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Dynamic measurement of dielectric properties of food snack pellets during microwave expansion☆

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ABSTRACT

The in situ dielectric properties of a starch-based food pellet have been measured during microwave expansion. A dual-mode cylindrical cavity allowed simultaneous microwave heating and dielectric measurements of a single pellet inside a quartz tube, ensuring uniform heating during microwave processing. The cavity included additional measurement devices to correlate the dielectric properties with the main parameters of the expansion process, such as temperature, expansion time, pellet volume and absorbed power.

A commercially available snack food pellet was used as the test material for expansion experiments. Results indicated that dielectric constant (ε') and loss factor (ε'') increased during heating, reaching a threshold value of $\varepsilon' = 12.5$ and $\varepsilon'' = 5.2$, around a temperature of 115 °C when the material expanded and the dielectric properties dropped abruptly due to the loss of water content and the increase in size.

This measurement procedure may provide useful material science information to improve the overall design of starch-based food pellets processed by microwaves.

1. Introduction

Next generation snack foods offer manufacturers the ability to deliver new and improved consumer experiences through control of texture, shape and colour, and to reach consumers by non-traditional channels, such as food service, street food and vending. The manufacture of the food snack in an intermediate form, a shelf stable, glassy half-product termed a pellet, enables high volume/low cost manufacturing to be separated from finish drying of the consumer-ready final product. These two stages (Riaz, 2006) typically comprise: (1) manufacture of the shelf-stable glassy pellet, formed at low pressure to prevent expansion, to a moisture content 10–12% (hereinafter expressed in wet basis), and (2) finish drying, causing expansion to a moisture content 1–2% (the "finished" product). To obtain the finished product from the pellet, the expansion or foaming procedure is typically accomplished commercially by baking (Chen and Yeh, 2000), hot air puffing (Nath et al., 2007) or immersion of the pellets in frying oil (Osman et al., 2000). Domestic microwave ovens are also used for home finishing of some pellet forms such as pappadums.

Thermal technology is one of the most delicate aspects of food processing (Meda et al., 2005). In conventional heating, the material absorbs energy as a result of thermal gradients through convection, conduction and radiation. By contrast, microwave energy interacts directly with the material molecules, leading to an energy conversion to heat rather than heat transfer. Consequently, microwave energy can reduce processing times and energy consumption, thereby improving energy efficiency. When microwave energy is applied to starch-based materials, the factor that initiates the heating process is the water content (Boischot et al., 2003). Accordingly, as the starch matrix heats up and the temperature increases, water molecules are transformed into superheated steam, creating local high pressure. If the temperature is sufficiently high, the pellet matrix experiences a phase transition from a glassy to a rubbery state and, combined with the high superheated steam pressure, expands (Moraru and Kokini, 2003). If microwave heating is terminated at the appropriate time, the matrix reverts to a glassy state and the foamed air cells are retained due to the mechanical resistance of the matrix in the glassy state, generating a

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crispy or crunchy texture that appeals to consumers. Conversely, the matrix might burn if microwave heating is not terminated timely (Gimeno et al., 2004).

The detailed study of this singular heating process is particularly challenging due to the complex and rapid transformations that occur during the short time period in which the microwave expansion takes place, even under irregular distribution of temperature and moisture. Despite this difficulty, there are several studies in the literature that can provide relevant information on the process. For example, Lee et al. (2000) analyzed the effect of gelatinization and moisture content of extruded starch pellets on some morphological and physical properties of the expanded products (puffing efficiency and bulk density, among others), finding that the optimal expansion by microwave heating was achieved when the starch was approximately half-gelatinized and the moisture content in the pellets was ~10%. Kraus et al. (2014) investigated the influence of microwave power, system pressure and sample mass on the volume expansion, moisture ratio and pore distribution of starch pellets during microwave vacuum processing. They determined that the surface temperature of the pellet largely depends on the moisture content, observing that as microwave absorption increases, the water removal and the kinetics for heat and mass transfer occur faster, inducing a higher number of nucleated vapor bubbles. A study carried out by Gimeno et al. (2004) analyzed the effect of xanthan gum and carboxymethyl cellulose addition to improve the mechanical and structural properties of extruded glassy corn pellets expanded by microwave heating. The authors concluded that a small addition (~1%) of these substances could improve the shape, structure, and texture of microwave-expanded corn pellets.

The majority of the experiments performed in these studies and other reported expansion trials made use of multimode microwave equipment, such as domestic home equipment (Camacho-Hernández et al., 2014; Lee et al., 2000; Zhou et al., 2006) or specialized laboratory equipment (Boischot et al., 2003; Gimeno et al., 2004). Multimode microwave chambers are known to produce uneven temperature distributions, especially in low moisture content products, which are affected by factors including oven cavity geometry, location of the sample and size of the workload. Moreover, multimode applicators lack specific information about the absorbed power by the samples. For example, Lee et al. (2000) reported a power of 700 W to expand 30 g of pellets for 70 s in a commercial furnace (RE-552N, Samsung), Zhou et al. (2006) applied 1000 W to expand 10 g of pellets in a microwave oven (R-8720M, Sharp), and Gimeno et al. (2004) expanded single pellets inside a laboratory apparatus (AVC-80 moisture-solids analyzer, CEM Corporation) at 600 W for different periods of time, up to 60 s. On the other hand, experimental analysis relies on measurements before and after the expansion process, without monitoring the behaviour during the heating process.

The precise knowledge of the food pellet properties and process-related parameters is important to fully understand the heating of such materials by microwave energy. In particular, the dielectric properties define the interaction of dielectric materials with microwaves and, consequently, these parameters are an essential variable to describe the heating behaviour of food pellets when applying microwave fields (Nelson and Datta, 2001). The permittivity is defined as a complex value. The real part (or dielectric constant) is related to the ability of a material to store energy when it is polarized under alternating electric fields. The imaginary part (or loss factor) quantifies the capacity of the material to absorb this stored electromagnetic energy and dissipate it into heat. Since the loss factor of food materials is highly correlated with the amount of water (Meda et al., 2005), the moisture content of pellets will have a significant effect on the microwave heating process.

The influence of moisture content on the dielectric properties of ground pellets has been reported recently by Kraus et al. (2013), who used a cylindrical resonant cavity and the cavity perturbation method (CPM). Some attempts have also been made to measure dielectric properties of pellets during foaming for packaging applications, as described in Peng et al. (2013). In the latter work, the microwave instrument described in Nesbitt et al. (2004) was also used for thermal and dielectric measurements. The volume of pellets was calculated before and after the expansion, however, the influence of volume changes in the dielectric calculations was not provided.

The aim of the present study was to determine in situ the evolution of dielectric properties of starch-based food pellets during expansion as they are heated by microwave energy. The microwave apparatus used in the study was based on the dual mode cylindrical cavity described in (Catalá-Civera et al., 2015), which is able to heat and measure simultaneously with two different microwave sources. This setup was modified including some additional devices to fit the specific needs of the expansion procedure. The experimental study was carried out using a single pellet placed in the uniform field of the cavity to maximize the even absorption of microwave energy during heating and expansion. Unlike previous approaches, the temperature, microwave absorbed power, volume and processing time was also monitored in situ during the expansion process and correlated with the dielectric properties of the pellet. The calculation of dielectric properties made use of an enhanced CPM with calibration coefficients of different volume to increase the accuracy of in situ measurements.

The findings obtained using the experimental system described here may be useful for a better understanding of the kinetics and processing conditions of the expansion process under microwaves. The dielectric properties may be valuable parameters for the modeling and design of energy efficient microwave heating chambers. Moreover, these results may help food researchers to further adapt the overall properties of this type of snack to the conditions needed during microwave heating.

2. Materials and methods

2.1. Food pellets

A pellet used to make a commercially available snack food was used as the test material. The pellet (11–13% wet basis moisture content) was formulated primarily from potato flakes and was designed to be finished by factory frying in hot oil to a final moisture content of 2%. Although not formulated for microwave heating, the pellet has been found to expand reasonably well in domestic microwave ovens. For example, 100 g of pellets of approximately 30 mm in length and 3 mm in diameter (placed in a plastic tub), when heated at full power for 120 s yielded around 70% of pellets which were fully expanded, with the remaining pellets under-expanded or burned. The finished product when fully expanded was 50–60 mm in length and 6 mm in diameter.

Prior to expansion with the microwave system described below, pellets of circular cross-section ~3 mm in diameter were cut into pieces of 10–11 mm in length with flat sides and equilibrated to room temperature (~23 °C). The approximate weight of a pellet was 0.09 g. The moisture content of pellets was determined from the weight loss after heating to 103 °C in a convection oven (Heraeus WU 6100) for 72 h.