ABSTRACT (inglese)

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Thesis title: Theoretical and experimental analysis of microwave heating processes
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Thermal processing is the major processing technology in the food industry and its purpose is to extend the shelf life of food products without compromising food safety. Apart from the positive effect of food treatments, such as the inactivation of pathogens, there are also some limitation by way of partial destruction of quality attributes of products, especially heat-labile nutrients, and sensory attributes.

The technological revolution, nutritional awareness, and continuous demand of the new generation have necessitated search for new or improved food processing technologies. Presently, several new food processing technologies, including microwave heating, are investigated to improve, replace, or complement conventional processing technology.

Microwave has been successfully used to heat, dry, and sterilize many food products. Compared with conventional methods, microwave processing offers the following advantages: 1) microwave penetrates inside the food materials and, therefore, cooking takes place throughout the whole volume of food internally and rapidly, which significantly reduces the processing time; 2) since heat transfer is fast, nutrients and vitamins contents, as well as flavor, sensory characteristics, and color of food are well preserved; 3) ultrafast pasteurization or sterilization of pumpable fluids minimizes nutrient, color, and flavor losses; 4) minimum fouling depositions, because of the elimination of the hot heat transfer surfaces, since the piping used is microwave transparent and remains relatively cooler than the product; 5) energy saving because of the absence of a medium between the sample and the MW; in addition, if the system is well projected, high efficiency can be reached (some authors showed the reduction of the energy costs during drying processes using microwaves, with a further improvement using air dryer and microwaves in sequence; moreover, consider the possibility to use alternative energy sources, eg. photovoltaic); 6) perfect geometry for clean-in-place system; 7) low cost in system maintenance; 8) space saving, if the system is compared with the traditional ones, based on boilers and surface heat exchangers.

On the other hand, there are some problems which prevent the diffusion of this technique; among them: 1) uneven temperature patterns of the food processed, due to the uneven temperature field inside the microwave cavity; 2) temperature readout and control problems, because traditional probes fail: in particular, the thermocouples disturb the measurement and are damaged by the electric field, while fiberoptic probes allow to know the temperature only in few points; 3) difficulties in predicting the temperature field, because of coupling of three physical phenomena, that is, electromagnetic wave propagations, heat transfer and, in most of cases, fluid motion. Consider that sizing, during the design phase, and the control, during the operating phase, could be based on theoretical predictions, avoiding the so called “trial and error” approach.

To address the critical points mentioned above, during the thesis work, theoretical models were developed and experimental tests were performed, with reference to “batch” and “continuous flow” processes.

In particular, after a brief description of the principles of microwave heating, some batch processes have been analysed, that is, apple drying and in-package heating of water and oil. In both cases, the use of infrared technique allowed to obtain the spatial temperature distribution of the samples under test.

Microwave drying has been applied to apple slices, and IR temperature detection allowed to keep under control their surface average thermal level in time; thus, this enables to follow the temperature-time curves during MW heating, according to the process at hand, within the limits specified.

An isothermal 2D unsteady model for mass transfer was employed to describe the measured drying kinetics of apples. Quite satisfying results were obtained applying the model to recover experimental data, probably due to operating at fixed temperature levels for the samples under test.

The analysis of the second kind of batch tests considered, the in-package heating of water and oil, allowed to show the sensitivity of the temperature distribution to the orientation of the samples, the mass and the dielectric properties. Moreover, a finite element method software, Comsol Multypisics, was used to develop a 3D numerical model, in order to predict the temperature distribution of the samples surface. By comparing experimental and numerical results, it was proven that the proposed finite-element simulation strategy is quite robust and can be suitably extended to encompass more complicated and realistic problems involving MW heating.

In the second section of the thesis, the continuous flow microwave heating processes have been analysed, which is more interesting, having in mind industrial applications.

The main aim was to develop a theoretical instrument, able to predict the bulk temperature distribution without great computational efforts. It was demonstrated that, in absence of significant temperature variations and for high velocities, constant dielectric properties can be considered, and an analytical model, accounting for uniform heat generation inside the liquid, could be used. Thus, it has been proven that, under suitable conditions, a quick response can be obtained adopting the analytical model. In the other cases, it’s necessary to take into account the modifications of the dielectric properties during the process; at this aim, an hybrid numerical-analytical solution was developed, which was compared with the one obtained by Comsol Multyphisics, considering the temperature dependence of the dielectric permittivity; the complete numerical solution (CN), because of the coupling of the heat transfer problem and the electromagnetic problem, required a great computational time. Unlike this, the new hybrid numerical solution reduced the time required for computation, obtaining only the electromagnetic solution with the numerical instrument and considering constant dielectric properties. The temperature dependence of the dielectric permittivity was included through a manipulation of the heat generation distribution, introducing a weighting function opportunely chosen: the latter took into account the variations of the dielectric loss factor. Thus, the heat transfer problem was analytically solved, feeding the heat generation term with the one obtained interpolating the weighted discrete heat generation distribution, using the Fourier Discrete Transform. The solution found by the described procedure was named “Enhanced Hybrid” (EH), because it improves the so-called “Basic Hybrid solution” (BH) through the introduction of the weighting function. Finally, a theoretical-experimental procedure was developed to measure the bulk temperature distribution in water flowing in a glass-pipe, subjected to microwaves. High-resolution thermal maps in real time were obtained by processing infrared thermographic images. Considering the equation of thermography for the case at hand, the temperature distribution with high resolution was obtained after a suitable calibration; the latter was required because of the presence of the grid. Thus, the developed procedure offers a great contribution for temperature measurement inside the microwave oven, taking into account that usually temperature is measured in few points. Such an approach is needed, since the uneven EM field causes an uneven spatial distribution of the temperature field.

In order to check the goodness of the fast hybrid model previously developed, the experimental results were compared with the EH solution, showing an acceptable agreement, with a better prediction for higher flow rates.