



HAL
open science

Microwave heating of low-loss dielectric food products

Sébastien Curet, K Robert, Eve-Anne Norwood, Clarissa Detomi de Albuquerque, Lionel Boillereaux

► **To cite this version:**

Sébastien Curet, K Robert, Eve-Anne Norwood, Clarissa Detomi de Albuquerque, Lionel Boillereaux. Microwave heating of low-loss dielectric food products. 18th International Conference on Microwave and High Frequency Applications - AMPERE 2021, AMPERE, Sep 2021, Gothenburg, Sweden. 10.5281/zenodo.5140406 . hal-04303218

HAL Id: hal-04303218

<https://institut-agro-montpellier.hal.science/hal-04303218>

Submitted on 23 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

MICROWAVE HEATING OF LOW-LOSS DIELECTRIC FOOD PRODUCTS

S. Curet, E. A. Norwood, K. Robert, C.D. Albuquerque, L. Boillereaux

*Oniris, Université de Nantes, CNRS, GEPEA, UMR 6144, F-44000 Nantes, France
sebastien.curet@oniris-nantes.fr*

Keywords: microwave heating, low dielectric properties, modelling, temperature distribution.

ABSTRACT

In the food industry, production of powdered materials enables to extend the shelf life of foods while preserving their intrinsic qualities. Moreover, in the case of high protein dairy powders, the application of a high temperature treatment (i.e. $T \geq 80^{\circ}\text{C}$) may modify proteins structure and thus their potential functionalities for further processing or incorporation within other food matrixes. This solution is particularly adapted in the context of a Clean Label approach where significant reductions of additives and other controversial ingredients are expected.

In this study, a microwave heat treatment is applied to a whey proteins isolate (WPI) powder in a dry state. The thermophysical properties of the WPI powder (density, specific heat and thermal conductivity) were measured or taken from literature. A dielectric characterization using a resonant cavity perturbation technique is also presented and the measurements confirmed the low dielectric loss factor of the sample.

A 3D numerical model, which includes a single mode microwave cavity working at 2.45 GHz, is also developed to understand the microwave interactions with the powdered food. Simulation results are discussed on the one hand in terms of electromagnetic field propagation within the rectangular waveguide and on the other hand by considering the temperature distribution within the powdered food. The model is experimentally validated with a pilot-scaled microwave equipment (2.45 GHz solid-state microwave emitter, impedance tuner and optical fibers probes). This study will give significant guidelines for the microwave heating optimization of low-loss dielectric products such as powdered food materials.

INTRODUCTION

In the food domain, dry heat treatments of powders are increasingly studied and used in order to improve the functional properties of food products such as dried ingredients. Several applications are classically encountered for egg products or dairy ingredients [1, 2]. Knowing that proteins are heat-sensitive components, the application of a high temperature treatment will allow to modify their structure and thus their functionalities. These modifications are of a great interest in the context of a Clean Label approach. The latter concept came from the desire to reduce additives and other controversial ingredients from the product ingredient list.

In this framework, the study is aimed at exploring the potential of using microwave technology to perform dry heat treatment on dried food materials, in particular on whey protein isolate powder. Microwaves have the ability to provide a volumetric heating within the food matrix, allowing to reduce the heating time and thus the energy consumption comparing to a conventional heating process.



Determination of thermophysical and dielectric properties of the WPI powder

The WPI powder was provided by a dairy company located in Brittany (France). The protein content was determined by the Dumas method using a FP828P carbon/nitrogen analyzer (LECO, St. Joseph, USA) and was of $88.58 \pm 0.01\%$ (wet basis).

The water activity (a_w) of the native powder was measured using an Aqualab PRE a_w meter (Meter Food, Pullman, USA) and was of around 0.2.

The thermophysical properties of the WPI powder were either measured or taken from literature (table 1).

Table 1. Thermophysical properties of WPI powder

Properties	Value	Unit	Source
Relative density (ρ)	425 ± 10	$\text{kg}\cdot\text{m}^{-3}$	Experimental
Specific heat (C_p)	1400	$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	Experimental
Thermal conductivity (k)	0.08	$\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{C}^{-1}$	[3]

The WPI powder is considered as a low moisture food ($a_w = 0.2$) with low dielectric properties such as non-fat milk powder or whole milk powder [4].

In this paper, the measurement of dielectric properties at X-Band Frequencies is performed by the cavity perturbation technique at room temperature [5]. The device consists in a straight WR340 waveguide. In its center, where the maximum electric field occurs, is located a cylindrical plastic tube filled with 1.8 mL of WPI powder. The antenna of the waveguide transition is connected to a vector network analyzer (Model ENA5062A, Agilent Technology, Malaysia). Resonance conditions of the microwave cavity are obtained by the use of an iris (made of copper material) placed between the waveguide transition and the applicator. A sliding short circuit is located at the end of the waveguide (figure 1).

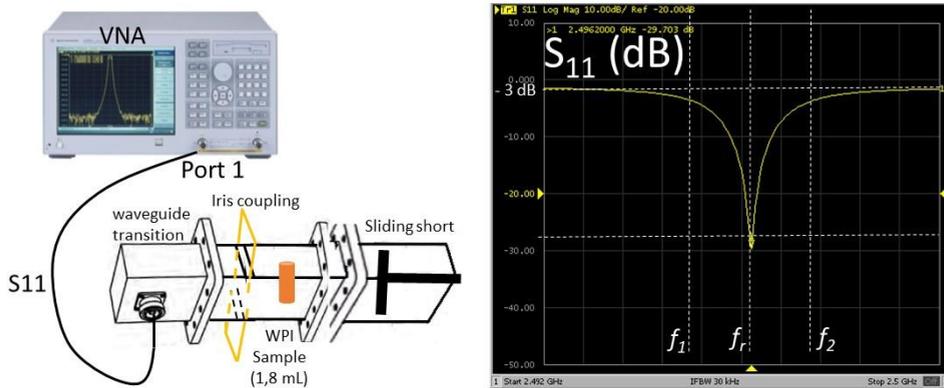


Fig. 1: Description of the experimental apparatus to measure the dielectric properties of the WPI sample (left), determination of the quality factor of the loaded cavity (right)

In a resonant cavity, the different losses of electromagnetic energy are characterized by quality factors that are linked by the following expression:

$$\frac{1}{Q_p} = \frac{1}{Q_0} + \frac{1}{Q_d} \quad (1)$$

Q_p is the quality factor of the cavity which reflects the ohmic losses at the metal walls and the dielectric losses due to the presence of dielectric materials in the cavity, Q_0 the quality factor related to the ohmic losses and Q_d the quality factor which corresponds to the losses within the dielectric materials.

In an empty cavity, $Q_d = 0$ (no specific dielectric charges), hence: $Q_p = Q_0$

In practice, the resonant cavity must be coupled to an external circuit. This coupling is defined by a quality factor (Q_{ext}). The external circuit has the effect of lowering the quality factor of the whole system.

The quality factor Q_l represents the total energy losses and is given by the following expression:

$$\frac{1}{Q_l} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \quad (2)$$

The quality factor for the loaded cavity (Q_l) is determined from the S11 (dB) signal from the vector network analyser (VNA) connected to the cavity (figure 1, right).

$$Q_l = \frac{f_r}{\Delta f} = \frac{f_r}{f_{2(-3dB)} - f_{1(-3dB)}} \quad (3)$$

The quality factor of the empty cavity is obtained from the reflection coefficient β calculated from the VNA (loaded cavity).

$$Q_0 = Q_l (1 + \beta) \quad (4)$$

Where β is the coupling coefficient issued from the voltage standing wave ratio.

The dielectric properties (dielectric constant ε'_r and loss factor ε''_r) of the material under test are calculated depending on the electromagnetic characteristics of the empty and loaded microwave cavity [5].

$$\varepsilon'_r = \frac{f_0 - f_1}{2f_1} \left(\frac{V_{cavity}}{V_{sample}} \right) + 1 \quad (5)$$

$$\varepsilon''_r = \left(\frac{V_{cavity}}{4V_{sample}} \right) \left[\frac{1}{Q_l} - \frac{1}{Q_0} \right]$$

Experimental apparatus and model design

The experimental apparatus consists in a solid-state microwave generator (SG 524, model AG340M3, Alter, Reggio Emilia, Italy) which supplies a monochromatic wave transmitted along the z-direction of a rectangular waveguide (cross-section 86 mm × 43 mm). The device also includes an antenna (transmission of the microwave input power until the waveguide transition), a 3-stub tuner for impedance matching, two quartz windows to

protect the upper and lower sides of the applicator, a water load and a shorting plunger (figure 2).

The temperature is measured at two locations within the WPI sample (T_1 near the upper surface and T_2 near the bottom surface). Temperature measurements are performed using type-K sheathed thermocouples and are recorded on a data logger (AOIP datalog, 91133 RisOrangis, France). The heat treatment is carried out with incident microwave power set at 180 W for 250 s.

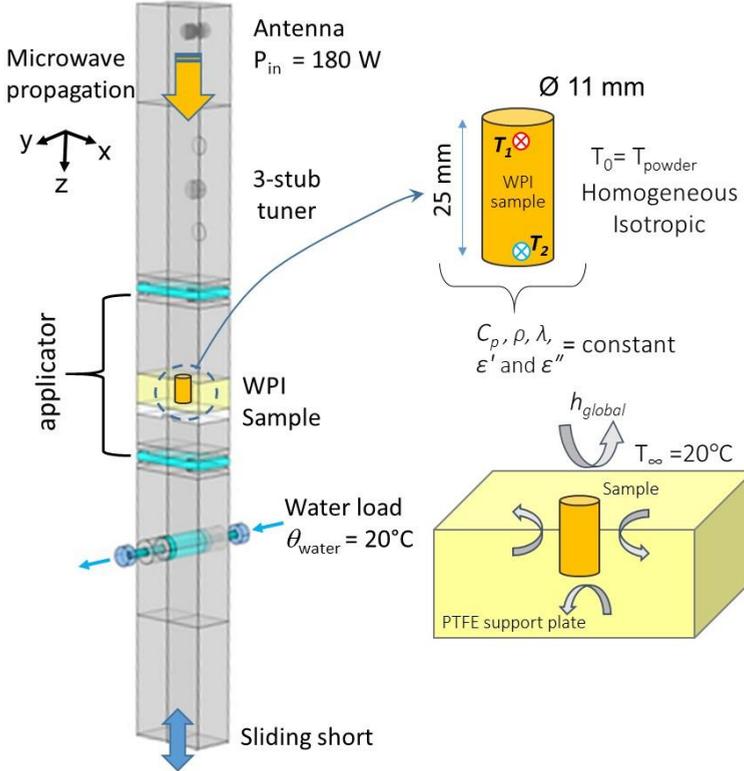


Fig. 2: Experimental microwave device

The real geometry of the microwave device is modelled with the COMSOL[®]Multiphysics 5.6 software package in order to predict the electromagnetic field distribution within the rectangular waveguide and the temperature distribution within the WPI sample.

The antenna is excited by a microwave signal at the input port (coaxial port, TEM mode). The RF module from COMSOL[®] is used to solve numerically the classical Maxwell's equations to obtain the electromagnetic field distribution within the rectangular waveguide (time-harmonic propagation of the electric field at 2.45 GHz).

$$\nabla^2 E + \omega^2 \mu \epsilon \left(1 - j \frac{\sigma}{\omega \epsilon} \right) E = 0 \quad (6)$$

$$\text{with } \epsilon = \epsilon' - j\epsilon'' = \epsilon_0 (\epsilon_r' - j\epsilon_r'') \text{ and } \sigma = \omega \epsilon_0 \epsilon_r''$$

ε_0 is the electrical permittivity of a vacuum (8.85×10^{-12} F/m), ε'_r is the relative dielectric constant, ε''_r , the relative dielectric loss factor. σ is the electrical conductivity of the material under consideration (S/m).

The generalized heat equation (with a source term due to microwaves) is solved to model heat transfer in a continuous medium, which depends on the thermophysical and dielectric properties of the WPI sample.

$$\rho C_p \frac{\partial T}{\partial t} = \text{div} (k \nabla T) + Q_{abs} \quad (7)$$

$$Q_{abs} = \frac{1}{2} \omega \varepsilon_0 \varepsilon''_r |E_{local}|^2 \quad (8)$$

The heat loss by convection around the sample is calculated by considering the global heat transfer coefficient which takes into account the heat losses at the boundaries [6].

RESULTS AND DISCUSSIONS

The table 2 depicts the dielectric properties of the materials under consideration within the rectangular waveguide.

Table 2. Dielectric properties of the materials at 2.45 GHz

Materials	Dielectric properties	Value	Source
Air at 20 °C	ε''_r	0	[7]
	ε'_r	1	
Dielectric material of coaxial antenna	ε''_r	0	[6]
	ε'_r	2.25	
Tap water at 20 °C (water load)	ε''_r	12.12	[8]
	ε'_r	80.10	
Quartz	ε''_r	0	[6]
	ε'_r	4.2	
Teflon® (sample holder)	ε''_r	$3.4 \cdot 10^{-4}$	[9]
	ε'_r	1.7	
WPI powder	ε''_r	0.015	This work (at 20°C and 2.49 GHz)
	ε'_r	1.8	

In this work, the dielectric properties of the WPI sample confirmed its low dielectric characteristics. The values found are in agreement with a previous work that compared different dielectric measurements as a function of frequency (open-ended coaxial probe method and the parallel plate method) dedicated to low-moisture foods [4].

Figure 3 displays the electric field distribution within the rectangular waveguide. The figure indicates that the standing wave propagates from the antenna to the end of the rectangular waveguide. Local variations of electric field strength are noticed along the microwave propagation direction, with a specific electric field peak near the antenna. Based on the experimental position of the 3-stub tuner and the sliding short, the model is able to predict the impedance matching condition as observed experimentally (the microwave reflected power is close to zero). In this configuration, both the water load and the WPI sample absorb the microwave input power (dielectric losses at the wall of the waveguide are considered as negligible).

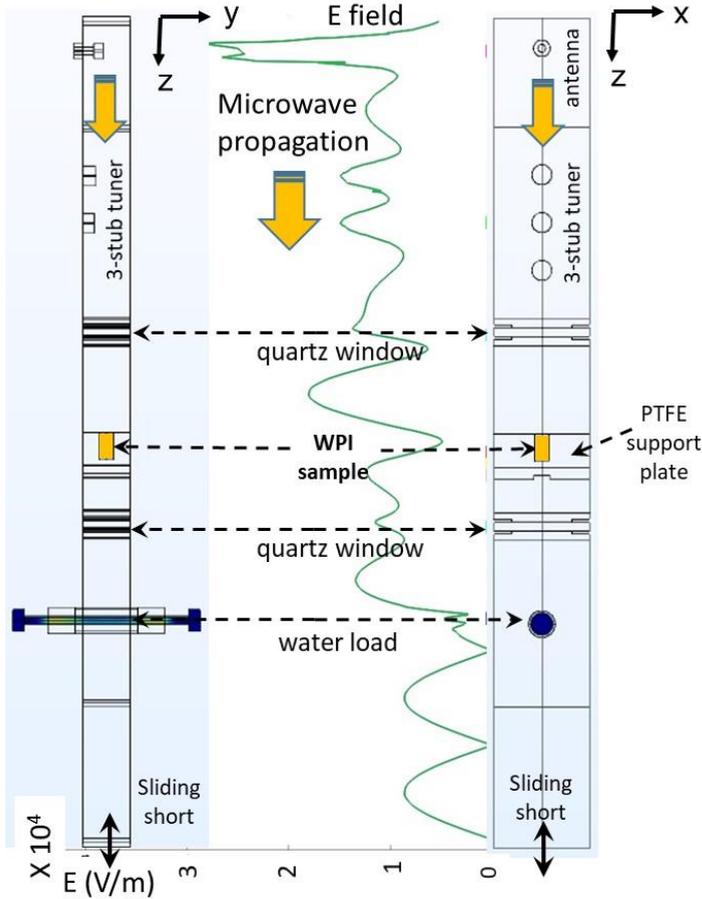


Fig. 3: Electric field propagation (*z*-component) within the rectangular waveguide

Figure 4 displays the temperature evolution at two different locations within the WPI sample. During microwave heating, uneven temperature distribution is observed as the bottom side clearly heats-up faster than the upper side (around 20°C of temperature differences between the top and bottom probes). Experimental temperature measurements are close to the model predicted values. Discrepancies between model and experiments are mainly due to the difficulty in determining the exact position of the sheathed thermocouples within the WPI powder. The model also considered that thermophysical and dielectric properties of the WPI powder are constant as a function of temperature.

The uneven temperature distribution within the WPI sample is also characterized in figure 5 with a temperature mapping following two cut plans located at the upper and lower sides. Hot spots are clearly identified at the center of the cylinder with a temperature gradient following the radius from the center to the external surface.

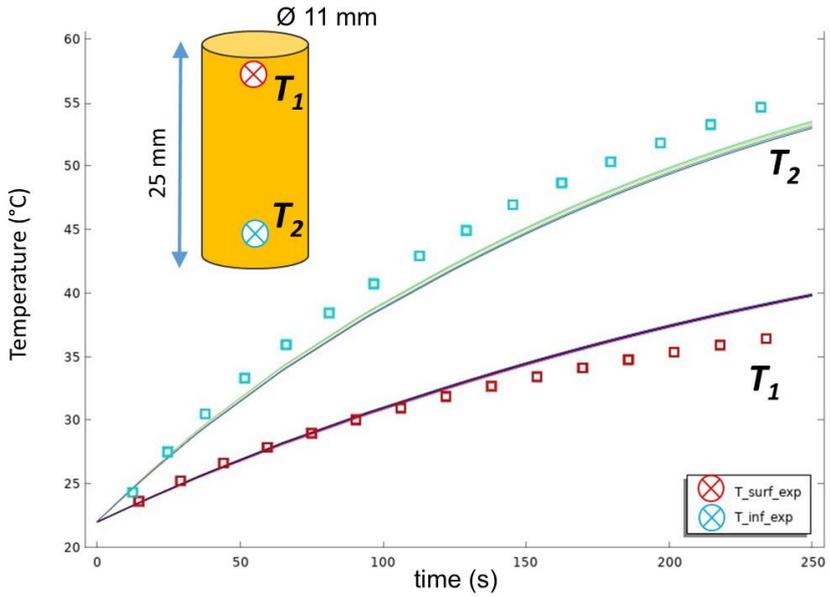


Fig. 4: Comparison between predicted and experimental temperatures within the WPI sample ($t = 250$ s)

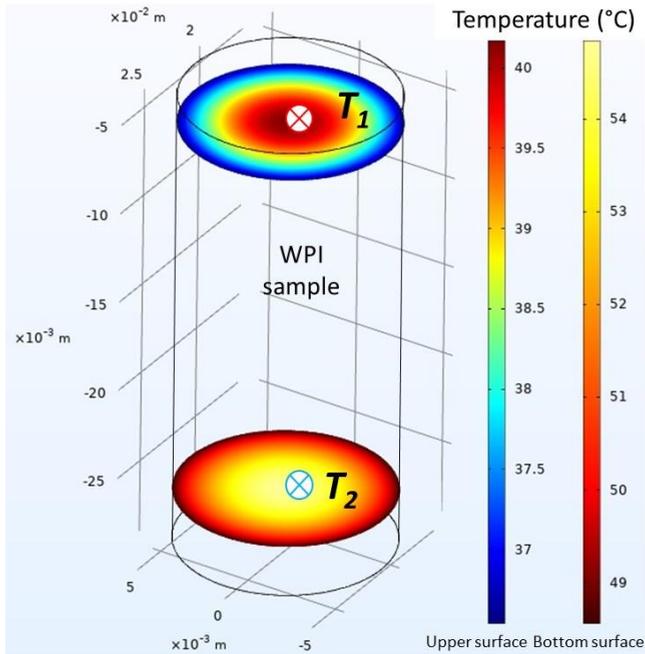


Fig. 5: Illustration of the heterogeneous temperature distribution within the WPI sample

CONCLUSION

In this research work, the objective was to investigate the potential of microwaves to provide a dry heat treatment of food powders. This study will give guidelines for the microwave dry heat treatment dedicated to low-loss dielectric products such as powdered food materials with low moisture content.

In terms of modelling, the microwave absorbed power is coupled to the heat transfer equation by considering a simple approach with constant thermophysical and dielectric properties. The numerical model is mainly used for the determination of the hot and cold spots location during the microwave dry heat treatment. This modelling approach could be used as a tool to control the heating process (modulation of microwave input power, frequency shifting of the solid-state emitter, rotation of the sample, ...).

It is now necessary to investigate the potential variation of thermophysical and dielectric properties of the whey protein isolate powder as a function of temperature. This work needs also to be extended to high temperature conditions (i.e. $T \geq 80^{\circ}\text{C}$) to study the potential modifications of proteins structures during microwave dry heat treatment.

REFERENCES

- [1] V. Lechevalier, C. Guerin-Dubiard, M. Anton *et al.*, "Effect of dry heat treatment of egg white powder on its functional, nutritional and allergenic properties," *Journal of Food Engineering*, vol. 195, pp. 40-51, Feb, 2017.
- [2] E. Schong, and M. H. Famelart, "Dry heating of whey proteins," *Food Research International*, vol. 100, pp. 31-44, Oct, 2017.
- [3] D. A. MacCarthy, "Effect of temperature and bulk density on thermal conductivity of spray-dried whole milk powder," *Journal of Food Engineering*, vol. 4, no. 4, pp. 249-263, 1985/01/01/, 1985.
- [4] S. K. Lau, D. Dag, S. Ozturk *et al.*, "A comparison between the open-ended coaxial probe method and the parallel plate method for measuring the dielectric properties of low-moisture foods," *Lwt-Food Science and Technology*, vol. 130, pp. 8, Aug, 2020.
- [5] A. Verma, and D. C. Dube, "Measurement of dielectric parameters of small samples at X-band frequencies by cavity perturbation technique," *Ieee Transactions on Instrumentation and Measurement*, vol. 54, no. 5, pp. 2120-2123, Oct, 2005.
- [6] C. D. Albuquerque, S. Curet, and L. Boillereaux, "Influence of heating rate during microwave pasteurization of ground beef products: Experimental and numerical study," *Journal of Food Process Engineering*, pp. 17, 2021.
- [7] J. H. Ye, T. Hong, Y. Y. Wu *et al.*, "Model Stirrer Based on a Multi-Material Turntable for Microwave Processing Materials," *Materials*, vol. 10, no. 2, Feb, 2017.
- [8] D. Salvi, D. Boldor, G. M. Aita *et al.*, "COMSOL Multiphysics model for continuous flow microwave heating of liquids," *Journal of Food Engineering*, vol. 104, pp. 422-429, Jun, 2011.
- [9] A. A. Salema, and M. T. Afzal, "Numerical simulation of heating behaviour in biomass bed and pellets under multimode microwave system," *International Journal of Thermal Sciences*, vol. 91, pp. 12-24, May, 2015.