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Modeling and process simulation of controlled microwave heating of foods by using of the resonance phenomenon

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HIGHLIGHTS

- Resonance was applied to improve the uniformity of internal temperature.
- 3D mathematical model was developed, by solving the energy transfer.
- Maxwell equations were solved using Comsol Multiphysics software.
- The numerical predictions allow to develop strategically internal patterns.
- More uniformity of the final temperature profiles was achieved.

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ABSTRACT

Experimental and theoretical analyses of the controlled heating of foods were done. The purpose of this paper is to demonstrate the favorable effects of the use of the phenomenon of resonance to improve the uniformity of internal temperature profiles in foods during microwave heating. Particularly, the effect of the changing the phases of two opposite electric field excitations and their interaction with food samples was focused. With this aim, a 3D mathematical model was developed, by solving the energy transfer balance during the microwave heating process. It permits to analyze the resonance phenomena by predicting the electromagnetic energy distribution outside and its value inside the foods through the solution of Maxwell equations. The mathematical model was employed to simulate temperature data obtained from prototype. The numerical predictions allow strategically develop internal patterns of heating altering the phases of the incident waves, that enable achieve greater uniformity of the final temperature profiles.

1. Introduction

Microwave heating of foods is an efficient method capable of generating energy inside the product through the interaction of radiation, mainly with water molecules. Microwaves are applied to different processes showing some advantages such as reduction of the environmental impact, energy saving compared to conventional methods, use of clean energy, spatial savings and decreasing of processing times [1].

The industrial application has certain disadvantages as low penetration of radiation in bulk products, low absorption of incident energy depending on the dielectric properties of materials and, finally, the uneven heating that occurs in foods with certain geometries and sizes as well as in foods which dielectric properties drastically change with temperature [2,3]. There is a similar problem with microwave thawing, due to preferential absorption of electromagnetic energy by liquid water compared to ice, caused by differences between dielectric properties ("runaway heating").

There is also experimental evidence that the shape and size of the product generates non-uniformity in internal temperature profiles during heating, particularly inside the cylinders and spheres and at the corners in parallelepiped shapes [4–8].

Several authors suggested some ways to reduce the intensity of non-uniformity in temperature profiles. Taher and Farid [9] and Gunasekaran and Yang [10] demonstrated the effectiveness of using power cycle during the microwave heating. As a disadvantage, the total process time is longer than under continuous power

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application. During microwave drying, Koné et al. [11] studied a drying strategy to improve the quality of dried products by using controlled power density. This technique is useful in drying process, where the mass of the product decreases strongly with the time and this provokes an increase of power absorption.

Geedipalli et al. [12] studied the role of a carousel in improving even heating of food in a microwave oven. They determined that the carousel helps in increasing the temperature uniformity of the food by about 40%. Another frequently used alternative is the movement of the material during the heating (use of fluidized beds, spouted bed dryers, rotary chambers, conveyor belts, etc.) [13].

Jet impingement (JI) is another method that was related to microwaves, giving rise to hybrid ovens [14,15]. In JI ovens, air can remove the water located at the surface of the food. At the same time, these ovens easily produce surface browning, needed in baked foods.

The variable-frequency technique is one of the most effective methods for improving field uniformity inside the resonant cavity. Conventional fixed-frequency microwave heating often results in localized heating as a result of local spatial fluctuations in the electromagnetic fields that cause non-uniform distribution within microwave cavities, thus leading to uneven heating and potentially poor product quality [16]. This technique works by sweeping through a band width of frequencies which are cycled through consecutively and launched into the cavity, resulting in different standing waves with many resonant modes. By sweeping through different frequencies, several possible cavity modes are excited, corresponding to different distributions of hot spots within the cavity. Then, these overlapped resonance modes result in a time-averaged uniformity. However, the geometry of the product should be taken into account: certain geometries, like spheres and cylinders usually cause maximum values at the center and the dielectric properties change due to the frequency dependence [17].

Nevertheless, the behavior of foods heating can be altered by working at a fixed frequency, knowing and technologically applying the resonance phenomenon inside the product in order to achieve more even temperature profiles.

The resonances are defined as values of maximum power absorption due to the interaction of the incident waves through transmitted and reflected waves within the material. For its application, the study of external behavior of the product should be complemented by the knowledge of internal behavior as well. This requires to control the pattern in the cavity and to characterize the profiles developed inside the product.

Resonances due to uniform plane waves were extensively studied by Bhattacharya and Basak, early in one dimensional samples [18,19]; therefore, for composite systems, like foods and ceramic plates [20–24]; they observed the resonance phenomena by the analysis of the individual traveling waves inside the sample, the transmitted and reflected waves, and their interactions. They established the position of maximum absorption points inside the sample, it occurs when the phase angle of transmitted wave coincides with the reflected one. Finally, their analysis permits to follow some useful strategies for optimal commercial processing.

In the present paper, we evaluate from the experimental and theoretical standpoints the controlled heating of foods, by changing the phases of two opposite electric field excitations and their interaction within food samples during thermal processing.

The purpose of this paper is to demonstrate the favorable effects of this electric fields phase change on the uniform heating of food. This work is an extension from a previous work [8].

Current work attempts to analyze the resonances by predicting the electromagnetic energy distribution outside and its value inside the foods through the solution of Maxwell equations. With this aim, we present a 3D mathematical model in order to solve the energy transfer during the microwave heating process. The analysis is focused into the product–radiation interaction, considering the dielectric properties of the product as temperature dependent. The numerical predictions allow us the study of the controlled microwave heating through the resonance phenomenon and to develop strategically internal patterns of heating by altering the phases of the incident waves, which achieve greater uniformity of the final temperature profiles.

2. Materials and methods

2.1. Experimental design

The aim of this work is to experiment with incident wave interference; according to this, the experimental procedure consisted in the heating of samples submitted to two incident waves impacting over both faces of the testing material.

An experimental oven with a 500 W magnetron oscillator was built (Fig. 1) to conduct food heating tests in a controlled way and coupled to a nonstandard waveguides system (80 × 32 mm) where the electromagnetic wave is conducted in the TE_{10} dominant mode with work frequency of 2.45 GHz. The design includes a microwave power generator, from which the signal is split into two equal and coherent wave fronts through a power splitter in waveguide and both signals are conducted through the elbows to a straight waveguide section where the testing sample can be introduced. The power splitter was built in order to be adapted to minimize reflections towards the microwave generating source, which may cause damage.

During the experiments, the average temperature increase after an exposure time (30 s) and the temperature history at a fixed position inside the sample were measured. The initial (room temperature) and final temperatures were recorded by T-type thermocouples connected to a data acquisition system. Besides, the temperature inside the samples was measured using an optical temperature sensor model FOT-L (Fiso Techno. Inc, Canada). The optical fiber probe worked in a rank from −40 °C to 300 °C with an accuracy of ± 1 °C. The probe was introduced inside the product from the upper wall of the waveguide, to record the material temperature during the heating experiments. The thermal histories were used to validate the proposed mathematical model.

The samples were contained in trays made of acrylic (material transparent to the radiation) with three sizes 80 × 32 × 100 mm (tray A), 80 × 32 × 50 mm (tray B) and 80 × 32 × 25 mm (tray C) (Fig. 2a). Preliminarily, trays were placed inside the waveguide. The straight section of the guide has a removable window through which the samples can be inserted; thus the electromagnetic waves may come into contact with both faces (Fig. 2b). In all cases, samples covered all the waveguide width and height, only varying their thickness.

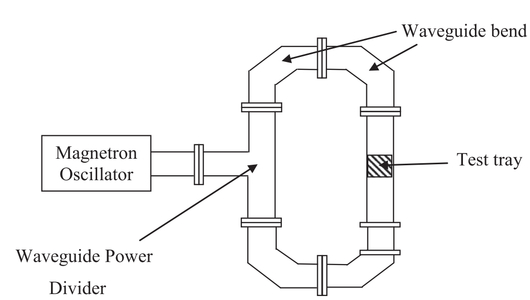

Fig. 1. Equipment top view diagram.