat foods in order to process them has had a spectacular evolution during the 20th century which has continued until the present time. Technologies such as ohmic heating, dielectric heating (which includes microwave heating and radio frequency heating) and inductive heating have been developed which can replace, at least partially, the traditional heating methods which rely essentially on conductive, convective and radiative heat transfer. They all have a common feature: heat is generated directly inside the food and this has direct implications in terms of both energetic and heating efficiency. Also infrared heating has been developed as a means of heat processing of foods.
These are called novel thermal processing technologies, meaning that the change in temperature is the main processing factor, as opposed to the novel non-thermal processing technologies such as pulsed electric fields, high pressure, pulsed light, ultrasound, gamma radiation, among others, where temperature may also change but is not the major responsible for food processing.

1. INTRODUCTION

The following text presents, in general terms, the main novel thermal processing technologies currently available. The main idea is to provide an overview of the field, while showing some particular examples of the research that has been recently conducted.

2. OHMIC HEATING (MODERATE ELECTRIC FIELDS)

In ohmic heating (OH) heat is internally generated due to the electrical resistance of foods [1]. Other electrical heating methods can be distinguished from OH as the latter:
- needs electrodes contacting the foods (e.g. in microwave electrodes are absent)
- uses an unrestricted frequency (except for the specially assigned radio or microwave frequency range)
- uses an unrestricted waveform (although typically sinusoidal).

OH has been successfully applied in food processing in the XIX century to pasteurize milk [2]. In 1938 the so-called “Electropure Process” was already used in approximately fifty milk pasteurizers in five US states and served about 50000 consumers [3]. Applications such as this were abandoned due to high processing costs [1] and due to the short supply of inert materials needed for the electrodes [4].
Despite of these early drawbacks research on ohmic applications in fruits, vegetables, meat products and surimi has kept on, mainly in the last two decades.

Aseptic processing is considerably developed in the food industry especially for liquid foods which are processed predominantly by means of heat exchangers. Their application to particulate foods is limited by the time required to ensure the correct processing of the centre of larger particles, often causing overcooking of the surrounding volume. Consequently, product safety is achieved at the expense of quality.

The renewed interest in OH technology is due to the fact that products are of a superior quality to those processed by conventional technologies [5-7]. The main advantages claimed for this technology are uniformity of heating and improvements in quality with minimal structural, nutritional or organoleptic changes [8]. Possible applications include most of the heat treatments such as blanching, evaporation, dehydration, fermentation as well as pasteurization and sterilization.

OH also features some disadvantages, namely those related with the high initial operational costs and the lack of generalized information or validation procedures.

Actually, OH is used industrially in North America, Europe and Asia to produce a variety of high-quality, low and high-acid products containing particulates. A considerable number of additional applications are being developed for this technology as shall be presented in the last part of this section.

Heating is achieved through the application of an electric field to a food with a given electrical conductivity (σ) by means of direct contact with electrodes. For such process, not only those two variables but also particle orientation and geometry are determinant of the success of the process.

The application of OH for food processing is still not well characterized and not all its potentialities have been fully exploited due to the complexity of the phenomena occurring during OH processing and the complexity of food materials. Novel applications and a deeper knowledge of current applications must be obtained and further research and development work on OH in these areas are essential [9].

2.1. Effects on microorganisms

The main mechanism of microbial inactivation under OH is surely the effect of temperature. However, the destruction of microorganisms by non-thermal effects such as electricity is still not well understood and generates some controversy as little work has been done in this field. The application of an electrical field may induce pore formation in membranes (similar to the electroporation mechanism used to transform cells in molecular biology studies) allowing a faster and efficient transport of the nutrients into the cells thus decreasing lag phase. Studies such as that of Cho *et al*. [10] provide evidence that OH may be useful in the food industry e.g. to shorten the time for processing yogurt and cheese production. The effect of an electric field on the thermal inactivation kinetics of a thermo tolerant, ascospore producing, filamentous fungus, *Byssochlamys fulva*, has been studied. This fungus may also produce patulin, an important mycotoxin. The death kinetics of *B. fulva* in strawberry pulp were determined and the *D* values obtained under OH (3.27 min) were half of those obtained under conventional heating (7.23 min).

2.2. Effects on enzymes

The use of enzymes in the food industry for processing reasons is very widespread. Enzymes may also have negative effects on food quality such as production of off-odours, tastes and altering texture. The effects of OH on enzyme activity have not been investigated extensively. There is a recent study by Castro *et al*. [11] where the effects of OH on the degradation kinetics of lipoxigenase (LOX), polyphenoloxidase (PPO), pectinase (PEC), alkaline phosphatase (ALP) and β-galactosidase (β-GAL) have been determined. This study demonstrated that the electric field has an additional effect on LOX and PPO inactivation, where much lower *D* values where found as compared to conventional heating, meaning that a shorter treatment is needed to achieve the same inactivation degree, thus reducing negative thermal effects in the other food components. In the case of PEC, ALP and β-GAL the electric field seems not to have an influence in enzyme inactivation kinetics as both conventional heating and OH *D* and *z* values are identical. The authors hypothesize that the presence of the electric field may disturb the metallic prosthetic groups present on LOX and PPO (and absent in PEC, ALP and β-GAL), thus causing the enhancement of activity loss.

2.3. Effects on vitamins

The degradation mechanism of vitamins (such as ascorbic acid) is specific to the particular system in which they are integrated. Using industrial strawberry pulps, Castro *et al*. [12] concluded that the reaction follows first order kinetics for both conventional and OH treatments, being the kinetic parameters identical for both heating processes. The conclusion was that the presence of low intensity electric fields (< 20 $V.cm^{-1}$) does not affect the ascorbic acid degradation. Similar conclusions were obtained by Lima [13] for orange juice systems.

3. MICROWAVE HEATING

Microwave (MW) technology dates back to the beginning of the 20th century but its industrial application has been facing new developments in the past three decades.
In the 90's annual sales in the EUA exceeded 10 million units which translates to a penetration rate in households of over 80 %.The European market presents similar trends.
Microwaves are a form of electromagnetic radiation, characterized by wavelength and frequency.
MW heating has a number of quantitative and qualitative advantages over conventional heating techniques namely:

- Speed
- Uniformity of heating (in some cases this uniformity may be reduced)
- Selective heating (microwaves couple selectively into materials that are more absorptive of the energy; although greater efficiency can be achieved, temperature profiles can develop in multi-component food systems).

Other advantages of MW heating systems, some depending on the application, are that it can be turned on or off instantly, the product can be pasteurized after being packaged, space saving or reduced noise levels. These advantages often yield an increased productivity and/or an improved product quality.
The main disadvantages claimed for this technology is the lack of experimental data needed to model MW heating and the need of engineering intelligence to understand and minimize uneven heating or thermal runaway.
The main applications of MW heating in food processing are: (re)heating, baking and (pre)cooking, meat tempering, blanching, pasteurization and sterilization, drying and freeze-drying.
MW heating involves two distinct mechanisms: dielectric and ionic.

The dielectric heating is mainly due to the presence of water. Due to their dipolar nature, water molecules try to follow the electric field associated with electromagnetic radiation as it oscillates at the very high frequencies listed and such oscillations produce heat.
The dielectric properties dictate, to a large extent, the behaviour of materials when submitted to MW field and it is, therefore, fundamental to characterize it.
The second major mechanism of heating with microwaves is through the oscillatory migration of ions in the food that generates heat under the influence of the oscillating electric field. The migration of ions towards oppositely charged regions results in multiple collisions and disruption of hydrogen bonds with water, both generating heat.
The MW heating process is affected by a number of parameters. Some of these critical process factors are MW frequency, moisture content, temperature, product parameters (including mass, density, geometry), and specific heat. The spatial distribution of MW absorption is affected by those parameters meaning that different heating rates (uneven heating) will be observed. Being so, different microbial inactivation extents will occur within the food product and may jeopardize food safety.
The main obstacles to industrial setting up of MW heating processes are the difficulties in controlling the process and the high energy costs associated with this technology. The changes of dielectric properties of food products during the heating processes are not yet fully understood or modelled and, consequently, the validation of the processes has to be done almost individually for each food product, slowing down the dissemination of MW industrial lines.

3.1. Microbial inactivation

Several studies report the inactivation kinetics of microorganisms in food systems when using MW and conventional heating methods. However, the comparison of the two methods is not very accurate either by lack of details of the methodology or due to the different techniques used for temperature monitoring [14]. MW heating is often reported to cause non-uniform heating. This fact leads to survival of food borne pathogens, including *Salmonella* and *Listeria monocytogenes* in cold spots which, in this case, are not the centre of the food. Being so, monitoring the internal temperature that would normally be lethal, may not be sufficient to ensure microbial food safety [15].
The inactivation curves for microorganisms using MW heating are similar to those obtained using conventional heating methods. Despite of this fact, an additional killing factor due to non-thermal effects was also discussed. Four major theories were proposed to explain non-thermal inactivation by microwaves: selective heating, electroporation, cell membrane rupture, and magnetic field coupling [16]. The non-thermal effect is still not well established but is currently accepted that MW energy may complement or magnify thermal effects by causing non-lethal injuries to the cells. The major drawbacks of MW heating are its non-uniform heating and unpredictability of cold spots which may put at risk safety of the food.

4. RADIO FREQUENCY HEATING

Radio frequency heating (RF) heating involves the transfer of electromagnetic energy directly into the product, therefore inducing volumetric heating due to frictional interaction between molecules [17]. In RF heating the food is placed between two capacitor plates, where it plays the role of a dielectric to which a high frequency alternating electric field is applied. Such field will force polar molecules (e.g. water) to constantly realign themselves with the electric field. This molecular movement is very fast due to the high frequency of

the field and will provoke generation of heat within the food by energy dissipation caused by molecular friction.
RF waves (as well as microwaves) are both within the radar range and this strongly limits the frequencies which can be used for applications other than communications. The fact that the wavelength at radio frequencies (e.g. 11 m at 27.12 MHz) is substantially greater than at microwave frequencies (e.g. 12 cm at 2450 MHz) justifies the significant advantages of RF over microwaves, especially in the case of food processing applications [18].
As compared with conventional heat processing technologies, RF heating presents similar advantages to ohmic and microwave heating which are essentially due to the generation of heat throughout the volume of the material to be processed. However, there are some specific advantages of RF over those alternative volumetric technologies, namely [18]:

- there is no need for electrodes contacting the food (in contrast with e.g. ohmic heating), allowing RF to be easily applied to both solid and liquid foods;
- due to the longer wavelength of RF, its power will penetrate more deeply in the foods as compared to microwave power;
- the construction of large RF heating systems is simpler then their microwave counterparts, and their application to continuous processes is straightforward; it is a technology particularly suited to large industrial applications.

RF's main disadvantages are [18,19]:

- the higher equipment and operating costs for an equivalent power output when compared to conventional heating systems and also to ohmic heating;
- the reduced power density when compared to microwave heating, meaning that larger RF heating systems are needed for the same power rating and also that slower heating rates are achieved with RF as compared to microwaves;
- the so far limited research efforts regarding e.g. the determination of food RF dielectric properties.

The relevant properties in RF heating are the relative dielectric constant (ε_r'), the relative dielectric loss factor (ε_r'') and the electrical conductivity (σ), which are the so-called dielectric properties. These properties affect RF heating e.g. in terms of their influence on temperature increase [20]. RF is also influenced by means of the penetration depth (d). The dielectric properties of foods are influenced mainly by frequency, temperature, water content and chemical composition [17].

4.1. The effects of radio frequency heating

Much in the same way as with the determination of dielectric properties, the effects of RF heating in microorganisms and food constituents (e.g. vitamins) have been scarcely studied (in comparison, for microwave heating there is much more information available) [21].
The possibility of a non-thermal effect of RF on the death kinetics of microorganisms has been discussed for about 60 years, and while some authors claim inactivation of microorganisms due to the non-thermal effect of RF (see, e.g., [22,23]), others claim precisely the contrary (see, e.g., [24-26]). Although no consensual results have been published so far, the clear trend is to consider that if a non-thermal effect of RF on microorganisms exists, it is negligible for the most usual operation conditions.
There is a significant amount of publications, some dating back from the 1940's, where the use of RF is described for various applications, including blanching, pasteurization/sterilization, thawing, drying, heating of bread/baking, meat processing, among others.

5. INFRARED HEATING

The applications for infrared (IR) radiation are very wide and include medical, dye, automobile and paper industries, among others. The discovery of this type of radiation dates back to 1800 when Sir William Herschel was attempting to determine the part of the visible spectrum, with the minimum associated heat, during astronomical observations.
The use of this technology in the food industry was first reported in the 50's for drying processes.
IR heating is the transfer of thermal energy in the form of electromagnetic waves. Within the IR spectra three different regions can be distinguished, depending on the wavelength: short waves (0.7 – 2.0 μm) that appear when temperatures are above 1000 ºC; medium waves (2.0 – 4.0 μm) when temperatures range from 400 to 1000 ºC and long waves (4.0 μm – 1 mm), when temperatures are below 400 ºC. The medium to long range wavelengths appeared to be the most advantageous to industrial applications since almost all materials to be heated or dried provide maximum absorption in the 3 to 10 mm region. However, new applications using short waves have been arising.
IR heating presents several advantages over conventional heating methods, some of them similar to the other types of electromagnetic heating, namely:

- Instant heat – there is no need for heat build-up because electric IR systems produce heat instantly.
- Reduced operating costs – depending on the insulation, type of construction and other factors, the energy savings can reach 50 %. Moreover, maintenance operations are restricted to reflectors cleaning and changing of the heat source.
- Clean and safe – there is no production of by-products and operating the IR equipment is a low risk task.
- Zone control – the IR energy does not propagate, it is absorbed only at the area it is directed into. This allows differentiating heating in nearby zones. Moreover, IR is not absorbed by the air so the surrounding air does not heat up.

IR radiation is electromagnetic radiation which is generated in a hot source (quartz lamp, quartz tube, or metal rod) by vibration and rotation of molecules. Heat is generated by the absorption of the radiating energy.
There are some critical factors in IR heating which must be considered; these are [27,28]: radiator temperature, radiator efficiency, IR reflection/absorption properties and IR penetration properties. Being so, the rate of heat transfer depends on the surface temperature of the heating and receiving materials, the surface properties of the two materials and the shape of the emitting and receiving bodies.
IR heating has been used for heating and cooking of soybeans, cereal grains, cocoa beans, nut, some ready to eat products, braising meat and frying and drying apple slices [29,30]. Drying of seaweed, vegetables, fish flakes and pasta is also done in tunnel IR dryers.
The use of IR technology in the food industry is still in the first stages of development and future trends will certainly be focused on:

- process control and equipment development;
- understanding the interactions between heating process and product's properties (organoleptic and nutritional);
- expanding the areas of application of IR heating.

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