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Welcome to the 54th IMPI Symposium

Each year, IMPI brings together researchers from across the globe to share the latest findings in microwave and RF heating theories and applications, and this year we have an outstanding array of researchers in attendance. If you are not yet a member of IMPI, we strongly encourage you to join. IMPI membership connects you to microwave and RF academia, researchers, developers and practitioners across the globe.

In light of the current COVID-19 pandemic, this is the first year in our history that IMPI has conducted this Symposium virtually. We would like to recognize the contributions of our technical hosts: John F. Gerling of Gerling Consulting and Eric Brown of Conagra Brands. We also wish to thank our Virtual Exhibitors: Mini-Circuits, MKS, Muegge GmbH, Odyssey Technical Solutions, pinkRF, SAIREM & Wave PIA.

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B. Reeja Jayan, Ph.D.
Associate Professor, Mechanical Engineering
Faculty Fellow, Wilton E. Scott Institute for Energy Innovation
Courtesy appointments in Materials Science & Engineering, Chemical Engineering, Electrical & Computer Engineering

Carnegie Mellon University
5111 Scott Hall, Pittsburgh, PA 15213
Phone: (412)268-4343
Email: bjayan@andrew.cmu.edu
Web: https://www.meche.engineering.cmu.edu/faculty/jayan.html

Keywords: Microwave, heating, materials, electromagnetic fields

ABSTRACT

Electromagnetic fields absorbed within a material may not be immediately converted to heat, but can instead result in field-driven "non-thermal" effects. In some cases, even new behavior evolves such as ceramics that are ductile and can be drawn into wires that survive high temperatures and other extreme environments that metals cannot. However, the underlying fundamental mechanisms behind these observations remain largely unknown. This talk will describe my lab's ongoing efforts to merge exploratory experiments and computation with data-driven methods to define new theoretical foundations that explain the behavior of groups of atoms under microwave radiation. Our goal is to demonstrate how such non-thermal effects of microwave fields can be used to engineer new materials and advanced manufacturing processes.

Continuous Flow Microwave Processing of Foods and Beverages: From 1 to 100 liters per Minute and Back in 25 Years

Josip Simunovic[1,2] and Michael Druga[2]

[1]North Carolina State University, Raleigh, NC, USA
[2] SinnovaTek Inc., Raleigh, NC, USA

Keywords: continuous flow, microwave processing, microwave assisted aseptic processing, food preservation, advanced thermal processing

INTRODUCTION

Continuous flow microwave processing is an advanced thermal processing technology used for heating and preservation of foods, beverages and biomaterials. In 1996 this technology became the focus of research and development efforts of the Food Engineering team at the Department of Food, Bioprocessing and Nutrition Sciences at North Carolina State University in Raleigh, NC. Also known as microwave assisted aseptic processing, it was identified and developed as the technology with the highest commercial potential for continuous sterilization and aseptic packaging of viscous, poorly conductive, thermos-sensitive and complex particulate products such as chunky soups, stews and sauces. Starting with the 1kW and 5kW bench top and pilot systems, to 60kW and 75kW semi-industrial installations, and continuing to 100kW, 200kW and 400kW commercial processing installations, recent development efforts have been concentrated on smaller capacity and mobile systems for distributed processing and production of customized and personalized nutrition products. Several novel and unique products have been enabled and commercialized using continuous flow microwave heating followed by aseptic packaging. This paper will provide a brief overview of the evolution of continuous flow microwave technologies, rationale for various system design and the growing list of food, beverage and biomaterial products introduced by industrial users of the technologies.

METHODOLOGY

Three main generations of continuous flow microwave processing system designs have been developed, tested and implemented at benchtop, pilot, semi-industrial and commercial production scales, resulting in 3 R&D and 6 industrial facilities, and multiple processing lines for a variety of food, beverage and biomaterial products.

Commercial packaging formats range from individual serving spouted pouches to multi-serving aseptic cartons to flexible packaging for food service intended to replace #10 cans, to 1000 kg bulk bag in box totes containing ingredients for bakery, beverage and infant food products.

Early models and initial benchtop and pilot capacity installations have been tested using 915 MHz cylindrical microwave applicators, starting with the first system in 1997. This led to the first commercial installation for processing of shelf stable aseptic sweet potato purees at Yamco (Snow Hill, NC).

The second generation of 915 MHz processing systems (AseptiWave systems) was initiated with the installation of the modular 75 kW travelling wave system coupled with an aseptic pouch filler at North Carolina State University and used in the largest commercial installation of the technology, Wright Foods in Troy, NC.

The third generation of the technology implemented the established AseptiWave and the novel Nomatic designs using 2450 MHz microwave generators for a broad variety of processing capabilities, with R&D and production installations at SinnovaTek in Raleigh, NC; North Carolina Food Innovation Lab in Kannapolis, NC; First Wave Innovations in Raleigh, NC and Panacea Nutrition in Danville, VA.

All three generations are in current commercial use and are maintained and supported by SinnovaTek.

Figure 1. Illustrates the current commercial offerings at different production scales

Figure 1. Three production scales of SinnovaTek microwave processing systems:

a) Benchtop – Nomatic - 2450 MHz ~ 1 ton per day
b) Pilot – AseptiWave – 915 MHz ~ 1 ton per hour
c) Commercial production – AseptiWave - 915 MHz ~ 4 tons per hour

RESULTS

Continuous flow microwave heating, pasteurization and sterilization technologies for foods, beverages and biomaterials have been in development for 25 years and in commercial production since 2007. Over 100 new products have been introduced to the consumer, food service and bulk ingredient commercial markets since the first installation.

Different generations of the technology, its developers and the resulting products have been recognized by professional, government and scientific organizations, including two IFT Food Technology Industrial Achievement Awards in 2009 and 2015.

Figure 2. Microwave processed food and beverage products

DISCUSSION

New installations and new applications of continuous flow microwave processing continue to grow in numbers, capacity and variety of outputs. The original objective of commercial production of high quality shelf stable aseptic particulate / multiphase products using microwave sterilization is still pursued. United States FDA recently recognized safety of microwave assisted aseptic processing. This event marked another significant positive development in these efforts.

Ready availability of an advanced thermal technology and its continued evolution from experimental to commercial scale establishes a new advanced level of capability for the food processing industry to produce high quality, shelf stable high acid, acidified and low acid foods and beverages.

Microwave processing technologies, in combination with the new aseptic packaging technologies, particularly the recent introduction of fully aseptic spouted pouch formats, opens the opportunity for development and commercial introduction of product lines previously unavailable in aseptically packaged shelf stable formats.

CONCLUSION

Continuous flow microwave processing technologies provide a commercially tested and viable advanced thermal processing option for the food industry to maximize safety, sensory quality, nutrient retention and profitability of established and novel food products in shelf stable packaging formats with ambient shelf life of 12 to 18 months, requiring no frozen or refrigerated storage or distribution.

Comparison of Microwave and Conventional Heating for CO_2 Gasification of Different Rank Coals

Candice Ellison[1,2], Victor Abdelsayed[1,2], Mark Smith[1], and Dushyant Shekhawat[1]

[1]National Energy Technology Laboratory, U.S. Department of Energy, Morgantown, WV, USA
[2]Leidos Research Support Team, Morgantown, WV, USA

Keywords: Gasification, microwave irradiation, coal rank, syngas.

INTRODUCTION

Gasification is a process used to convert solid organic- or fossil-fuels (e.g. biomass or coal) into syngas ($CO+H_2$), which can be further upgraded to hydrocarbons via Fisher-Tropsch process, used to generate energy in solid oxide fuel cells, or directly combusted for heat. Chars generated during gasification are considered of additional value. Microwave-assisted processes have been shown to alter product conversions due to the selective nature of microwave heating resulting in product distributions that are not observed under conventional, thermal processes [1]. Feedstock chemical and structural properties, which differ among each coal rank, can impact the yields and conversion during gasification. In addition, differences in dielectric properties between different coals lead to different microwave attenuations. Coal dielectric properties are affected by coal properties such as fixed carbon content, ash content, sulfur, moisture, and density [2]. To better understand the effect of coal rank on products from microwave-assisted gasification, this study compares yields from CO_2 gasification under microwave and conventional heating of different rank coals.

METHODOLOGY

Three coals of different rank (lignite, sub-bituminous, and bituminous) were gasified under microwave and conventional heating. During microwave CO_2 gasification, a single mode 2 kW, 2.45 GHz system (Sairem) was used in pulsed mode to maintain a setpoint temperature of 700˚C as measured by an infrared pyrometer. During conventional CO_2 gasification, a drop-bed tube furnace reactor was used. In both reactors, the coal sample (3 g) was heated in a quartz tube to 700˚C under CO_2 flow (67% CO_2/Ar) with continuous downstream gas analysis by MS and GC. All three coals were tested under microwave and conventional heating under the same temperature and flow conditions. The product and gas yields were analyzed.

RESULTS

In all cases, microwave-assisted gasification yielded less char with greater conversion to syngas compared to conventional gasification (Figure 1). Gasification of lignite coal yielded the largest quantity of tars owing to the high volatile matter composition of the parent coal. The highest syngas yields were produced from CO_2 gasification of sub-bituminous coal under microwave irradiation, while bituminous coal yielded the least syngas under both microwave and conventional heating.

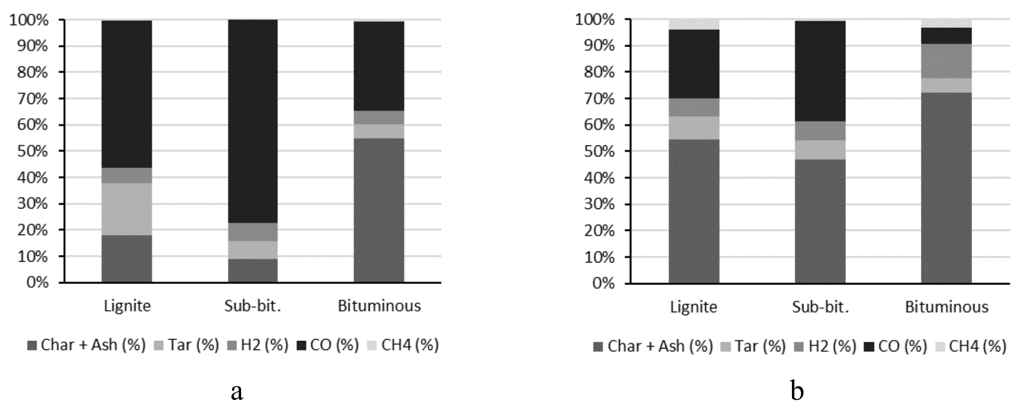

Figure 1. Yields from CO_2 gasification of three different rank coals under (a) microwave and (b) conventional heating.

DISCUSSION

The higher syngas yields with microwave-assisted gasification compared to conventional gasification could be attributed to the selective heating during microwave irradiation. While the bulk gasification temperature was the same for all tests, the selective nature of microwave dielectric heating results in localized hotspots, which assists the gasification reaction and increased conversion to syngas.

CONCLUSION

Microwave-assisted gasification increases syngas yields compared to conventional heating for all coal ranks. Sub-bituminous coal is found to be the best suited for microwave gasification due to its high conversion to syngas while minimizing tar yields.

REFERENCES

[1] Y. Fernández, A. Arenillas, J.M. Bermúdez, J.A. Menéndez. Comparative study of conventional and microwave-assisted pyrolysis, steam and dry reforming of glycerol for syngas production, using a carbonaceous catalyst. *J Anal Appl Pyrol.,* vol. 88, no. 2, pp. 155-159, 2010.
[2] X. Zheng, B. Wang, J. Guo, D. Zhang, J. Zhao. Factors influencing dielectric properties of coal of different ranks. *Fuel,* vol. 258, no. 116181, 2019.

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Microwave Sintering of $BaTiO_3$ for Multilayer Ceramic Capacitors

Juan A. Aguilar-Garib, Osvaldo Tijerina-García and Javier Garza-Guajardo

Universidad Autónoma de Nuevo León, Facultad de Ingeniería Mecánica y Eléctrica,
San Nicolás de los Garza, NL, México

Keywords: Microwave sintering, $BaTiO_3$, MLCC's.

INTRODUCTION

It has been reported that microwave processing decreases sintering temperature of some ceramics, such as zirconia and lithium aluminosilicate [1], suggesting that those results could be extended to other ceramics. Yasuoka *et al.* [2] compared microwave sintering of pellets of 18 mm diameter in a kitchen oven at 800 W for 30 minutes followed by 960 W for 10 minutes, with SiC as susceptor, against conventional sintering at 1140°C for 2 hours, with a heating rate of 10°C/min.

It is proposed in this work that the dielectric of multilayer ceramic capacitors (MLCC's) based on $BaTiO_3$, is suitable to be sintered in the same way. The MLCC's are fabricated with thin layers produced by type casting of a barbotine. Then the electrodes are printed over each layer, and in turn stacked to obtain an interdigitated electrode structure. Industrial MLCC's sintering is conducted under reductive conditions for preventing electrode oxidation and promote oxygen vacancies in the dielectric. In this work the dielectric was sintered without the electrodes, which could affect the electric field inside the sample or produce joule heating [3].

METHODOLOGY

The microwave cavity was fed with a 2.45 GHz magnetron taken from a kitchen oven, 1100 W nominal power, coupled to a WR284 waveguide system with a circulator, dummy load, and a directional coupler, so that forward and reflected power were registered. The electronics was modified so that that it was possible to adjust the power output all the time that the on/off control had the equipment operating.

The temperature was measured with a shield thermocouple and controlled with an on/off device as in reference [4]. It was confirmed that the thermocouple was in such position that did not exhibit self-heating. The layers of $BaTiO_3$ were prepared by tape casting and stacked in the same form than the MLCC's, but without the electrodes and larger to be handled easier, 12.7 mm x 12.7 mm x 1.5 mm. These samples were placed in an alumina crucible with 5 g of graphite as thermal susceptor and reducing agent, and then set in the microwave cavity for being sintered at 1050°C and 1150°C. These temperatures are often reported in literature [2, 5-7]. The samples were exposed to microwaves for 20 minutes, at a heating rate 10°C/min. For conventional heating, the samples were placed in the same crucible, with graphite as well, in an electric resistance furnace. However, 20 minutes were not enough for conventional sintering, hence, these tests lasted 120 minutes each with the same heating rate.

RESULTS AND DISCUSSION

Figures 1 and 2 show the plot of forward and reflected power against time for one of each of the tests at the proposed temperatures. They include the heating, maintaining (20 minutes) and cooling time, and that is the reason for the long time to reproduce the heating rate observed in the conventional tests. These figures also show the on/off control frequency as well as a more susceptible sample at higher temperature noticeable by the decreasing of the reflected power. At least alumina responds increasing the imaginary part of permittivity with the temperature [8] and that could be the reason for that behavior.

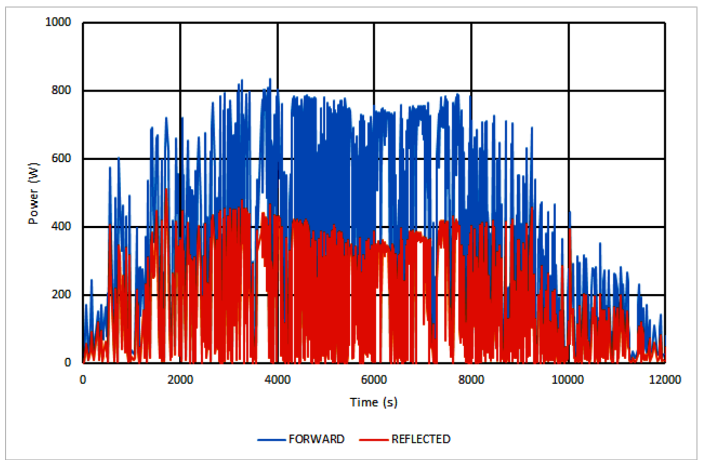

Figure 1. Forward and reflected power along the test conducted at 1050°C.

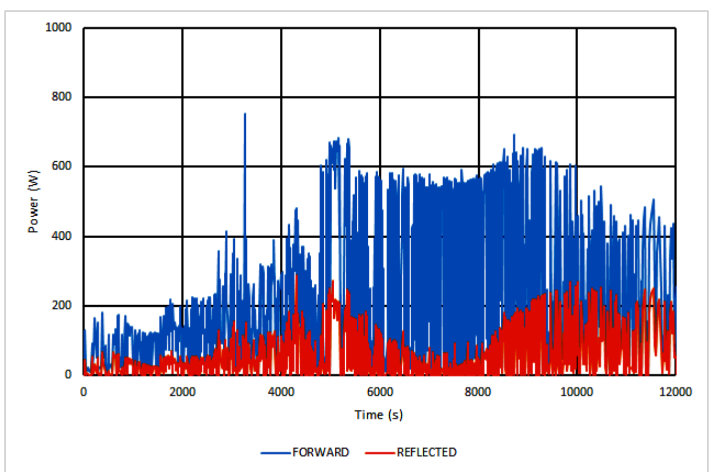

Figure 2. Forward and reflected power along the test conducted at 1150°C.

The temperature control was an important issue because the sample was getting hot too quickly so that the proposed heating rate was exceeded. Temperature was maintained within a ±20°C of the setpoint control. The average sintering degree was determined by the achieved density (Table 1) against the theoretical density of $BaTiO_3$ (6.02 g/cm^3).

Table 1. Relative density of the sintered layers.

Temperature	Conventional	Microwave
1050°C	0.92	0.91
1150°C	0.89	0.92

Yasuoka *et al.* [2] reported that $BaTiO_3$ sintered conventionally exhibited different dielectric properties than the material sintered with microwaves (at unknown temperature processing), which is not directly comparable. In this work the temperature is comparable for both processes, while microwave processing was faster, although it was not confirmed that the products are indeed the same in terms of other properties.

CONCLUSION

Sintering of MLCC´s $BaTiO_3$ based dielectric is possible with microwaves and under these conditions was faster, 20 minutes vs. 120 minutes. Comparison of the product was based on relative density, but dielectric properties must be considered. A contribution of this work is that compares two sintering processes in similar conditions of temperature.

REFERENCES

[1] Amparo Borrell and Maria Dolores Salvador (October 31st, 2018). Advanced Ceramic Materials Sintered by Microwave Technology, Sintering Technology - Method and Application, 2018.
[2] Masaki Yasuoka, Yutsuki Nishimura, Takaaki Nagaoka and Koji Watari. Advances in Technology of Materials and Materials Processing, 6[2] (2004) 270-275.
[3] Juan A. Aguilar-Garib, Osvaldo Tijerina-García, Javier Garza-Guajardo. Sintering of MLCC's Barium Titanate with Microwaves, *17th International Conference on Microwave and High Frequency Heating* AMPERE 2019, Valencia, Spain, September 9-12, 2019, 457-462.
[4] J. Aguilar-Garib, Advances in Induction and Microwave Heating of Mineral and Organic Materials, IntechOpen, 2011, 243-268.
[5] R.K. Patel, P. Kumar, C. Prakash, D.K. Agrawal, Ceramics International, 2012, 38, 1585-1589.
[6] S. Derling, H.-P. Abicht, Journal of Microwave Power and Electromagnetic Energy, 1996, 31, 221-227.
[7] A. Domer-Reisel, S. Schöps, A. Lenk, G. Schmutzler, Advanced Engineering Materials, 2007, 9, 400-405.
[8] J. Aguilar, J. Pearce. British Ceramics Transactions, Vol. 102 (2), pp 52-56, 2003.

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Microwave-Assisted Extraction (MAE) of Anthocyanins from Different Genotypes of Purple Fleshed Sweet Potatoes (PFSP)

T. Bhatia[1], J. Simunovic[1] and K.P. Sandeep[1]

[1]Department of Food, Bioprocessing, and Nutrition Sciences, North Carolina State University, Raleigh NC, USA

Keywords: microwave-assisted extraction, dielectric properties, anthocyanins, purple-fleshed sweet potatoes, total phenols

INTRODUCTION

Microwave assisted extraction (MAE) is one of the emerging technologies for extraction of different types of polyphenolic compounds, including anthocyanins from biomaterials, fruits, and vegetables such as purple-fleshed sweet potatoes. Dielectric properties determine the interaction of microwaves with materials in general and food materials, particularly. Therefore, knowledge of dielectric properties can help in determining the extent of heating of food materials using microwaves. (Nelson, 2015).

Purple-fleshed sweet potatoes (PFSP) have an intense and rich purple color in the skin and flesh of the storage roots due to accumulation of anthocyanins (Philpott, et al., 2003) with the main anthocyanins being cyanidin and peonidin (He, et al., 2016). The major reason for the development of PFSP were for their use as natural colorants as they exhibit different colors at different pH levels – orange red at pH 1 and mustard yellow at pH 13. They are now gaining popularity as a dietary source of anthocyanins and are considered superfoods with various health benefits. These benefits include anti-inflammatory properties, anti-cancer potential and anti-ulcer potential, boosting the immune system and protecting the cardiovascular system (Steed, 2007).

The main objective of this study was the microwave-assisted extraction of anthocyanins and phenols from six genotypes of PFSP using an optimized material to solvent ratio and time-temperature combination, with water as the solvent.

MATERIALS AND METHODS

Six genotypes (NCP-13-0030, NCP-13-0005, NCP-06-0020, NCP-13-0285, NCP-13-0315, and Stokes) of PFSP were chosen for this study. Samples were provided by the NCSU experimental fields of the Sweet potato Breeding Program (Clinton, NC). Dielectric properties of samples were measured in the temperature range of 23 °C to 135 °C using an open-ended coaxial probe (Model HP 85070B, Agilent Technologies, Palo Alto, CA) connected to a network analyzer (Model HP 8753C, Agilent Technologies, Palo Alto, CA) as shown in Figure 1.

Material to solvent ratios of 1:1 were used for the extraction of anthocyanins and total phenols. Hundred grams of blanched sample was weighed and placed in 300 ml Pyrex bottle. Then, 100 milliliters of water was added to the bottle. The extraction process was then initiated using a batch microwave oven (Model No. SD767W, 2450 MHz, 1200 Watts, Panasonic USA, Newark, NJ), which was equipped with a fiber optics sensor work station (Fiso Technologies, Quebec, Canada) at different time-temperature combinations based on data from literature (Lemmens, et al., 2010; Dutta, et al., 2006). Extraction was followed by filtration of the extract using a 0.25inch fine mesh strainer (Winco DWL International, New Jersey, USA). Additionally, the extract was centrifuged at 5000 rpm for 10 minutes using a centrifuge (Thermo Fisher Scientific Sorvall legend XTR, Waltham, MA). Finally, the supernatant of the extract was transferred to 50 ml amber colored disposable conical test tubes (Thermoscientific, New Jersey, USA) and stored at -20 °C before further analyses.

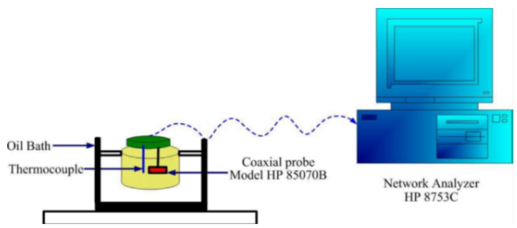


Figure 1: Schematic diagram of the network analyzer setup for measurement of dielectric properties (Adapted from Kumar, 2006)

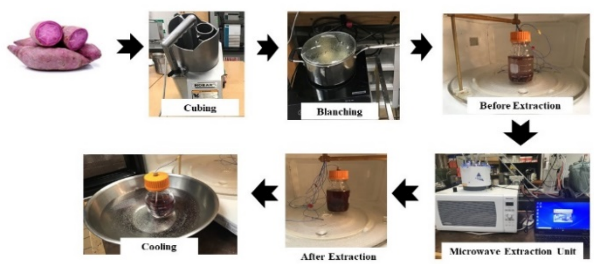


Figure 2: Flow diagram representing microwave assited extraction of anthocyanins

RESULTS

Table 1: Microwave assisted extraction (MAE) of total phenols and anthocyanins from different cultivars of PFSPs

Genotype	Total Phenolic Content (mg/ 100 g)	Total Anthocyanins Content (mg/100g)
NCP-13-0030	541 ± 6^{c}	16 ± 0.5^{c}
NCP-06-0020	686 ± 4^{a}	31 ± 1^{a}
NCP-13-0315	669 ± 4^{b}	22 ± 1^{b}
Stokes	289 ± 1^{f}	21 ± 0.2^{d}
NCP-13-0285	262 ± 4^{d}	43 ± 0.2^{a}
NCP-13-0005	233 ± 4^{e}	20 ± 0.4^{e}

Data are expressed as mean ± standard deviation of duplicates. Similar letters within columns indicate there was no significant differences as per Tukey HSD test ($p > 0.05$)

DISCUSSION

Dielectric constant decreased with increasing temperature whereas dielectric loss factor and loss tangent increased with increasing temperature, indicating that an increase in temperature would result in a more rapid heating of PFSPs at higher temperature levels. Total phenolic content (per 100 grams) of six genotypes of PFSPs was as follows: NCP-13-0030 – 548.55 mg, NCP-13-0315 – 816.22 mg, NCP-13-0285 – 727.16 mg, NCP-06-0020 – 906.36 mg, NCP-13-0005 – 722.84 mg, and Stokes – 398.68 mg. Phenols obtained using microwave assisted extraction of different PFSP genotypes at 100 °C for 9 minutes (per 100 grams) ranged from 232.94 mg to 686.12 fw with an extraction efficiency ranging from 32.2% to 98.7%. Total anthocyanin contents (per 100 grams) of PFSPs was as follows: NCP-13-0030 – 54.16 mg, NCP-13-0315 – 63.92 mg, NCP-13-0285 – 64.21 mg, NCP-06-0020 – 63.75 mg, NCP-13-0005 – 34.22 mg, and Stokes – 66.50 mg. The anthocyanin after MAE extraction at 100 °C for 9 minutes (per 100 grams) from different genotypes of PFSP ranged from 16.12 mg of sample to 43.30 mg fw of sample with an extraction efficiency ranging from 29.8% to 67.4% for different genotypes of PFSPs.

CONCLUSION

Microwave-assisted extraction of phenols and anthocyanins from different genotypes of PFSP using water as a solvent was proven to be a viable technology to obtain extracts of bioactive compounds using a safer and environmentally friendly technology. This was considered a safe and clean technology because water was used as a solvent in place of chemicals such as hexane. The optimal material (PFSP) to water ratio (1:1) and time-temperature combination (100°C for 9 minutes), determined from preliminary experiments were used to efficiently extract anthocyanins from PFSP. Additionally, these anthocyanins can be incorporated in various foods and beverages to promote human health and can potentially also replace artificial colorants used in the food industry. Another important aspect of this research is the reduction of food waste by extraction of functional bioactive ingredients from sub-grade fruits and vegetables as well as waste and by-products of this technology into food and beverage products such as flour for human use or as animal feed.

REFERENCES

[1] Nelson, S.O. (2015). "Dielectric properties of selected food materials." In Dielectric properties of agricultural materials and their applications, 147-165. Cambridge MA: Academic Press.
[2] Philpott, P., Gould, K.M.K., and Lewthwaite, L.F.L. (2003). "Enhanced coloration reveals high antioxidant potential in new sweet potato cultivars." Journal of the Science of Food and Agriculture, 83: 1076-1082.
[3] He, W., Zeng, M., Chen, J., Jiao, Y., Niu, F., Tao, G., He, Z. (2016). "Identification and quantitation of anthocyanins in purple-fleshed sweet potatoes cultivated in China by UPLC-PDA and UPLC-QTOF-MS/MS." J. of Agricultural and Food Chemistry, 64(1): 171-177.
[4] Steed, L. (2007). "Nutraceutical and rheological properties of purple-fleshed sweet potato purees as affected by continuous flow microwave-assisted aseptic processing." Raleigh, NC: North Carolina State University.
[5] Lemmens, L., Vleeschouwer, K., Moelans, K., Colle, I., Van Loey, A., and Hendrickx, M. (2010). "Beta-carotene isomerization kinetics during thermal treatments of carrot puree." Journal of Agricultural Food Chemistry, 58: 6816-6824.
[6] Kumar, P. (2006). "Aseptic processing of a low-acid multiphase food product using a continuous flow microwave system." Raleigh, NC: North Carolina State University.

Simulation of Temperature Fields in Microwave Processing of SiC_f/SiC Composites

Jon Binner[1], Roger Morell[2], Matthew T. Porter[1], Petra Kumi[3], and Vadim V. Yakovlev[3]

[1]School of Metallurgy and Materials, University of Birmingham, Birmingham, U.K.
[2]National Physical Laboratory, Teddington, London, U.K.
[3]Department of Mathematical Sciences, Worcester Polytechnic Institute, Worcester, MA, USA

Keywords: ceramic matrix composites, microwave heating, multiphysics simulation.

INTRODUCTION

The aerospace industry is one of the largest and arguably the most important to the composite materials sector. For many aerospace applications, the exceptional mechanical properties of composites, such as high strength, low weight and high stiffness are of utmost importance [1]. To this end, chemical vapor infiltration (CVI) is a promising advanced manufacturing technology [2]. CVI is a process in which a solid substance is deposited into a porous preform by the thermal decomposition of a reactive gaseous mixture. This process may be at least an order of magnitude quicker and more energy-efficient if carried out under the influence of a microwave (MW) or RF field [3]-[5]. However, our most recent advancement of MW-enhanced CVI has provided insight on unexplained experimental observations and a lack of reproducibility.

Here we present computational results aiming to clarify the puzzling facts, understand causes for the formation of microwave-induced temperature fields, and suggest a means for achieving superior control of the equipment. Simulations were carried out on the process involving heating of layered discs of woven SiC fibers.

METHODOLOGY

A computer model reproduces the experimental system, which consists of a large microwave cavity with waveguide excitation (SAIREM's Labotron HTE M30KB CL PRO) and a SiC fabric disc sandwiched between two alumina foam rings encapsulated in a quartz reaction chamber, as shown in Figure 1. The temperature characteristics of the electromagnetic (EM) and thermal (T) material parameters for quartz and alumina foam were obtained from the literature and measured expeirmentally for the SiC fabric; they serve as input data for the model. A finite-difference time-domain (FDTD) EM model built in the *QuickWave*™ (*QW*) [6] environment generates frequency characteristics for the reflection coefficient at five temperatures, in the range from 25 to 1,200°C, as represented by corresponding values of of the EM material paraemters. An EM-T coupled model is

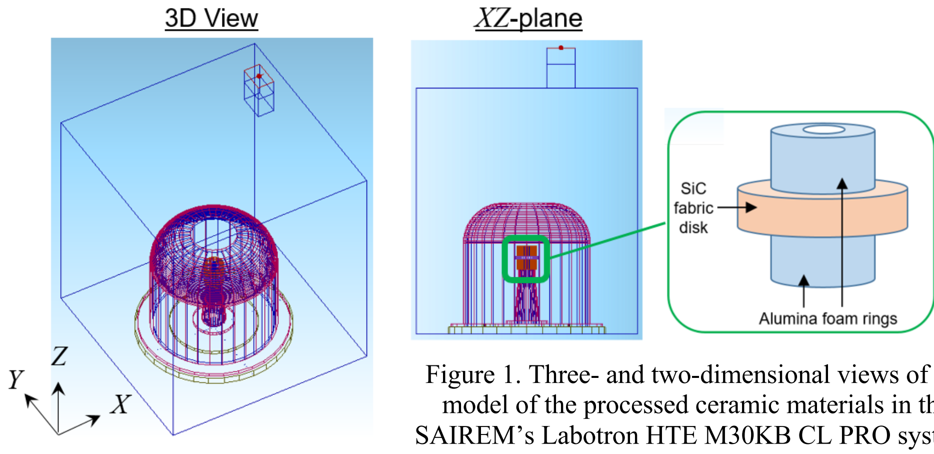


Figure 1. Three- and two-dimensional views of the model of the processed ceramic materials in the SAIREM's Labotron HTE M30KB CL PRO system.

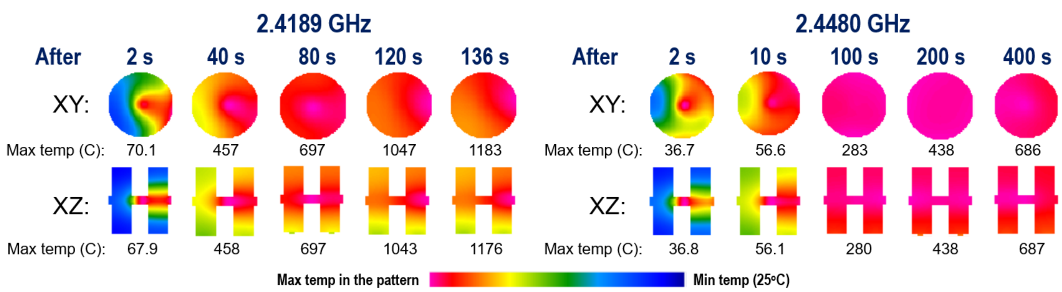


Figure 2. Evolution of the temperature field in the central horizontal plane through the SiC fabric disc (diameter 55 mm, height 8 mm) (*XY*-plane) and in the central vertical plane through the disc and the alumina foam rings (outer diameter 50 mm, inner diameter 14 mm, height 25 mm) (*XZ*-plane); fast (at 2.4189 GHz) and slow (at 2.448 GHz) heating simulated with the heating time step in the EM-T iterative procedure being 0.5 s and 1.0 s, respectively; input power 1,100 W.

implemented with the *QW Basic Heating Module* (*BHM*) [6] as an iterative procedure simulating temperature fields at ten frequencies, a mixture of resonant and non-resonant.

RESULTS

Simulations of the heating of the SiC fabric discs at the frequencies at which the reflection coefficient increases, decreases and stays nearly unchanged with increasing temperature were carried out. Accordingly, the heating at those frequencies appears to happen with very different heating rates; temperature patterns in Figure 2 illustrate examples of two typical (one fast and one slow) processes.

By both visual inspection of the pattern and using quantitative metric of uniformity of heating patterns η [7], we conclude that the slower processes provide more uniform temperature distributions within the processed composite than the fast ones; that can be contributed to high thermal conductivity of SiC fabric. The values of η varies from 0.02 (the slowest heating) to 0.1 (the fastest one).

The results obtained for the input power of 1,100 W show that at frequencies at which energy coupling is high, the maximum temperature (T_{max}) of 1,200ºC can be reached in 120-220 s. When the coupling is poor, the SiC disc may not be heated up to T_{max} = 700ºC even after 400 s. The slow processes provide more uniform temperature distributions than the fast ones, however; in the latter, when T_{max} ~ 1,200ºC, the minimum temperature (T_{min}) may be about 900ºC. Analysis of the patterns suggests that the time evolutions may be combinations of two trends: amplification of the field magnitude in the *hot spots* and spreading of the peaks of the distributions due to thermal conductivity. Our results show and explain all such experimentally observed phenomena as a change of heating rate with time, substantial variations in process characteristics due to minor geometrical changes, etc

DISCUSSION AND CONCLUSION

With an unknown frequency characteristic of the magnetron source feeding the microwave system, the developed coupled EM-T model did not intend to mimic the actual ME-CVI production of the SiC_f/SiC composites. Instead, the objective of the modeling effort was to break down the complex EM-T occurrence into multiple components in order to help analyze it, explain some experimental observations, and suggest a means of better control over the process.

For the disc of 55 mm diameter and 8 mm height, computations have revealed about 40 strong resonances in the 2.4-2.5 GHz frequency range. Simulation of heating by microwaves at different, even very close, frequencies has shown very different heating rates and temperature patterns which has explained the effect of the strong sensitivity of the performance on small changes in geometry. Variation of frequency characteristics with temperature sheds some light on the variation of the heating rate in time with the input power remaining constant. The results indicate that potential benefits to the ME-CVI process would occur with the use of a solid-state microwave source.

REFERENCES

[1] V. Giurgiutiu, Ed., *Structural Health Monitoring of Aerospace Composites*, Academic Press, 2015.
[2] O. Florez, R.K. Bordia, D. Nestler, W. Krenkel, and G. Notz, Ceramic fibers based on SiC and SiCN systems: current research, development, and commercial status, *Advanced Engng Materials*, vol. 16, no 6, pp. 621-636, 2014.
[3] D. Jaglin, J. Binner, B. Vaidhyanathan, C. Prentice, B. Shatwell, and D. Grant, Microwave heated chemical vapor infiltration: densification mechanism of SiC_f/SiC composites, *J. Am. Ceram. Soc.*, vol. 89, no 9, pp. 2710-2717, 2006.
[4] J. Binner, B. Vaidhyanathan, and D. Jaglin, Microwave heated chemical vapour infiltration of SiC powder impregnated SiC fibre preforms, *Advances in Applied Ceramics*, vol. 112, no 4, pp. 235-241, 2013.
[5] J. Binner, V. Venkatchalam, and M.T. Porter, High and ultra-high temperature ceramic matrix composites fabricated by rapid chemical vapour infiltration, *44th Intern. Conf. & Expo on Advanced Ceramics and Composites, Daytona Beach, FL, January 2020,* pp. 30-31.
[6] *QuickWave*, 1998-2019, QWED Sp. z o.o., www.qwed.com.pl.
[7] P. Kumi and V.V. Yakovlev, Computational procedure for quantitative characterization of uniformity of high frequency heating, *Proc. 53rd IMPI Microwave Power Symp., Las Vegas, NV, June 2019*, pp. 123-125.

Microwave Holography for Timber Assessment

Graham Brodie[1], Berhan Ahmed (Shiday)[1], Deepan Babu Thanigasalam[1], Peter Farrell[1], Allison Kealy[2], and John R.J. French[3]

[1]University of Melbourne, Parkville, Victoria, Australia
[2]RMIT University, North Melbourne, Victoria, Australia
[3]University of the Sunshine Coast, Maroochydore, Queensland, Australia

Keywords: Microwave, Diffraction, Detection.

INTRODUCTION

Assets such as wooden structures or buried pipes and cables can be difficult to non-destructively monitor or locate. Wooden structures such as power poles and timber framing are susceptible to infestation from decay causing fungi or insects, such as termites and borers. Buried assets, such as pipes or electrical cables, can be difficult to accurately locate. Embedded objects, such as decay fungi, termites or electrical cables, within another medium, such as timber or soil, will perturb propagating electromagnetic fields, creating a diffraction pattern (i.e. a hologram) that can be used to non-destructively detect the presence of these objects [1]. This paper highlights one simple application of microwave holography which could monitor wooden assets.

METHODOLOGY

A total of twelve wooden stakes of 200 x 65 x 65 mm *P. radiata* (softwood) and twelve stakes of *E. regnans* (hardwood) of the same dimensions were exposed to soil containing decay fungi for 12, and 16 weeks in an Accelerated Field Simulator (AFS), which is a climate conditioned room that simulates humid tropical conditions. The AFS was used to speed up the decay processes of the wood stakes. After removal from the soil, the samples were washed to remove all soil and oven dried at 60 °C for three days. The stakes were allowed to equilibrate with the laboratory's ambient temperature and relative humidity for several weeks prior to testing with a HB100 microwave module.

The HB100 microwave motion sensor operates as an X-Band Bi-Static Doppler transceiver module. Although the HB100 system is designed for other purposes, the mutual coupling between the transmitting and receiving antennas of this module depends on the bulk dielectric properties of the space in front of the module (Figure 1). The simple design of the HB100, with its built-in Dielectric Resonator Oscillator (DRO), built in micro-strip patch antenna arrays and its cheapness make the HB100 a potential candidate for simply and cheaply determining the properties of wood when the module is placed in direct contact with the surface of wooden structures. The output from the HB100 radar module was fed into an Arduino analogue to digital converter module (A/D Converter).

The HB100 system was placed on the surface of the timber such that the transmitting and receiving antennas were in good contact with the timber surface. Measurements were made in two orientations, with the microwave's electric field perpendicular to the wood grain and with the microwave's electric field parallel to the wood grain.

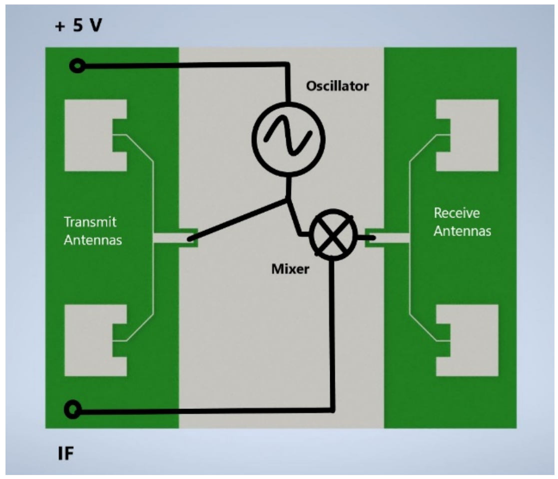


Figure 1. Schematic diagram of the HB100 Bi-Static Doppler transceiver module

RESULTS

Figure 2 shows that wood density significantly declined with longer exposure in the AFS, particularly in the soft wood samples. This is indicative of the level of decay incurred by the wood samples during the experiment. Figure 3 demonstrates that the HB100 microwave module system can readily discern the level of decay exposure, in both hardwood and softwood samples, when the microwave field is oriented perpendicular to the wood grain. Discernment between the levels of decay exposure is lost when the microwave's field is oriented parallel to the wood grain.

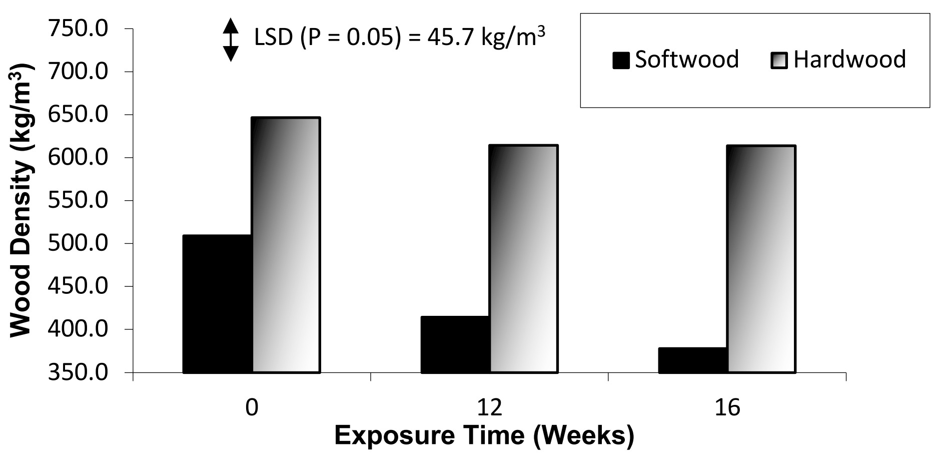


Figure2. Mean wood density as a function of exposure time to fungal decay

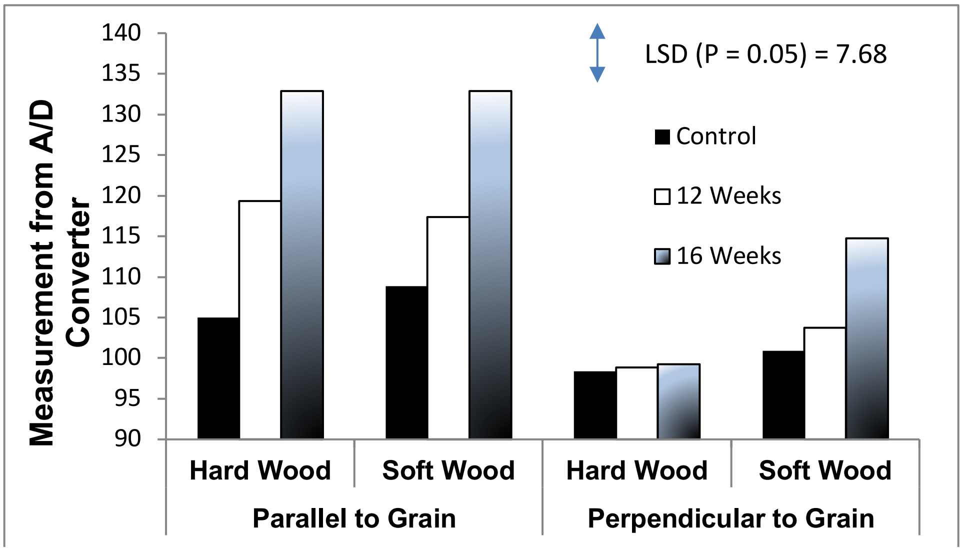


Figure 3. Output from the HB100 microwave module (measurements are numerical values from a 10-bit Analogue to Digital Converter) as a function of wood type and microwave field orientation relative to the wood grain.

DISCUSSION

Wood is an an-isotropic material with the dielectric properties being much higher when the electromagnetic field is polarized along the wood's grain rather than across the grain [2]; therefore, orientation of the microwave fields affects the response of the system. The HB100 is quite cheap, so it can be easily deployed to monitor assets like power poles or building components. Although it is not described here, the system also responds to termite movement and moisture encroachment in timber [3].

CONCLUSION

Microwave fields are diffracted by materials in their path. Diffraction alters the mutual coupling between antenna systems, resulting in an interference pattern, which is effectively a hologram.

REFERENCES

[1] S. I. Ivashov, V. V. Razevig, I. A. Vasiliev, A. V. Zhuravlev, T. D. Bechtel and L. Capineri, Holographic Subsurface Radar of RASCAN Type: Development and Applications, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* vol. 4, no 4, pp. 763-778, 2011.

[2] G. I. Torgovnikov, *Dielectric Properties of Wood and Wood-Based Materials* Springer-Verlag, Berlin, 1993.

[3] G. Brodie, E. Harris, P. Farrell, N. A. Tse, A. Roberts and J. Kvansakul, In-situ, noninvasive investigation of an outdoor wooden sculpture, *Proc. ICOM-CC 17th Triennial Conference*, *Conference, Location*, *2014*, pp. 1-9.

Microwave Soil Treatment Alters Soil Biota

Muhammad Jamal Khan[1], Stephanie D. Jurburg[2] and Graham Brodie[1]

[1]School of Agriculture and Food, Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Dookie Campus, Australia

[2]Synthesis Centre, German Centre for Integrative Biodiversity Research (iDiv), Halle-Jena-Leipzig, Leipzig, Germany

Keywords: Microwave weed control, Soil biota, no-till agriculture

INTRODUCTION

Microwave soil treatment for weed suppression and crop growth has been evaluated for the past decade in Australia. Numerous studies have reported a profound effect of pre-sowing microwave soil irradiation on weed seed emergence [1, 2] and subsequent crop growth and yield [3]. In the case of pre-emergence weed management, this rapidly increases the soil temperature and devitalises the weed seedbank by generating micro-steam explosions in the seeds, leading to their mortality in the top soil horizons, and thus preventing the emergence of weeds [1, 4]. Soil is a complex heterogeneous environment [5], harboring a wealth of bacteria, fungi, protozoans, nematodes, and arthropods, which may be adversely affected by the MW soil treatment. However, the influence of microwave (2.45 GHz) soil treatment on soil bacterial communities is unclear. Therefore, a microcosm study was conducted to examine the effect of microwave soil treatment on soil bacterial communities.

METHODOLOGY

Indigenous soil microcosms were treated under the horn antenna of a microwave weed prototype for three durations (30, 60 and 90 sec) as well as an untreated control. Immediately after soil heating (T0) and 28 days after heating (T28) the soil was collected at two depths (0-5cm and 5-10cm) from the microcosms in duplicate to evaluate the bacterial communities' responses based on 16S rRNA sequencing.

RESULTS

Microwave soil treatment significantly reduced ($p<0.001$) bacterial communities' richness, and the communities did not recover to their pre-heating state in the studied time (Figure 1). The combined effect of microwave soil treatment and penetration depth was assessed at phylum and genus level. At 0-5cm depth, the relative abundance of Proteobacteria increased and Firmicutes decreased with high temperature exposure (90 sec), and over time, Proteobacteria remained dominant in the communities and Firmicutes showed recovery (Figure 2 bottom panel). At the genus level, the relative abundance of Kaistobacter, Micromonosporaceae, TM7-1 and Xanthomonadaceae increased significantly at T28 compared to T0 with high temperature exposure (Figure 2 top panel). These results have been published in Khan, Jurburg [6].

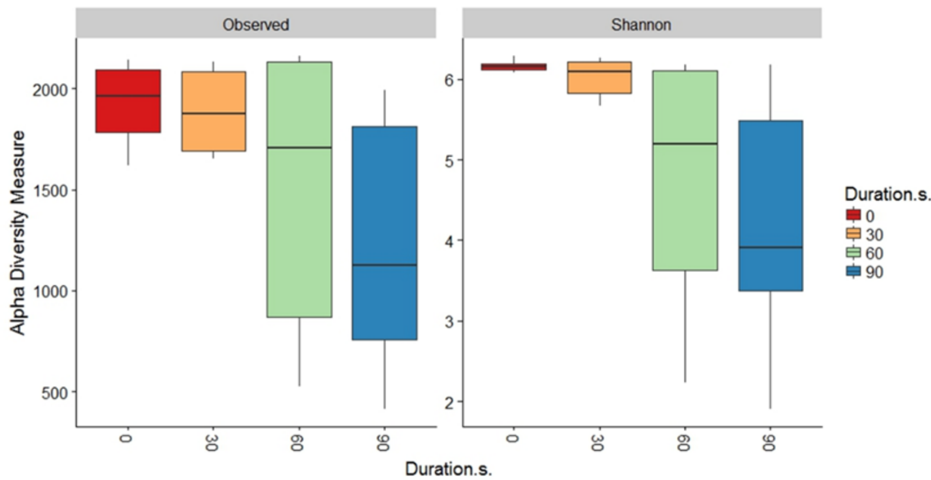


Figure 1: Variation in bacterial diversity against microwave soil treatment.

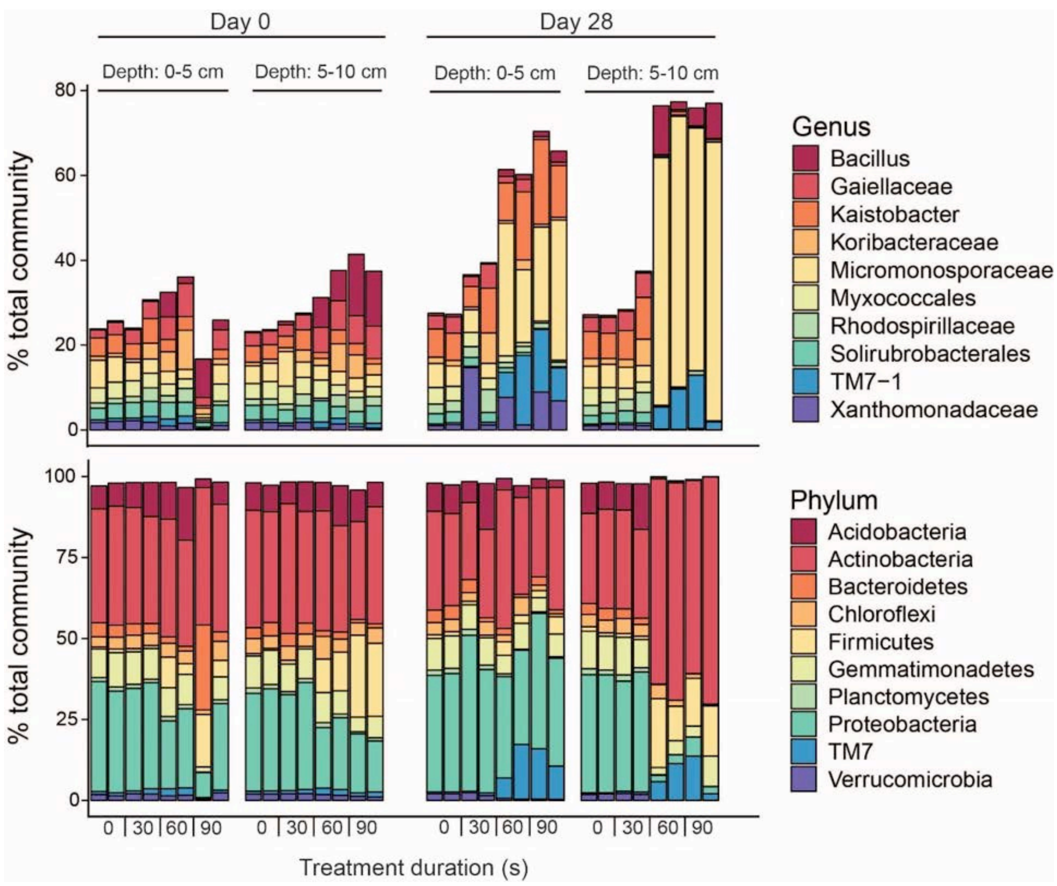


Figure 1: Relative abundance of the predominant bacterial taxa (bottom) and genera (top) that significantly changed over time in response to microwave soil treatment.

DISCUSSION

It appears that microwave soil treatment enormously alters the soil bacterial communities and the communities' recovery requires more time after soil heating; however, the reshaping of bacterial communities showed the higher relative abundance of some beneficial soil taxa. They showed faster recovery at T28 and dominated the communities. In addition to that, numerous studies showed that microwave soil treatment increases soil carbon and nitrogen [7, 8]. Therefore, it can be postulate that the higher availability of yield limiting nutrient after microwave soil treatment can be partially associated to the triggering of dormant beneficial taxa, for example: Micromonosporaceae in this study. However, it is important to note that the increase in soil carbon and nitrogen does not mean it will sustain the soil fertility. It can reduce the soil quality on a long-term basis. We suspect that factors such as soil type, cropping history and soil organic matter content may affect our findings and require further investigation.

CONCLUSIONS

It can be concluded that, the proposed soil temperature for pre-emergence weed control (75-80℃) alters the soil bacterial communities. However, whether the functioning of the soil microbial communities is altering or not warrants further research.

REFERENCES

1. Khan, M.J., et al., *Microwave Soil Treatment Improves Weed Management in Australian Dryland Wheat.* Transactions of the ASABE, 2018. **61**(2): p. 671-680.
2. Khan, M.J., et al., *Microwave Soil Treatment Increases Soil Nitrogen Supply for Sustained Wheat Productivity.* Transactions of the ASABE, 2019. **62**(2): p. 355-362.
3. Brodie, G., et al., *Microwave Weed and Soil Treatment in Agricultural Systems.* Global Journal of Agricultural Innovation, Research & Development, 2018. **5**: p. 1-14.
4. Khan, M.J., G. Brodie, and D. Gupta, *The Effect of Microwave Soil Treatment on Rice Production under Field Conditions.* Transactions of the ASABE, 2017. **60**(2): p. 517-525.
5. Lu, Y., et al., *An empirical model for estimating soil thermal conductivity from texture, water content, and bulk density.* Soil Science Society of America Journal, 2014. **78**(6): p. 1859-1868.
6. Khan, M.J., et al., *Impact of microwave disinfestation treatments on the bacterial communities of no-till agricultural soils.* 2019.
7. Maynaud, G., et al., *Short-term effect of 915-MHz microwave treatments on soil physicochemical and biological properties.* European Journal of Soil Science, 2019. **70**: p. 443-453.
8. Zagal, E., *Effects of microwave radiation on carbon and nitrogen mineralization in soil.* Soil Biology and Biochemistry, 1989. **21**(4): p. 603-605.

Examination of Vulcanization of Tire Rubber by Microwave Heating

K.Okumura[1], A. Saiki [2], M. Hojo [2], T. Takizawa[2], S. Horikoshi [1]

[1] Sophia University, 7-1, Kioi-cho, Chiyoda-ku, Tokyo, 102-8554, Japan
[2] Bridgestone Corporation, 3-1-1, Ogawahigashi-cho, Kodaira-shi, Tokyo 187-8531, Japan

Keywords: Microwave, Tire rubber, Dielectric properties, Vulcanization,

INTRODUCTION

Production of rubber, which began in the 18th century, became widely used on a daily basis due to optimization of synthetic rubber and vulcanization. Rubber generally improves rubber elasticity (elastomer) by forming a three-dimensional network of molecules by vulcanization. Generally, in the vulcanization of rubber, when the vulcanization time is long and high temperature treatment is performed, the physical and chemical properties of the rubber deteriorate. For this reason, vulcanization at a low temperature in a short time is required, but it is difficult to achieve due to low thermal conductivity. This research aims to develop microwave vulcanization of tire rubber and produce "short time, low temperature, high quality" rubber. Especially, in this presentation, (i) the interaction between rubber and microwave was verified by measuring the dielectric factor of rubber raw materials and their mixtures. Moreover, by systematizing this, the feature of microwave heating in tire rubber was theoretically predicted. In addition, (ii) a rubber vulcanization experiment using microwave heating was performed to verify the advantages of the process compared to existing heat transfer methods (conventional heating).

METHODOLOGY

Dielectric properties in the range of 300 MHz to 6.5 GHz were measured for samples in which each component of the existing tire rubber material, the rubber material, and the compounding ratio thereof were changed. In addition, the interaction between microwave and rubber material was verified by measuring with a vector network analyzer while changing the sample temperature using a plate heater. In addition, using a Teflon mold, the characteristics of microwave heating (MWH) and conventional heating (CH) were compared.

RESULTS AND DISCUSSION

(i) Theoretical prediction of the characteristics of microwave heating in tire rubber

The relative dielectric loss of each single component such as a vulcanizing agent, an antioxidant, and a filler used for rubber and rubber was measured. Among the various tire rubber components, the component with the highest microwave heating efficiency was carbon black (CB). Furthermore, CB was blended with the isoprene rubber (IR), and the relative dielectric loss was measured. Increasing the amount of CB increases the relative dielectric loss, so CB becomes the rate-determining substance for microwave heating (**Figure 1a**). Also, the value of the relative dielectric loss increased exponentially as the amount of CB increased. For this reason, it was considered that the CB increase in the rubber greatly changed the distance between the CB and the rubber molecules, thereby forming a conductive circuit. In addition, it is considered that interfacial polarization occurs due to the Maxwell-Wagner effect from the difference in relaxation time between the conductive CB and the rubber as the insulator. The relative dielectric loss before and after vulcanization of the rubber was measured. Vulcanization of rubber significantly increased the dielectric loss (**Figure 1b**). It was expected that this was because the ability of CB to form a conductive circuit was promoted along with the formation of a crosslinked structure by vulcanization.

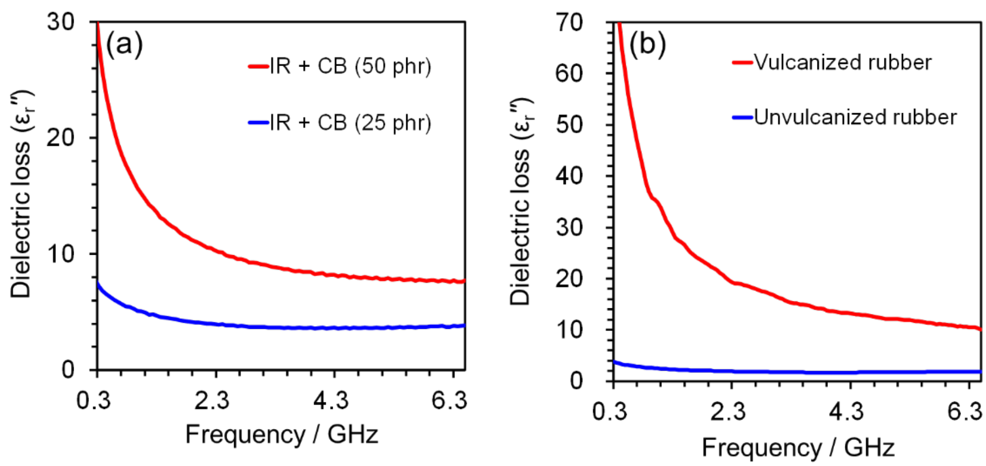


Figure 1(a) Relative dielectric loss at 300 MHz to 6.5 GHz for isoprene rubber (IR) and carbon black (CB; 50 phr or 25 phr). **(b)** Relative dielectric loss at 300 MHz to 6.5 GHz for before and after vulcanization of rubber compounded with IR, CB and vulcanizing agent.

(ii) Vulcanization by microwave heating (MWH)

As a result of heating by microwaves, there was a problem that bubbles were generated inside the heated rubber. Vacuum processing was applied to remove moisture and volatile components that are the source of bubbles. Furthermore, a mold made of Teflon was prepared to suppress the generation of bubbles by pressurization. After heating, the crosslink density of the sample heated by the microwave heating device and the conventional heating device was measured (**Figure 2**). The crosslink density is measured as an index to obtain physical properties when rubber is heated. As a result, high crosslink density and rapid heating and power saving were obtained by microwave heating as compared with conventional heating.

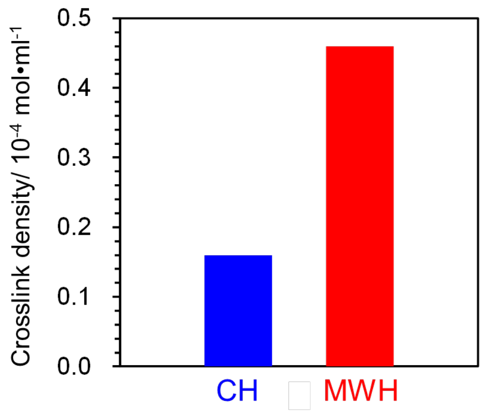


Figure 2 Crosslink density by conventional heating (CH) and microwave heating (MWH)

CONCLUSION

In this study, the interaction between microwave and rubber material was verified by measuring the dielectric factor. In addition, vulcanization was performed by microwaves, and advantages were obtained in terms of crosslink density as compared with conventional heating.

Development of Microwave Curing Adhesive

Y. Arai, S. Horikoshi

Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo, 102-8554, Japan

Keywords: Microwave curable adhesive, Epoxy resin adhesive, Hot melt adhesive, Dielectric factor, Magnetic field

INTRODUCTION

Adhesives consist of a reactive adhesive, a hot melt adhesive, and a solvent adhesive. In recent years, precision and miniaturization of electronic components have been remarkably advanced, and adhesives have been used for joining them. In addition, switching from steel to CFRP (carbon fiber reinforced plastic) and the like as to reduce the weight of car bodies requires adhesives. However, since the curing of the thermosetting adhesive requires heating, this can lead to degradation of electronic components and other plastics directly by heating or by heat conduction. On the other hand, an adhesive that can be cured even at a low temperature is not practical because it requires a long time for curing and an unused adhesive cannot be stored for a long period of time, and thus there is a trade-off between temperature and curing performance. Recently, an adhesive using an ultraviolet curable resin, which is one of reactive adhesives, has been used to solve this problem. However, ultraviolet rays, which are light, are sometimes reflected and do not reach the bonding surface and are often used for temporary fixing. In this study, we focused on microwaves as an energy source for curing. The experiments were conducted using epoxy resin adhesives and hot melt adhesives as targets with the following objectives: (i) Search for the rate-determining element of microwave heating progress of existing adhesives, (ii) Comparison of curing behavior between conventional heating and microwave heating, and (iii) Application search for microwave sensitive adhesive.

METHODOLOGY

In the experiment of epoxy resin adhesive, epoxy resin (JER828EL), phthalic anhydride (curing agent), and 2-ethyl-4-methylimidazole (2E4MZ) (curing accelerator) were mixed at a mass ratio of 100 *vs.* 80 *vs.* 10, respectively. The resulted mixed adhesive was cured. In the curing experiment, the adhesive applied to the container was microwave heated with a single mode applicator connected to a 2.45 GHz semiconductor oscillator. Microwave power was used in the range of 5 W to 20 W was applied, and heating took place at the position where the electric or magnetic field intensity was maximized. In the conventional heating method, the heater was preheated to 160 °C as to have the same heating time as the microwave heating. Using Differential scanning calorimetry

(DSC)enabled to confirm 123.4 °C as the curing temperature of the epoxy resin adhesive used in this experiment.

RESULTS AND DISCUSSION

(i) Search for the rate-limiting component of microwave heating for existing adhesives

The rate-determining component of microwave heating in epoxy-anhydride adhesives was studied from the viewpoint of dielectric loss. Changes in dielectric loss due to heating of epoxy resin (JER828EL), phthalic anhydride (curing agent), and 2E4MZ (curing accelerator) alone were measured. At the beginning of the reaction, the mixture of the accelerator and the curing agent showed a high dielectric loss, but when the temperature was raised to 100 °C, the dielectric loss of the pure epoxy resin was significantly increased. In addition, comparing the temperature rise behavior during microwave irradiation, it was found that in the temperature range below 60 °C (lower temp.), the reaction intermediate between the curing agent and the curing accelerator was the rate-determining component for microwave heating, , Figure 1. On the other hand, in the high temperature range above 60 °C (higher temp.), it was found that the epoxy resin was the rate-determining component for microwave heating.

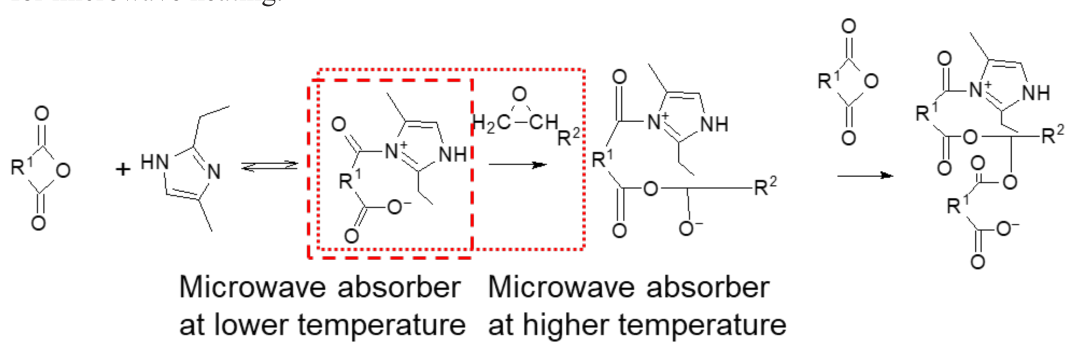


Figure 1. Reaction diagram and microwave absorber component vs. temperature

(ii) Comparison of curing speed between conventional heating and microwave heating

The curing rates by conventional heating and microwave heating (maximum electric field strength and maximum magnetic field strength) were compared. In this experiment, two types of curing agents (cis-1,2-cyclohexanedicarbon anhydride hardener and acetic anhydride hardener) were used, but in both cases it was found that microwave heating has an energy saving effect of more than 10 times compared to conventional heating. Uncured curing agent remained during conventional heating, but high-quality curing proceeded under microwave heating.

(iii) Application search for microwave sensitive adhesive

As one of the developments of microwave-curable adhesives, microwave responsiveness was investigated by mixing a microwave-generating substance as a filler with a hot-melt adhesive composed mainly of ethylene vinyl acetate. The used filler was activated carbon, magnetite, and ionic liquid ([bmim]Cl and [bmim]$FeCl_4$) (**Figure 2**). The hot-melt adhesive containing no filler did not soften even when subjected to microwave heating. When a softening test of the adhesive was performed with conventional heating, the same softening was shown under all the filler conditions. On the other hand, it was found that activated carbon and magnetite softened quickly by microwave electric field heating.

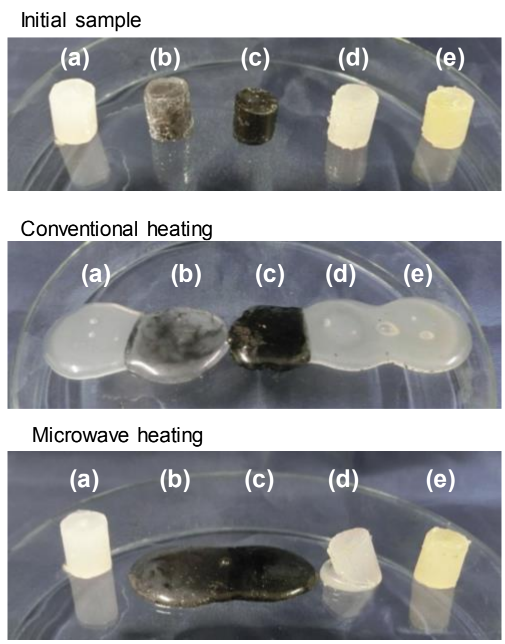


Figure 2. Pictures of melting of hot melt adhesive with (a) Non-added sample b) Magnetite added sample (c) Activated carbon added sample (d) [bmim]Cl added sample (e) [bmim] $FeCl_4$ added sample by conventional heating and microwave heating.

CONCLUSION

In the microwave curing of the epoxy-anhydride adhesive, sole components did not heat up in response to the microwave but only when mixed with an intermediate as a microwave absorber. In addition, it was suggested that the addition of a microwave absorber enables selective hardening and selective peeling by a magnetic field.

Microwave 3.0
Solid State Ovens, Personalization and Mass Customization

Steven J. Drucker

Droaster Laboratories LLC, Greer SC, USA

Keywords: Solid state ovens, timing, personalization, mass customization, technology innovation, farm to sofa.

INTRODUCTION

Solid state microwave technology innovations linger just over the horizon. Unlike a hurricane, the timing and extent of their landfall remains uncertain. Microwaves' first wave of innovation peaked in 1987 when the food industry switched to microwave safe packaging. Microwaves' second wave of innovation emerged in the late 1990's with the proliferation of Not Ready To Eat frozen foods. At the impending outset of microwave's third wave of innovation microwave oven commoditization is reflected in market statistics, and both microwave food and ovens are mass produced. Can solid state oven technology innovations enable the transition from mass production to mass customization, and satisfy consumers' thirst for farm to sofa personalization?

MICROWAVE 1.0

Microwaves' first two waves of innovation centered on convenience. From the late 1960's onward—coincident with the initial incorporation of microprocessors into kitchen appliances—microwave oven pricing trended downwards. Unsurprisingly, household penetration increased. In 1987 the leading frozen TV dinner company—Swanson—abandoned its iconic aluminum trays in favor of 100% microwave safe packaging.

Subsequently, consumers, torn between the halcyon call of convenience as opposed to the sub-mediocre palatability of frozen microwave foods, voted with their pocketbooks and increasingly turned away from Ready To Eat ("RTE") processed microwave frozen foods. By the early 1990's microwave frozen food sales plummeted. Food companies largely abandoned microwave products and had sold off their microwave R&D laboratories for salvage.

With barely a wimper Microwave 1.0 came to a close.

MICROWAVE 2.0

While microwave frozen food product sales plummeted, two promising trends emerged. By 1997 microwave popcorn sales had reached over $650 Mm per year (following the technology enabling introduction of metallic susceptors embedded in popcorn bags), and microwave frozen snacks' (such as Bagel Bites and Pizza Rolls) sales climbed to over $225 Mm per year. Consumer demand for convenience was strong, and the food industry took notice. The result was the industry wide proliferation of Not Ready To Eat ("NRTE") microwave frozen foods. NRTE microwave foods delivered increased palatability, superior visuals and greater resemblance to freshly cooked food. Mystery solved—NRTE microwave frozen food sales soared.

In mid 2006 an NRTE potentially fatal flaw manifested itself. Food companies had become increasingly dependent on outsourced supply chains—the source of maximum cost efficiency but all too frequently also the source of food born bacterial pathogens. NRTE frozen microwave foods required heating uniformity, time and temperature levels so as to assure compliance with National Advisory Committee On Microbiological Criteria For Foods ("NACMF") mandated e coli and salmonella kill levels. Neither the consumer population of microwave ovens, nor consumers themselves, let alone existing package instructions could meet NACMF standards. An escalating avalanche of food safety recalls ensued.

To its credit, the food industry overcame these challenges. Microwave frozen food annual sales blossomed into the $21 Billion market to which we are heir today.

MICROWAVE 3.0

87,000 different ways to get your coffee. Door Dash, Uber Eats and their cohort of farm to sofa meal delivery platforms. Such is the emblematic consumer demand for convenience and personalization. How can the mass market dependent microwave food and oven industries adapt? It's not a question of "can"—rather a question of must. The reality is that a single food product ("SKU" or stock keeping unit) requires a minimum of $10Mm in sales to remain viable. Microwave oven industry statistics illustrate that oven production has become so commoditized that just a very few mainland China factories manufacture more than 85% of the world's microwave ovens. How do the microwave food and oven industries adapt to consumer demand for personalization and mass customization?

The answer is Microwave 3.0.

Design and Realization of a Very High Power Solid State Microwave Hemp Drying System

Kenneth Kaplan

Cellencor, Inc., Ankeny Iowa, USA

Keywords: Solid state microwave generator, biomass dryer, microwave drying, hemp drying.

INTRODUCTION

This paper describes the design and implementation of a 400 kilowatt L-band solid state industrial microwave drying system. It is believed to be the first of its kind in the world. The application is drying freshly harvested industrial hemp, a sensitive high value agricultural product, which is further processed to produce cannabidiol (CBD) oil. The harvest must be dried quickly in order to prevent spoilage and to allow for further processing. The system was designed by Cellencor and installed in a newly constructed plant located at a 10,000 acre hemp farm at an isolated and remote site near Yuma, Arizona. There are three harvests per year. The hemp is dried by the microwave system from about 40% to 60% moisture content to 10%. The dry help is then pelletized for shipment to an extraction facility. At harvest time, a very high process rate of at least 40,000 pounds (18,000 kg.) per day is required.

METHODOLOGY

The applicator (see Fig. 1) is a stainless steel vessel with an internal agitator. It operates in a batch mode with a capacity of 400 cubic feet (5 square meters). This corresponds to a load of 6000-8000 pounds (2700–3800 kilograms) of chopped hemp. The applicator circulates the biomass which results in highly uniform drying. The applicator is mounted on four load cells to continuously measure the weight of the load, and has two infrared temperature sensors looking down into the body of the vessel, and two thermocouple sensors on the bottom of the vessel.

Microwave power is supplied by eight 50 kilowatt PTL-50 L-band (902-928 MHz) solid state microwave generators manufactured by Crescend Technologies, Schaumburg IL (see Fig 2a). The applicator has four WR-975 waveguide feeds feeding into the top of the vessel. Pairs of generators have their outputs combined and are operated as four 100 kilowatt "virtual generators".

The output power combining technique is only possible with solid state generators. Of each pair, one generator is a master unit. Its exciter output also drives a slave generator.

The phase and amplitude of the slave drive signal is automatically adjusted by the PrecisePower software suite running on the control computer, resulting in a nearly perfect balance at the combiner. The individual waveguide power outputs of the generator pair are combined to a single output using a waveguide Magic Tee (see fig. 2b). A high power waveguide circulator follows to protect the generators from excessive reflected power. As it turned out, the design of the applicator plus frequency agility of the solid state generators provide a very good impedance match under all load conditions, with a typical return loss of -15 dB or better.

Figure 1. a) The 400 ft^3 applicator. b) View of the top side of the applicator. Top connections include four waveguide feeds, material fill port, and exhaust ports.

Each generator is equipped with an embedded control computer. These communicate over Ethernet with the system supervisory which is a Windows PC. The supervisory computer provides complete setup and maintenance functions for each generator including fully remote operation, maintenance, and diagnostics over the Internet. It also acts as a bridge to an Allen-Bradley programmable logic controller (PLC) which manages the entire drying operation, including control of complex material handling equipment. The actual operator control point is a touch panel HMI screen connected to the PLC, which provides "one button" operator control. The microwave operations are adaptive and fully automatic.

Figure 2. (a) View of the eight Crescend Technologies PrecisePower™ PTL-50 solid state microwave generators. The vertical risers are part of the water cooling system. (b) The power

outputs of pairs of generators are combined using Magic Tees as illustrated above. The coaxial cables are for the excited drive from the master to the slave unit.

The overall drying cycle has three phases. First, a fill valve on the top of the applicator is opened and conveyers fill the applicator with chopped biomass. The fill valve is then closed. The second step is drying. The agitator is started, and microwave power is applied. Return loss, weight, and temperature are constantly monitored and recorded by a control computer. Microwave power does not need to be decreased by the control computer until near the very end of the drying cycle. Sampling of material during the commissioning of the system confirmed highly uniform moisture content and temperature due to the action of the agitator. Determination of the end of the process (a target moisture content of 10%) is based on a combination of load weight and temperature. The final phase is the unload cycle. A discharge valve on the bottom of the applicator is opened, and a conveyor carries the dried product to a pellet mill.

RESULTS

The system performance is summarized below:

Batch drying time: 2-3 hours, depending on initial moisture content.

Typical throughput: 3000 dry lbs./hr. (1360 kg/hr.) with 40% initial moisture content

Maximum drying temperature: 115°F (46° C).

DISCUSSION

Until now, drying large volumes of freshly harvested biomass has been an unsolved problem for industrial hemp producers due to the high drying temperature of conventional dryers (typically 600° or more) , which can degrade and reduce the yield of CBD and other essential oils. The remarkably low drying temperature (approximates 120° F) of the microwave system produces a superior product as confirmed by laboratory analysis of cannabinoid and terpene content which indicated virtually no losses after microwave drying

The inherent reliability of solid-state microwave generators as compared to magnetrons is a tremendous benefit in this application. The plant operators have very limited maintenance ability, and the site is isolated and remote, not easily accessible to service personnel. During a harvest campaign, any down-time is very costly.

The frequency agility of solid-state generators also allows an optimal match to the load, resulting in maximum energy efficiency and greatly reducing the possibility of arcing within the applicator and waveguide.

CONCLUSION

Microwave drying is a superior method for processing high value biomass such as industrial hemp. Use of solid state microwave generator technology improves energy efficiency (about 50% versus 30% for convection dryers) permits a higher level of control integration, and offers outstanding reliability in a critical application.

High-Power Remote Plasma Sources and Applied Technologies

Mohammad Kamarehi, Ken Trenholm, Marco Garuti, Olivia Keller
[1]MKS Instruments / P&RGS, Wilmington, USA
[2]MKS Instruments/ P&RGS, Wilmington, USA
[3]MKS Instruments / Alter Products, Reggio Emilia, Italy
[4]MKS Instruments / P&RGS, Wilmington, USA

Keywords: Microwave RPS, Slow Wave, Conjoining Electric Fields, Toroidal RPS

INTRODCUTION

Microwave and RF Remote Plasma Sources (RPS) are used in semiconductor wafer processing as well as advanced industrial applications. Viable and practical high-power RPS technology, however, has been more challenging to develop due to limited understanding of applying both relevant and correct microwave and RF mode of operation as well as proper cooling technique of the plasma vessel. Extensive research has been conducted in understanding the intricacies of the technology leading to development and design of viable and practical core technologies for high-power Remote Plasma Sources.

This paper reviews and presents the concept, theory and research conducted in developing core technologies and related applications for such Remote Plasma Sources.

METHODOLOGY AND TECHNICAL DISCUSSIONS

I. Microwave-based Remote Plasma Source - Theory and Concept

There are two distinct and unique core technologies which have been researched and applied to the Remote Plasma Sources. These core technologies are a) Slow-Wave Helical Coil Coupling with Integrated Water Cooling and b) Solid State Resonant Cavity with Conjoining Electric Fields.

a. Slow-Wave Helical Coil Coupling with Integrated Water Cooling

Microwave coupling to the processing gas is based on utilizing the slow-wave surface current concept and propagation along the surface of a helical copper coil. The microwave energy gradually couples to the plasma in the axial direction of the plasma tube. The coupling is achieved via the near-field electric component between the inner part of the coil and the gas flow in the vacuum. In addition, the coil also provides an integrated water cooling path to the plasma tube separated by a thermally conductive material which is also microwave transparent. The nature of the cooling tube does not allow microwave coupling to the water and almost all energy is coupled to the gas generating the plasma. Figure 1. depicts a high-level illustration of the concept.

Cooling in the slow-wave helical coil technology enabled high-power applications (e.g. 1.5, 3.0, and 6.0 kW) which was generated by switch-mode microwave power generators to further narrow the bandwidth of the operating frequency for improved and accurate impedance tuning and hence power coupling as well as continuous power control.

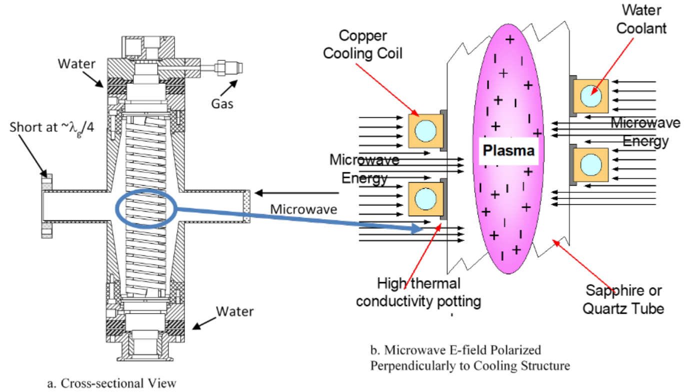
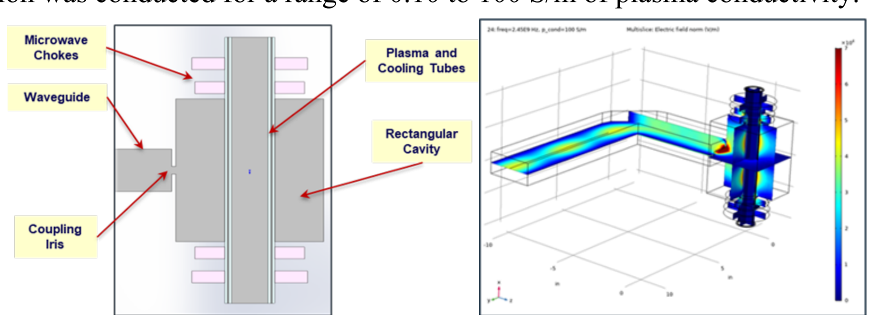


Figure 1. High-level illustration of the slow-wave helical coil coupling with integrated water cooling concept: cross-sectional view (a) microwave E-field (b)

b. Solid State Resonant Cavity with Conjoining Electric Fields

A new and novel Remote Plasma Source has been researched and developed for applications up to 1 KW of microwave energy. The new RPS utilizes solid state technology and a resonant cavity having conjoined electric fields where two uniform electric field vectors conjoin to form an elongated electric field vector along the axial direction of the plasma tube. The elongated and uniform electric field vector, in turn, forms a uniform plasma in the axial direction of the plasma tube allowing the use an air-cooled plasma tube. The resonant cavity can be excited via waveguide or coaxial coupling methods.

Microwave Transverse Electric (TE) field configuration having three mode integers (*mnp*) known as TE*mnp* are applied. The conjoining fields are derived by setting the axial mode integer (*p*) to multiple of λg/2 where λg is the guide wavelength in the axial direction of the plasma tube. Figure 2. shows a) conceptual design schematics of the resonant cavity with conjoining electric fields, and b) the COMSOL simulation of the intended TE*mnp* mode, which predicted and demonstrated the conjoining electric field formation. The simulation was conducted for a range of 0.10 to 100 S/m of plasma conductivity.



a. Conceptual Design Schematic b. COMSOL Simulation Predicting Conjoining E. Fields

Figure 2. TE*mnp* resonant cavity: Conceptual Design Schematic (a) COMSOL Simulation (b).

The primary application for the Solid State Cavity with Conjoining Electric Field technology is “Atomic Layer Deposition” where layers of semiconductor material having atomic dimension is repeatedly deposited on the semiconductor wafer.

II. RF-based Remote Plasma Source Utilizing Toroidal Technology - Theory of Toroidal Transfer Coupling

The basic technology was based on the theory of a transformer in which the primary current in a primary coil induces an inductive current in the secondary coil via Faraday’s induction law. As illustrated in Figure 3, a ferrite core confines the electromagnetic fields to improve magnetic field coupling and to reduce stray RF. The technology is designated as Toroidal, since the plasma vessel used is in a shape of a Toroid. The secondary coil was conceived as plasma vessel essentially replacing wire winding of a secondary transformer.

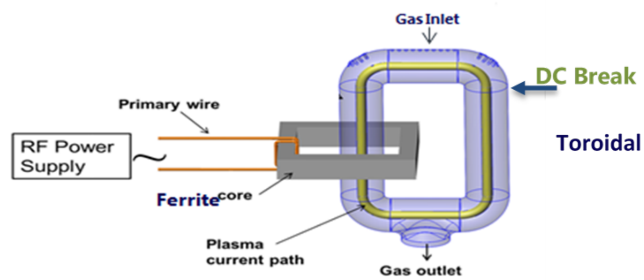


Figure 3. Toroidal Applicator Design Concept.

The power delivered to the secondary coil stems from the AC, converted to rectified DC and then to 400 KHz RF using various power conversion topologies utilizing MOSFET technology and power train circuits. A complex control system provides plasma power control, voltage and current feedback, and plasma power control stability. The toroidal power rating is directly correlated to the flow capability through the Toroidal plasma vessel.

The plasma impedance tuning in toroidal technology was inherent and intrinsic to the gas and power parameters and did not require an external tuning device. The toroidal plasma impedance absorbed the amount of RF power required to maintain a fixed current through the plasma and therefore maintaining a fixed and stable plasma impedance.

Conclusion

Extensive research has led to successful development of two high-power Remote Plasma Sources, microwave-based and RF toroidal-based, currently being utilized in Semiconductor and Advanced Industrial process applications.

Design and Testing of an Innovative Solid State RF Portable Device for Curing Resins in the Construction Sector

F. Dughiero[1], M. Bullo[1], A. Marconi[1], C. De Massari[2], J. Schaetzle[3]

[1]University of Padua, Padua, Italy
[2]InovaLab, Padua, Italy
[3]Fischerwerke GmbH & Co. KG, Freiburg, Germany

Keywords: radiofrequency curing, construction, solid state, chemical anchoring, Multiphysics simulation

INTRODUCTION

The building construction process requires the realization of foundations. Nowadays, shorter times are required. One of most time-consuming process is the chemical fixing of rod or anchor on concrete bases to guarantee high tensile loads. The state-of-the-art process takes up to 2 days and is influenced by environmental conditions (humidity and temperature). This work presents an innovative radio frequency device that realizes the curing of fixing resins directly on site and needs few minutes. This document deals with the results of a collaboration between Fischerwerke, the University of Padua and Inovalab (spin-off of the same university) on the design of a technology based on electromagnetic fields at radio frequency (RF), for curing process of resins.

Curing is a chemical process with different durations depending on the chemistry of resins and the surrounding temperature. For this reason, the worker is asked to use his practical knowledge and expertise in order to evaluate the quality of the resin application process. A typical use of resins is when anchor rods (threaded fasteners embedded in concrete foundations) are needed with the purpose of supporting different kinds of structures. The items can become “workable” after many hours if epoxy resins are used, so the chemistry research is oriented to shorten the curing time.

There are well known systems based on epoxy resins. The reactive resins are manufactured in a two-component process using epoxy resins and polyamine hardening agents and they are commonly used for heavy duty anchoring. As an example, the curing time is 10 hours if room temperature is +20 to +30 °C, but it becomes 80 hours when room temperature is -5 to +10 °C. Other chemical anchors, like vinylester-based ones can be fully cured after 30 minutes, but they can just reach about 50% - 70% of the pull-out force. It is clear that a technology able to fast cure epoxy-based anchors would be very attractive.

RF CURING PROJECT

The project on which Fischerwerke, University of Padova and Inovalab are involved has been on the conceptualization of a new generation curing system providing heating inside the resin by means of RF (in particular in the range of tens of MHz) in order to achieve a fast and even curing. The project resulted in a feasibility analysis developed by using multi-physics simulations and laboratory prototypes in order to demonstrate the characteristics of this new process and its industrialization feasibility. Moreover, the choice of designing a low power solid-state generator prototype (max rated power 200 W) and a matcher tailored for such an application lead to a light portable system (to be fed by battery) easy for the worker both to use and to manage. On the basis of both numerical simulations, electrical impedance measurements and experimental tests, the first anchoring systems have been designed.

EXPERIMENTAL METHODS

Experimental tests have been carried out according to the following procedure:

1. The mortar is injected bubble-free from the drill hole base bonding the entire surface of the anchor rod with the conductive grid and the drill hole wall and seals off the drill hole (the anchor rod together with the conductive grid are inserted manually to the ground of the drill hole with slightly rotation);
2. Immediately after, the system is fed by a 100 W RF average power at 27.12 MHz in order to reach 120°C; then the temperature is maintained until the end of the test (10 minutes overall);
3. After about 10 minutes, when the system is at ambient temperature, a pulled-out test is made.

RESULTS

The transient thermal profile of resin outside the grid has been continuously monitored by k-type thermocouples, and a typical measurement is reported in Figure 1. Figure 2 shows the temperature distribution of mortar for a sample pulled out from concreate immediately after the end of the temperature rising. The thermal image has been obtained by means of a thermal digital camera.

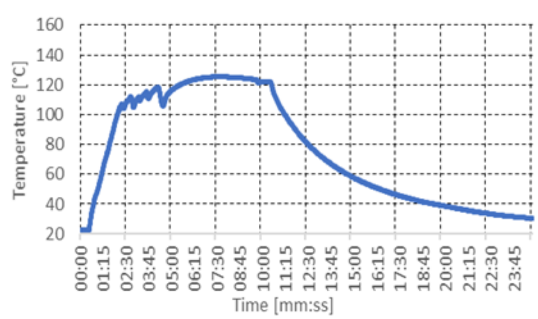
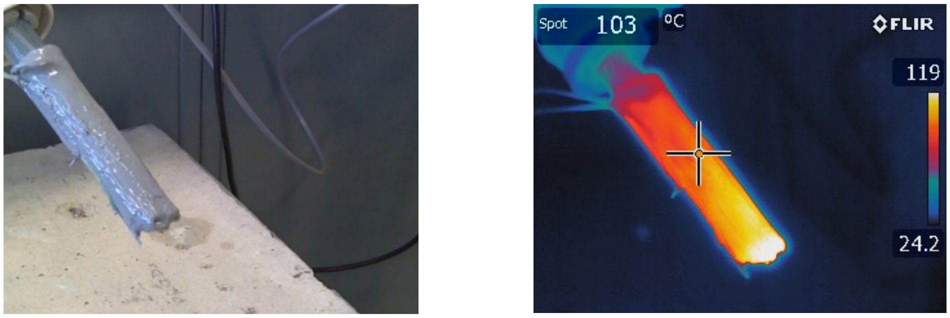


Figure 1. Mortar's transient thermal profile (20°C ambient temperature) inside the concrete due to RF heating (max power: 100 W)



a) b)

Figure 2. a) sample after the temperature rising and b) thermal image of the same sample

Pulled-out tests on samples compared with non-treated samples have shown that it's possible to reach nearly 95% of the pull-out force in 20min (10 min heating, 10 min natural cooling) instead of waiting 10h to fully cure an epoxy system at 20°C.

DISCUSSION

The very good results presented in the previous section are more than satisfactory and demonstrate the technical feasibility of the process. The next step, that we are already doing, is the adaptation of the technology to the typical workplace by means of a "ad hoc" solid state RF generator which must be light, portable and "easy-to-use".

CONCLUSION

The study shows the feasibility of a RF process for curing resins in the construction sector. Together a theoretical analysis and prototype have been presented which is able to guarantee a practical application of the method and an economic advantage on its usage. The results presented could represent a real revolution in the construction sector, and in particular the foundation construction phase, where the RF solid state technology can be used for the first time.

REFERENCES

[1] S. Lupi, Fundamentals of Electroheat: Electrical Technologies for Process Heating, Springer International Publishing, 2016.
[2] P. Alazard and A. Gourdenne, Radiofrequency (27.12 MHz) activation of the curing reaction of epoxy resins of DGEBA type, Macromolecular Symposia, vol. 122, no 1, pp.185-190, 1997.
[3] Patent pending: Elektrisch leitende Umhüllung für eine chemische Verankerung - Electrically conductive coating for chemical Anchoring – fischerwerke and University of Padova - Authors: M. Bullo, F. Dughiero, M. Martini, M. Miotto, T. Dominik - 2018

Comparison of Low and High Ripple Magnetron Power Supplies for Microwave Heating Processes

John F. Gerling

Gerling Consulting, Modesto, CA, USA

Keywords: Magnetron power supply, output waveform ripple, linear transformer, switch mode, industrial microwave heating

INTRODUCTION

Microwave energy is used as a source of heat in a variety of industrial processes [1]. In most microwave heating processes, magnetrons are the preferred source of microwave power due to relatively low cost, high output power capability and robustness compared to other sources [2]. Magnetrons require electrical power for operation, typically from one or more power supplies having unique features and functionality [3] that differentiate them from ordinary electrical power supplies for non-magnetron applications. Different types of magnetron power supplies are commercially available in various configurations as needed for different magnetrons and microwave heating processes. An understanding of magnetron and heating process characteristics is important for selecting the most appropriate magnetron power supply for a given application.

CONTINUOUS WAVE (CW) MAGNETRONS

Magnetrons operate as a vacuum tube oscillator with internal resonant cavities [4] and driven by a strong DC voltage (aka anode voltage). The magnetron frequency of oscillation is determined primarily by the geometry of the resonant cavities in its anode structure. This frequency can vary within a limited range due to various factors such as anode current (output power), anode temperature and reverse (reflected) power. Figure 1 illustrates the relationship between output power and the center frequency of oscillation.

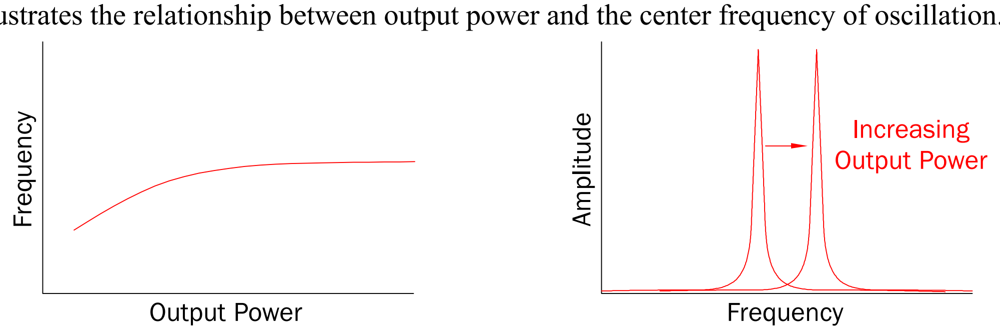
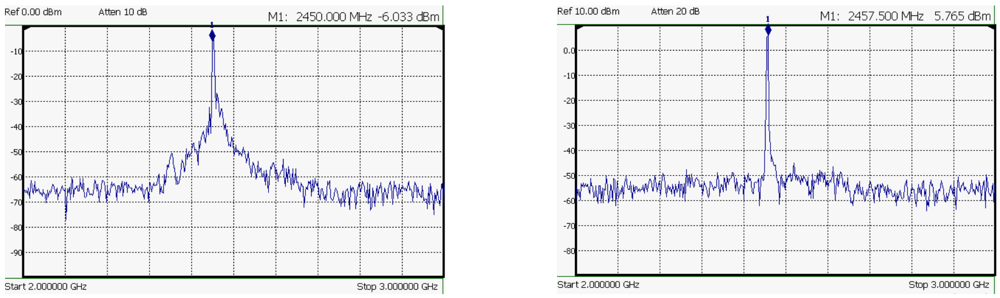


Figure 1. Output frequency vs. output power for typical CW magnetrons.

POWER SUPPLY OUTPUT WAVEFORMS

Magnetron power supplies designed for use in industrial systems are available in a variety of configurations to satisfy the requirements of different applications. The microwave output spectrum varies for different types depending primarily on the waveform of the anode voltage signal. Figure 2 illustrates the output spectrum for high and low ripple waveforms.



(a) (b)

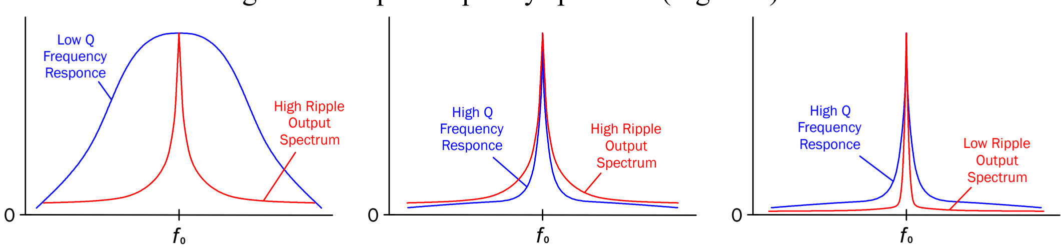
Figure 2. Output frequency spectrum for high (a) and low (b) ripple anode voltage waveforms.

MICROWAVE PROCESS LOADS

An important element of microwave processing systems is the applicator used to couple microwave energy to the process load. The applicator and load together can be represented electrically as a resonant circuit having a response center frequency f_0 and half-power (3 dB) bandwidth Δf. The quality factor Q of a resonant circuit is defined as:

$$Q = \frac{\omega_0(energy\ stored)}{(time\text{-}averaged\ power\ loss)} = \frac{\omega_0}{\Delta\omega} = \frac{f_0}{\Delta f} \qquad [5]$$

Average power loss in microwave heating processes is primarily related to size and dielectric loss factor of the process load. It can be seen that as losses in the circuit increase the frequency response bandwidth Δf increases and the quality factor Q decreases. The importance of this relationship becomes apparent when comparing the frequency response bandwidth to the magnetron output frequency spectrum (Figure 3).



(a) (b) (c)

Figure 3. Comparisons between microwave output spectrum and load frequency response.

Absorption of microwave energy by the process load requires the microwave source output frequency to be within the response frequency bandwidth of the load (Figure 3a and c). If the microwave source output frequency is outside of the load response bandwidth then microwave energy absorption is reduced (Figure 3b).

COMMON INDUSTRIAL PROCESSES

Characteristics of industrial processes vary from one application to another and may favor one microwave power waveform over another. For example, some plasma processes are intolerant of pulsed power delivery due to rapid recombination of dissociated molecules during the period between pulses. Some high speed processes may require low ripple to ensure uniform heating. Table 1 categorizes several common industrial processes that may be sufficiently similar to others enabling a prediction of the preferred waveform.

Table 1. Characteristics and waveform preference of some common industrial microwave processes.

Brief Description	Cavity Size	Load Loss	Load Volume	Q-Factor	Suggested Waveform
Food processing, conveyorized	Large	High	High	Low	High ripple
Rubber processing, extrusion	Medium	High	Medium	Low	High ripple
Ceramic sintering	Small	Low	Low	High	Low ripple
Ceramic drying	Large	High	High	Low	High ripple
Pharmaceutical vacuum drying	Large	High	High	Low	Low ripple
Plasma processing, downstream	Small	High	Low	Medium	Varies
Waste treatment (liquid, solid)	Large	High	High	Low	High ripple
Polymer curing	Medium	Medium	Medium	Medium	Varies
Thin film drying	Small	Medium	Low	High	Low ripple

CONCLUSIONS

The selection between low and high ripple magnetron power supplies is based on process requirements as much as cost. Low ripple power supplies may be preferred for processes that are sensitive to frequency or minute fluctuations in electric field intensity. Lower cost high ripple power supplies may be preferred for processes that are highly absorptive of microwave energy and tolerant of pulsed microwave energy delivery.

REFERENCES

[1] H.S. Shulman, Microwaves in High Temperature Processes, *Industrial Heating*, Business News Publishing Company, March 2003.
[2] J.F. Gerling, Solid State Industrial Microwave Generators Are Here – Are They Ready? *AMPERE Newsletter*, Issue 80, March 2014.
[3] F.G. Hammersand, E.L. Adams, The Care and Operation of High Power Magnetrons in Industrial Applications, RCA Corporation.
[4] Magnetron Theory of Operation, *Application Note*, Communications and Power Industries, Inc., July 2016.
[5] A.C. Metaxas, R.J. Meredith, Industrial Microwave Heating, *IEE Power Engineering Series*, Peter Peregrinus, Ltd., pp. 152-153, 1983.

Microwave Oven Output Power – An Overview

Robert F. Schiffmann

R. F. Schiffmann Associates, Inc., New York City, USA

Keywords: microwave ovens; power output measurement; power vs. performance; effects of temperature, sample size &container

ABSTRACT

The term" Microwave Oven Output Power" is ill defined and raises more questions than answers. For example:

- What does it mean?
- How is it measured?
    - Influence of sample size, sample container & temperature
- How does it relate to product performance?
- What do consumers know about the output power of their microwave ovens, and how accurate is what they know?
    - How does that affect the heating of prepared foods?
- What do manufacturers tell consumers about the microwave output power of the ovens they purchase?
    - How do they arrive at these values?

The two procedures recommended for the measurement of microwave oven output power are IEC 705 and IEC 60705. What is the difference between the two of them? How relatable are they to the heating of food products?

In this study we examine these questions, as well as describing the early history of this technology.

Development and Validation of Analytical Chart for 915 MHz Single-Mode Microwave Assisted Thermal Processing Conditions

Y. Gezahegn[1], J. Tang[1], P. Pedrow[2], S. Sablani[1], F. Liu[1] and Z. Tang[1]

[1] Biological Systems Engineering Department, Washington State University, Pullman, WA 99164, USA
[2] School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA 99164, USA

Keywords: Chart; Dielectric properties; Heating rate; Microwave processing; Salt content.

INTRODUCTION

Microwave thermal processing, such as thawing, tempering, drying, pasteurization and sterilization, have wide applications in the food industries. Microwave heating has gained popularity over conventional heating due to its higher heating rates, less cooking time and minimal nutritional degradation. Moreover, it is convenient to operate, a cleaner work environment and needs less plant space. With the intention of industrial-scale microwave thermal treatment of pre-packaged foods, a 915 MHz single mode microwave-assisted thermal pasteurization and sterilization systems was developed at Washington State University, WA, USA [1]. In microwave heating, understanding the relation between dielectric properties, salt content, thickness and heating temperature of a food is critical to accurately predicting the power dissipation and heating rate of food in the center layer. Understanding this relationship helps to accurately determine the cold spot temperature to ensure food safety [2]. Hence, this research aims to develop an analytical chart that will relate the food dielectric constant, loss factor, salt content, thickness and preheating temperature with the dissipated power and heating rate to accurately predict the cold spot temperature in the center layer of food.

METHODOLOGY

The main assumptions used in microwave heating are: a 915 MHz single-mode electromagnetic plane wave was traveling from water to food perpendicularly, rectangular shaped, homogeneous food was used, and only the microwave power term was considered as the heat source. The electric field (V/m), dissipated microwave power (W/m^3) and heating rate (°C/sec) inside the food at a distance z from the interface is given by equations (1), (2) and (3), respectively [2].

$$E = \frac{T_{w/f} E_O}{1 + R_{w/f} e^{-\gamma_f L}} \left(e^{-\gamma_f Z} + e^{-\gamma_f (L-Z)} \right) \qquad (1)$$

$$P(z) = 2\pi f \varepsilon_O \varepsilon_r'' |E|^2 \quad (2)$$

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \frac{P(z)}{\rho C_P} \quad (3)$$

Where: subscript w and f, denotes water and food, respectively. E_O, T, R, γ, ε_o, ε', ε", f, ρC_P, L and Z represents incident electric field intensity, transmission coefficient, reflection coefficient, propagation constant, the dielectric permittivity of vacuum, dielectric constant, loss factor, frequency, specific heat volume and thickness, respectively.

At first, using equations (1) and (2) dissipated power at the center layer of food was plotted against different dielectric loss factors. Secondly, the dielectric loss factor was measured and plotted against varying temperature at a different set of salt contents. The relation between dielectric constant and loss factor was determined for the former part of the graph since the dielectric constant will vary with different loss factors. Two sets of graphs were superimposed using MATLAB2019a software to shed light on the complex relationship between dielectric properties and processing conditions, as shown in Figure 1, where dissipated power and heating rate can be related using equation (3). HP 8752C Network Analyzer and 85070B open-end coaxial dielectric probe (Agilent Technologies, Santa Clara, CA) were used to measure the dielectric properties of food samples. Differential scanning calorimeter (DSC, Q1000, TA Instruments, New Castle, DE) was used to measure the specific heat as described by [2].

RESULTS

Figure 1 shows the analytical chart relates the food dielectric constant, loss factor, thickness, salt content, heating temperature with possible power dissipation (heating rate) in the center layer of the food. The first part of the chart, which has open parabolic lines, relates power dissipation with loss factor (blue axes), and the second part that is upward open quadratic lines relates heating temperature with loss factor (black axes). In reading the chart, the same colored power dissipation curves from the first plot and the quadratic temperature lines from the second plot must go together. The black inclined arrow indicates the increase of dielectric constant with step 5 from 60 to 80 in the direction of the arrow. The values of the dielectric constant are represented using black dashed lines. In the validation using 0% salt 22 mm, 0.6% salt 22 mm, 0.6% salt 40 mm, 0.1% salt 40 mm and 0% salt 35 mm mashed potato sample the temperature prediction error was 0 – 2%, 0 – 3%, 0 – 6%, 0 – 9%, and 0 – 6%, respectively.

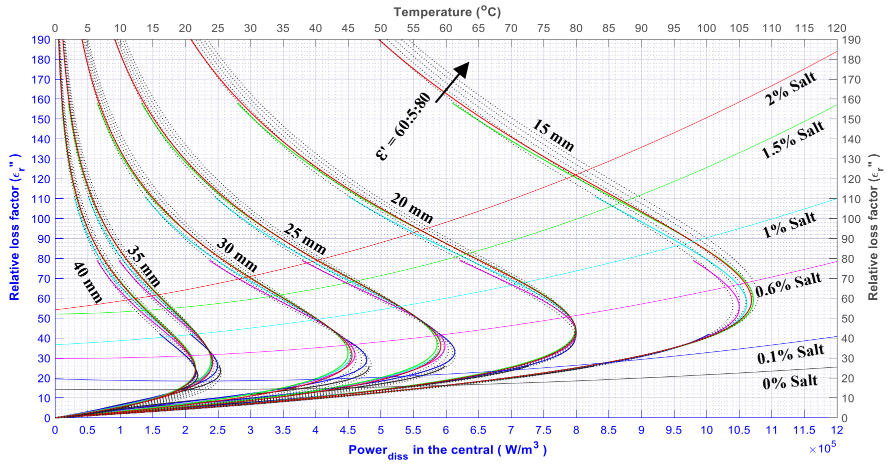


Figure 1. Analytical chart for mashed potato sample with varying thickness salt content

DISCUSSION

The chart provides five main aspects of information. First, dielectric constant (start from heating temperature – go vertically until the intersection with the salt content line – go horizontally to read value). Second, heating temperature for maximum power dissipation (start from power dissipation curve peak of a certain thickness and salt content – go horizontally until the same salt content line – go vertically to read value). Third, heating rate (start from heating temperature – go vertically until the intersection with the salt content line – go horizontally to read the value of dissipation power of a certain thickness) using equation (3) we can find heating rate. Fourth, microwave heating time (start from heating temperature – go vertically until the intersection with the salt content line – go horizontally to read the value of the power of a certain thickness) using equation (3) and dT (target - heating temperature) we can find the heating time. Fifth, optimal salt content for maximum power dissipation (starting from heating and target temperatures determine a range of dissipation power for a certain thickness at various salt content) the salt content that has a range of power dissipation close to the peak will be optimal.

CONCLUSION

The analytical chart accurately predicts dielectric properties and processing conditions that saves time and resources.

REFERENCES

[1] J. Tang, "Unlocking Potentials of Microwaves for Food Safety and Quality," *J. Food Sci*., vol. 80, no. 8, pp. E1776-E1793, Aug. 2015.

[2] D. Jain, J. Tang, P. D. Pedrow, Z. Tang, S. Sablani, and Y.-K. Hong, "Effect of changes in salt content and food thickness on electromagnetic heating of rice, mashed potatoes and peas in 915 MHz single mode microwave cavity," *Food Res. Int*., vol. 119, no. August, pp. 584-595, May 2019.

Interest of Dry Heat Treatment of Wheat Flour by MICRO-WAVE at Low Temperature

A. LE-BAIL[1,4], D. BASTO[2,1], G. DILER[1,4], D. QUEVEAU[1,4], C. JONCHERE[3,4], E.A. NORWOOD[1,4], P. LE-BAIL[3,4], J.P. BERNARD[5], D. VENNIN[5]

1 ONIRIS UMR CNRS GEPEA 6144, 44300 Nantes France
2 Università degli Studi di Milano - DeFENS , 20133 Milano– Italy
3 INRA-BIA, 44300 Nantes France
4 SFR IBSM 4402, 44000 Nantes France
5 SAIREM 82 Rue Elisée Reclus, 69150 Décines-Charpieu France

Contact : alain LE-BAIL, alain.lebail@oniris-nantes.fr, jpbernad@sairem.com, dvennin@sairem.com

Keywords: flour, starch, powdery food, thermal process, functional food ingredient

INTRODUCTION

Although hydrothermal treatments on flour (starch pre-gelatinization) are common (Paulik et al., 2019), dry heat treatments have been poorly studied. At low temperature (LT<100 ° C), disinfection, correction of amylase activity (Aref, 2016) e.g. are targeted while maintaining the functionality of gluten. At high temperature (above 100°C), wheat proteins are damaged (gluten, starch surface proteins) and functional flours, equivalent to chlorination, are obtained that can be used for partial substitution of wheat flour (e.g. bread to improve the texture) or total substitution (e.g. application in cakes) (Chesterton et al., 2014, Keppler et al., 2018). This project aims at evaluating the interest of microwaves as an alternative treatment to conventional thermal processes for dry heat treatment at low temperature.

METHODOLOGY

Wheat flour type 55, without additives, was used for the experiments (10.68% protein, water content 13.79% (wb), Hagberg falling number of 394s). The thermal treatment was either done in standard oven (SO) in an electrical standard oven (MIWE model CO 1.1208-Germany), the flour being installed in a tray inside the oven. The microwave treatment (MW) was done either in a domestic oven model Sharp R-941 or in a continuous MW tunnel (TMW 2450-80, SAIREM, France) (Figure 1). The time-temperature evolution was monitored with several optical fibers (MW) or with thermocouples to apply the same temperature levels for each thermal treatment. The heating up was quite rapid for MW (< 5 min), whereas it took 10 to 30 minutes for SO thermal process. The cooling after treatment was done in a domestic mixer to obtain uniform samples. A comparison of treatments done at LT (55-65-75-85-95°C) was carried out. Several analytical tests have been done (Alveograph-Chopin, Farinograh-Brabender, SRC, RVA-Perten.) as well as baking tests. In this presentation, a focus is proposed on the impact on the heat treatment at LT on flour functionality in baking tests and on pasting properties of flour based on RVA tests.

RESULTS – LOW TEMPERATURE TREATMENT AND BAKING TESTS

Microwave heat treatment (MW) on wheat flour leads to lower water loss than conventional (SO) heat treatment (**Error! Reference source not found.**). The treatments, both MW and SO, up to 75°C. didn't modify the functional properties of the flour. However, MW heat treated flour showed an increase in P/L value during Alveograph tests (Chopin-France) above 75°C (Figure *4*) indicating a higher damage of flour proteins for MW than for SO treatment. The gelatinization temperature was unchanged for LT treatment with both SO and MW treatment. Baking tests confirmed that until 75°C, no major changes of the flour functionality was affected; breads with similar volumes were obtained as shown in Figure 3.

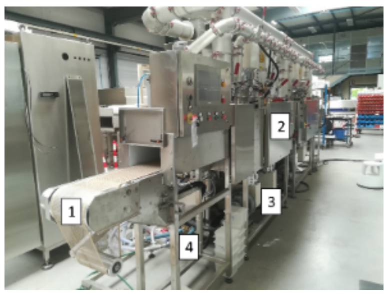


Figure 1: TMW 2450-80 by SAIREM. Main components: (1) Conveyor belt, max speed = 0.75 m/min), (2) Two MW cavity (3 m total), (3) Magnetron (16 kW max), (4) Water system for protect the MW emitter. Optical fibres (1.5 mm diam. – 5 m long) were used during conveying

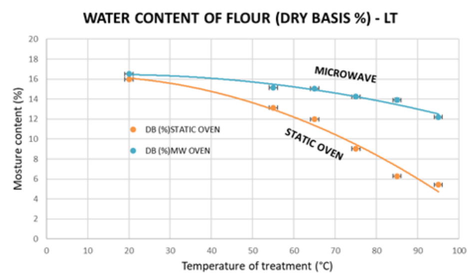


Figure 2: Water content of flour (Dry basis %) treated by LT process. MW treated samples exhibited a lower water loss than Static Oven treated samples.

Conventional heat treated flour (SO) Microwave heat treated flour (MW)

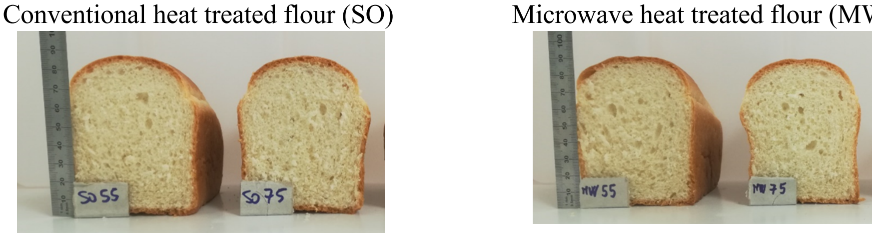


Figure 3: Breads made low temperature dry heat treated flour with SO (left) and MW (right) treated flour at 55 and 75°C showing similar volumes.

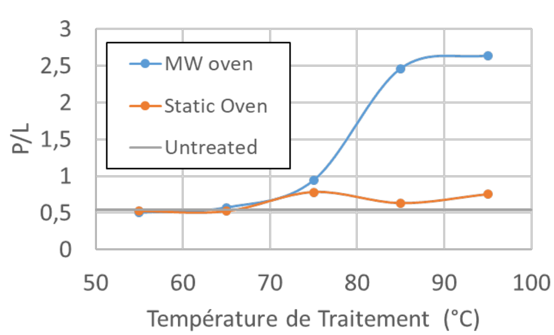


Figure 4: P/L value from Alveograph test (Chopin) of untreated & LT treated flour. An increase in P/L value above 75°C indicates that in our conditions (1 minute plateau at temperature of treatment), MW treated flour was more affected than SO treated flour.

RESULTS – DISINFESTATION OF *TRIBOLIUM CONFUSUM*

The tests were carried out on flour supplied by a local milling company, contaminated with *Tribolium Confusum*, a crawling insect also known as Brown Flour Tribolion, which feeds mainly on flour and cereal grains. It is a beetle of the *Tenebrionidae* family measuring between 2.6 and 4.4 mm and has a reddish brown colour. The complete development from egg to adult takes place in about six weeks under favorable climatic conditions (between 32 and 35°C). The microwave treatment (MW) was carried out in the Sharp R-941 oven (the flour being installed in plastic container), with two target temperatures of 65°C (MW 65) and 75°C (MW 75) respectively. A MW power of 600W was used allowing a rise in temperature in around 60 s with MW against around 10 min in SO conditions. Similar treatment was applied in conventional oven. The flour was then cooled and left for incubation in a climatic chamber at 32.5°C and 70% relative humidity. 3 batches were made per treatment temperature. The flour was passed through a 280 µm mesh sieve to detect the presence of eggs (average size 0.6 x 0.3 mm), larvae and insects. An additional 2 mm mesh sieve was used to retain macroscopic waste (textiles, metal...) and a 1.25mm mesh was chosen as the optimal mesh to retain a majority of insects/larvae (without retaining wheat bran). Results showed that all larva and insects were inactivated by both conventional and MW treatment at 65°C and 75°C. The interest in MW process is its effectiveness and capability to be operated in a continuous process (conveyor).

PASTING PROPERTIES

The pasting properties was determined using an RVA tests (Perten – Australia). 3g of flour was mixed with ca. 25 g of deionized water; the water was adjusted based on the water content of the four to obtain a standard sample of 14% moisture content. A standard temperature profile was applied (AACCI Approved Method 76-21.01, 1997) resulting in graphs displaying the evolution of the rheology of the starch suspension with characteristic info such as peak viscosity, final viscosity and holding strength calculated with the TCW software (Perten). MW samples exhibited a higher viscosity than SO with 10 to 50% increase in peak viscosity. This could be explained by a more efficient impact of MW process, resulting in a faster leaching and dispersion of starch biopolymers during gelatinization.

CONCLUSION

MW technology appeared as a relevant alternative to conventional thermal processes for the dry heat treatment of flours as it permits to obtain a much faster heat up than conventional technics based on contacting the flour with a hot surface or treating the flour in a static oven. MW also yielded less water loss than conventional heating method (static oven). LT treatment showed that the functional properties of the wheat flour were affected above 75°C in particular in the case of MW treatment. This temperature level makes it possible to consider microwaves for the disinfection of flours, which was successfully validated with a flour contaminated with *Tribolium Confusum* or also reduction of amylase activity (Aref., 2016) or the adjustment of the water content. Pasting properties tests showed a more efficient impact of MW process vs conventional process resulting in a higher viscosity of the gelatinized starch suspension. The interest in dry heat treatment of flour by MW yielded several advantages among which a rapid and efficient process compared to conventional processes.

REFERENCES

Aref, M. M., Noël, J.-G., & Miller, H. (2016). Inactivation of Alpha-Amylase in Wheat Flour with Microwaves * . *Journal of Microwave Power*, *7*(3), 215–221.

Chesterton, A. K. S., Wilson, D. I., Sadd, P. A., & Moggridge, G. D. (2014). A novel laboratory scale method for studying heat treatment of cake flour. *Journal of Food Engineering*, *144*, 36–44.

Keppler, Silvia. (2017). *Dry Heat Treatment Of Flour : Addressing Quality And Safety PhD thesis, School of Chemical Engineering, Univ of Birmingham - UK*. (Feb 2017).

Paulik, S., Jekle, M., & Becker, T. (2019). Mechanically and thermally induced degradation and modification of cereal biopolymers during grinding. *Polymers*, *11*(3), 1–13.

Impact of Microwave Heating on Starch Properties and Texture in Sandwich Bread

Roua BouOrm[12], Vanessa Jury[12], Lionel Boillereaux[12] and Alain Le-Bail[12]

[1]ONIRIS, BP 82225, 44322 Nantes, France
[2]UMR GEPEA CNRS 6144 - ONIRIS, 44307 Nantes, France

Keywords: Microwave heating, starch granules, staling, amylose leaching, firmness

INTRODUCTION

Microwave (MW) bread baking remains one of the most interesting alternatives due to its high volumetric power, less baking time, and its relatively low space demand. MW baking was used to provide bread with less acrylamides, which can be considered as "healthier" [1]. Therefore, producing high-quality microwave- baked products is a challenge for food technologists. Since starch is the main component of most baked goods, an in-depth understanding of the effects of MW on starch will play an important role in improving the quality of "MW products". The aim of this study was to compare the effect of MW baking and conventional baking on starch structure at different scale and on staling in sandwich bread.

METHODOLOGY

The samples were analyzed in terms of moisture content, amylopectin retrogradation and amylose-lipid crystallization using differential scanning calorimetry method and crumb firmness after baking and after 1, 3, 6 and 14 days of storage.
First order kinetics model was used to fit the evolution of the staling parameters.

$$\Delta \boldsymbol{HM}(\boldsymbol{t}) = \Delta \boldsymbol{H}_\infty + (\Delta \boldsymbol{H}_0 - \Delta \boldsymbol{H}_\infty)\boldsymbol{exp}(-\boldsymbol{t}/\boldsymbol{\tau}) \quad (1)$$

$$\boldsymbol{EM}(\boldsymbol{t}) = \boldsymbol{E}_\infty + (\boldsymbol{E}_0 - \boldsymbol{E}_\infty)\boldsymbol{exp}(-\boldsymbol{t}/\boldsymbol{\tau}) \quad (2)$$

Where $\Delta \boldsymbol{HM}$ (t) is the modeled melting enthalpy of amylopectin (equation (1)) with $\Delta \boldsymbol{H}_0$ and $\Delta \boldsymbol{H}_\infty$ representing the melting enthalpy at initial and final times respectively where τ is the time constant and t the storage time (in days). A similar equation was used to model the crumb hardening EM (t) (equation (2)) with $\boldsymbol{E}_0$ and $\boldsymbol{E}_\infty$ corresponding to the Firminess at initial and final times. The structure of the starch granules was investigated using environmental scanning electron microscopy (ESEM). The effect of different baking modes was analyzed based on tests done at 7°C/min with conventional baking (done in a MIWE – deck oven) and MW baking (2450 MHZ, 1050 W). A convection microwave oven type Sharp-Inverter was used for MW baking; its power was adjusted to obtain the same heating rate as for conventional baking.

(a) (b)

Figure 1. MIWE –deck oven (a) and Microwave oven (b)

RESULTS

The results showed that MW baking was able to modify the gelatinization mechanism.
It was found that the melting enthalpy of amylopectin retrogradation and amylose-lipid crystallization were more important in MW baking than in conventional baking (Fig.2a). The evolution of crumb firmness during storage was faster and the crumb was firmer in the case of MW baking compared to conventional baking (Fig.2b). The increased firmness of breadcrumbs baked with MW seemed to be related to the phenomena of amylopectin recrystallization and amylose crystallization with a melting endotherm higher for MW baking. Morphological observations showed that starch granules in MW baked breads were not completely disrupted and dispersed, with the presence of starch granules remnants (Fig.2c). A heating rate of 7°C/min in MW baking resulted in the formation of superficial cracks and granule deformation while in conventional baking, no ghost of starch granules were visible, the crumb being made of a continuous starchy gel with very few granules remnants. These results could be explained by differences in the mechanisms involved in starch gelatinization; in the case of conventional baking, the starch undergo a progressive hydration, swelling and dispersion of the starch biopolymers. In the case of MW baking, the starch granules appeared as disrupted.

DISCUSSION

Palav et al (2006) have described that in the case of MW baking, starch granules were rising in pressure resulting in a more pronounced leaching of amylose, whereas starch granules remnant contained a higher amount of amylopectin [2]. Amylopectin and amylose are two poorly compatible biopolymers; in the case of MW baking, it seems that the segregation between amylose and amylopectin was more marked, resulting in a) a more cohesive amylose gel outside the starch granule remnant, and b) a less pronounced attack of amylopectin by alpha-amylase and a subsequent faster retrogradation (recrystallization) of amylopectin pooled within the granules remnant. The determination of the soluble amylose in the crumb has confirmed this hypothesis.

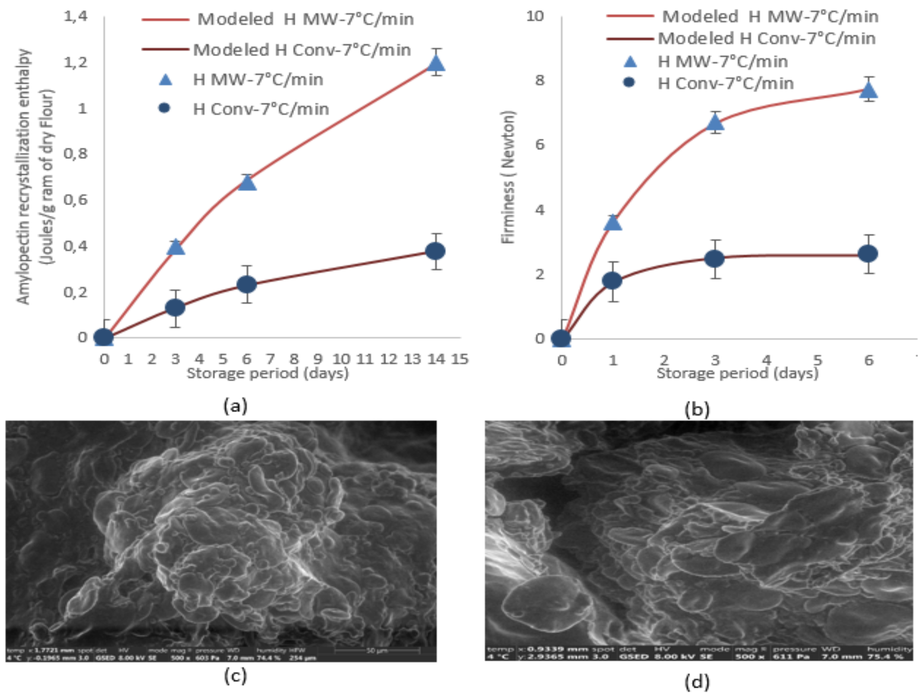


Figure 2. Evolution of the melting enthalpy of the retrograded amylopectin (a) and crumb firminess (b) in MW and conventional baked crumb during the storage. Starch Microstructure evaluation using ESEM in MW (c) and conventional (d) baked crumb

CONCLUSION

As a conclusion, the obtained results showed that the disruption of the starch granules in bread samples under MW baking was more pronounced than in conventional baking at the same heating rate and yielded i) an increase of the amylose leaching and ii) a disruption of starch granules with less dispersion of amylopectin. This resulted in the formation of a more cohesive amylose network in the crumb and in higher level of amylopectin recrystallization. Amylopectin crystals act as “water well” and are responsible in trapping the water that is the main plasticizer of the crumb; therefore, a faster staling was observed with MW baking with a firmer crumb. Further tests are considered with faster heating rates using MW baking.

REFERENCES

[1] S. Chandrasekaran, S. Ramanathan, and T. Basak, Microwave food processing-A review, *Food Res. Int.,* vol. 52, no 1, pp. 243–261, 2013.
[2] T. Palav, K. Seetharaman, Mechanism of starch gelatinization and polymer leaching during microwave heating; *Carbohydr. Polym.,* vol. 65, pp. 364–370, 2006.

Microwave: A Solution to Mitigate Checking and Breakage of Dry Cereal Products during Storage

P. Le-Bail[1,3], M. Bedas[1,3], L. Ribourg[1,3], C. Jonchère[1,3], J.P. Bernard[4], D. Vennin[4], A. Le-Bail[2,3]

1 INRAE-BIA, CS 71627 Site de Nantes-Géraudière 44300 Nantes France
2 ONIRIS UMR CNRS GEPEA 6144, 44300 Nantes France
3 SFR IBSM 4402, 44000 Nantes France
4 SAIREM 82 Rue Elisée Reclus, 69150 Décines-Charpieu France

Contact : Patricia Le-Bail patricia.le-bail@inrae.fr

Keywords: biscuit, breakage, microwave, glass transition, water content

INTRODUCTION

The BRICE project is a four-year regional collaborative project set up to address an industrial problem, the fragility of dry cereal matrices such as biscuits, crackers, rusks etc. Indeed this fragility leads to a decrease in the client's palatability and to dissatisfaction. The term fragility here encompasses the phenomena of checking (cracks) and breakage (quoted "C&B" in the rest of the paper) at the macroscopic and microscopic level.

All the products concerned by this study have in common a very low water content (less than 5%), which leads to reaching a "glassy" state of the material. The glassy state describes a non-crystallized solidified structure, which is very fragile from a mechanical point of view. The dry cereal products leaving the baking process inevitably have heterogeneity in water distribution; they are drier at the surface of the product than at the center. A literature study showed that it is this heterogeneity in water distribution, which seems to be at the origin of the problem of C&B as described by (Dunn & Bailey, 1928; Duncan, 1998; Kim & Okos, 1999; Saleem, 2005; Manley, 2011; Besbes, Jury, Monteau, & Le Bail, 2013; Goldstein & Paul, 2016). Re-balancing the local water content between the more or less hydrated zones of the cracker is one of the possible strategies to mitigate C&B. Indeed, the driest outer zone are undergoing a glassy state transition during post-baking cooling; meanwhile the central zone is contracting due to a combined contraction caused by a thermomechanical (cooling) and an hydro-mechanical (water migration centre/surface) phenomenon. In this context, the cooling stage and the temperature of the product represents an important lever, which makes it possible to pass or not the glass transition and to facilitate or not the rebalancing of the water content of the product.
Saiyad et al. 2001 clearly demonstrated that a microwave treatment of crackers after baking made it possible to reduce C&B during storage. Modeling and measurements of local water content have shown that microwave treatment yielded a more homogenous water content in the products.

It appears from the state of the art that the problems of C&B of dry cereal products can be attributed a priori to many physical, structural, temporal factors, etc. Thus, in this project, the tracks envisaged to mitigate C&B have focused on an approach aiming to better control the state of the matter at the end of baking and to develop strategies allowing redistributing the water within the matrices at exit of baking in order to relax the mechanical stresses that could have accumulated in the product.

METHODOLOGY AND RESULTS

A visual count of cracks was performed on 50 biscuits. One day after the production of the biscuits, there were 89 ± 11% of products with checking and a rapid evolution is observed with 91 ± 5% of checked biscuits on day 7 (average from 4 different production batches). A study of the water content at the center of the biscuit and on the periphery was carried out with the help of a Karl Fischer V30S Volumetric KF Titrator (INV 2017-169950) and fitted with a Stromboli oven (INV 2017-171642) from Mettler Toledo. The results revealed an inhomogeneous distribution of the water in the volume of the biscuit. There was therefore a large water gradient present in the biscuit after baking. It was also observed that the homogenization of the water in the biscuit was effective quite late (> 24 h), resulting in the presence of stresses and C&B of the biscuits.

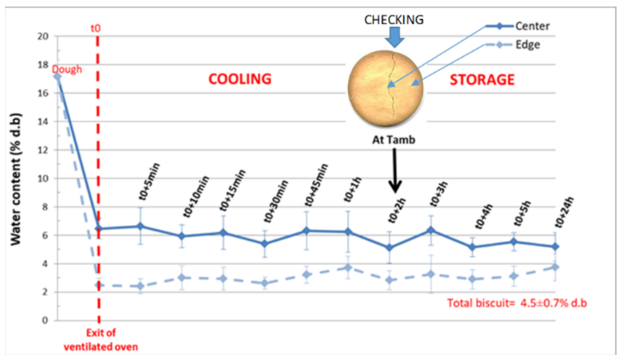


Figure 1: Karl Fischer study: the water loss of biscuits, in percent (based on dry basis) at center and at edge of the biscuit, as a function of time during cooling and storage. A difference of 2 to 3 % was observed, resulting in the apparition of cracks within less than 24 h after baking and cooling.

Bernussi and Ahmad have shown that products with a center/edge water gradient of less than 1% (d.b) before they return to room temperature have less stress and do not crack (Bernussi et al., 1998; Ahmad et al., 2001). In order to reduce this water gradient on the biscuits, microwave processing has been combined with hot air. The MW treatments after baking were done on the biscuits in presence of hot air in a 4 kW microwave (2450 MHz) prototype conveyor oven (SAIREM, France). The specific energy applied to the biscuits was adjusted thanks to specific mass flow rate and level of emitted MW power.

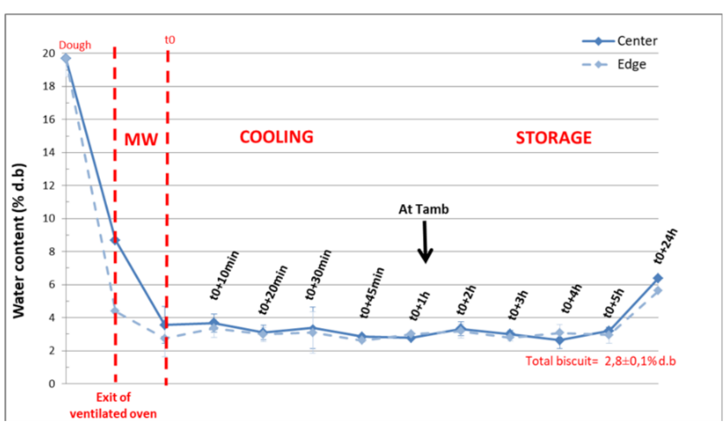


Figure 2: Karl Fischer study: the water loss of biscuits, in percent (based on dry basis), as a function of time before and after microwaves (MW), during cooling and storage.

The water distribution was modified compared to the reference biscuits (without MW). Indeed, the water balance in the product was achieved in less than 10 minutes after the MW processing, and the moisture content gradient was below 1% after MW treatment for the highest specific energies applied. The biscuits reached a temperature close to the glass transition temperature for these conditions.

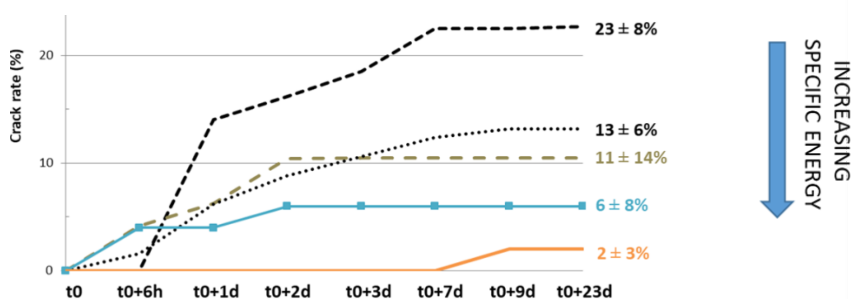


Figure 3: visual count of cracks (%) of MW processed biscuits after baking during cooling and storage (exit of oven, 6hours, 1, 2, 3, 7, 9, 23 days) for different specific energies applied to the biscuits. The increase in applied specific MW energy yielded a significant reduction of C&B.

CONCLUSION

This study showed the interest of MW processing after baking of dry cereal products such as biscuits to mitigate the risk of checking and breakage. A strong reduction in the rate of C&B was observed with increasing specific energy applied to the biscuits. Sensory tests (not shown) showed that the quality of the biscuits was not affected with appropriate specific energy levels and appropriate operating conditions of the MW treatment. MW therefore seemed to be a good alternative for homogenization of the water in the product, leading to a reduction (or even disappearance) of the fragility phenomenon and of C&B observed on dry cereal products during cooling and following storage

REFERENCES

Ahmad, S. S., Morgan, M. T., & Okos, M. R. (2001). Effects of microwave on the drying , checking and mechanical strength of baked biscuits. Journal of Food Biochemistry, 50, 63–75.

Bernussi, A.L.M., Chang, Y.K., & Martinez-Bustos, F. (1998). Effects of Production by Microwave Heating After Conventional Baking on Moisture Gradient and product Quality of Biscuits (Cookies). Cereal Chemistry, 75(5), 606–611.

Besbes, E., Jury, V., Monteau, J. Y., & Le Bail, A. (2013). Water vapor transport properties during staling of bread crumb and crust as affected by heating rate. Food Research International, 50(1), 10–19. https://doi.org/10.1016/j.foodres.2012.09.041

Dunn, J. A., & Bailey, C. H. (1928). Factors influencing checking in biscuits. Cereal Chemistry, (5), 395–430.

Duncan, M. (1998). Baking and cooling of biscuits. Woodhead Publishing Limited, 80.

Goldstein, A., & Paul, S. (2016). Baked Product Staling : Mechanisms , Determinations , and Anti-staling Strategies. Encyclopedia of Food Grains (2nd ed.). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100596-5.00167-0

Kim, M. H., & Okos, M. R. (1999). Some physical, mechanical, and transport properties of crackers related to the checking phenomenon. Journal of Food Engineering, 40(3), 189–198. https://doi.org/10.1016/S0260-8774(99)00055-2

Saleem, Q. (2005). Mechanical and fracture properties for predicting cracking in semi-sweet biscuits. International Journal of Food Science and Technology, 40(4), 361–367. https://doi.org/10.1111/j.1365-2621.2004.00920.x

Manley, D. (2011). Manley's technology of biscuits, crackers and cookies. (Tec & Nut., Ed.) (Woodhead P). Cambridge, England.

Comparison of Microwave-Assisted Thermal Pasteurization and High Pressure Processing as Pasteurization Methods for Green Beans

Sumeyye Inanoglu[1], Gustavo Barbosa-Canovas[1], Mei-Jun Zhu[2], Shyam S. Sablani[1], Frank Liu[1], Zhongwei Tang[1], Juming Tang[1*]

[1] Department of Biological Systems Engineering, Washington State University, P.O. Box 646120, Pullman, WA 99164-6120, USA
[2] School of Food Science, Washington State University, P.O. Box 646376, Pullman, WA 99164-6376, USA

Keywords: pasteurization, microwave, high pressure processing, safety, and quality.

INTRODUCTION

There has been an increasing consumer desire for high quality minimally processed and convenient foods. The food industry is seeking new processing technologies to meet such consumer desire by producing microbially safe ready-to-eat (RTE) meals with adequate shelf-life for distribution in cold chains. High pressure processing (HPP) is a novel non-thermal pasteurization technology that has been used commercially in production of several high-quality food products including vegetables such as guacamole. The goal of this research was to evaluate the effect of microwave-assisted pasteurization system (MAPS) in comparison with HPP using two levels (mild and severe) for pasteurization conditions on quality of green beans. The mild pasteurization should obtain a 6-log reduction of *L. monocytogenes* in low-acid foods with the shelf-life of ≤ 10 days at ≤ 5°C, while the severe pasteurization should obtain a 6-log reduction of non-proteolytic *C. botulinum* for a product shelf-life of ≤ 6 weeks at ≤ 5°C, respectively [1].

METHODOLOGY

Based on literature review, the mild pasteurization conditions were selected as 70°C-2 min for MAPS and 600 MPa-10 min at 25°C for HPP. For the severe pasteurization conditions, 90°C-10 min was selected for MAPS, and 600 MPa-20 min at initial temperature of 45°C were selected for HPP (Table 1) [2]. The quality attributes such as color, chlorophyll content, texture, and pH of green beans were determined at 2°C for 36 days and 10°C for 20 days for mild pasteurization and at 2°C for 14 weeks and 7°C for 7 weeks for severe pasteurization.

Table 1. Process conditions for thermal and HPP, and target microorganism for each process.

Intensity Level	Processing Conditions		Target Pathogen
	Thermal	High Pressure	
Mild pasteurization	$F_{70°C}$=2 min	600 MPa for 10 min, 25°C	*Listeria monocytogenes*
Severe pasteurization	$F_{90°C}$=10 min	600 MPa for 20 min, T_i=45°C	Nonproteolytic *Clostridium botulinum* type E spores

RESULTS

Mild conditions of high-pressure treatment resulted in a 3.7 ± 0.5–log CFU/g reduction in *L. innocua*, whereas MAPS processing showed a 9-log CFU/g reduction. Fig. 1 shows the effect of storage on the color change of green beans pasteurized under mild conditions. A decrease in greenness and an increase in yellowness were observed during storage at 2, 7 and 10°C for MAPS and HPP pasteurization. The similar chlorophyll degradation of green beans was observed in both MAPS and HPP pasteurized green beans ($p>0.05$). The severe pasteurization for both methods resulted in higher degradation in chlorophyll content in comparison with mild pasteurization. Both mild pasteurization treatments had no significant effect on firmness, whereas severe pasteurization of MAPS resulted in lower firmness values compared to severe pasteurization of HPP ($p>0.05$). The pH of pasteurized green beans stored at 2°C was similar for MAPS and HPP. However, the pH of green beans significantly decreased during storage at 7 and 10°C with bulging, putrid smell, or discoloration.

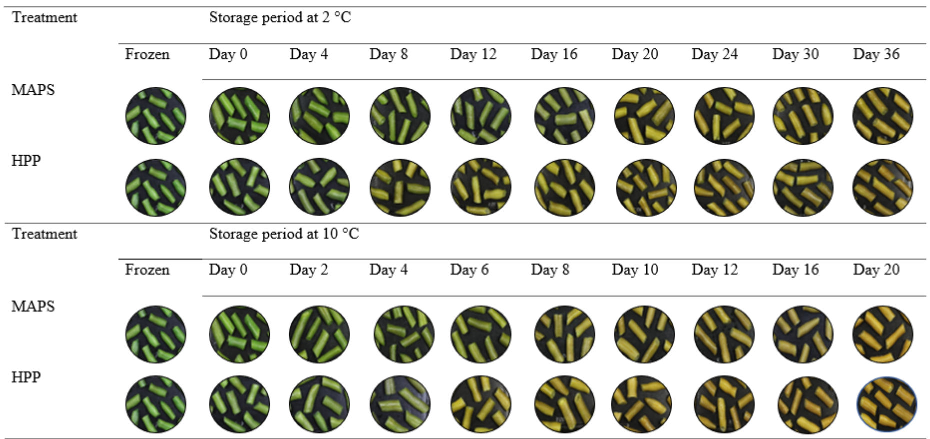


Figure 1. Effect of storage on color change of mild pasteurized green beans.

DISCUSSION

Similar color change after both pasteurization methods shows that the processing temperature of MAPS did not negatively affect the color of green beans. The results of chlorophyll degradation show correlation with color of pasteurized green beans. The severe MAPS conditions resulted in less retention of firmness in comparison with the severe HPP pasteurization and the mild MAPS pasteurization. This can be attributed to the higher processing temperature (90°C), which results in β-eliminative depolymerization of pectin (softening). Microbial growth, mainly of acid-producing microorganisms, might be responsible for the decrease in pH and the undesirable appearance and smell.

CONCLUSION

This work shows that mild pasteurization conditions of HPP and MAPS treatments used in this study had different antimicrobial efficacies against *L. innocua* in green beans. Although the processing temperature of MAPS is higher than HPP, similar color retention and chlorophyll degradation was obtained in green beans for both intensity levels. The severe MAPS conditions cause softening in green bean tissues, while the severe HPP conditions were effective in the prevention of firmness loss.

REFERENCES

[1] USFDA. *Control of Listeria monocytogenes in refrigerated or frozen ready-to-eat foods: draft guidance*. 2008; http://www.fda.gov/Food/GuidanceRegulation/GuidanceDocumentsRegulatoryInformation/FFoodProcessingHACC/ucm073110.htm].

Knockaert, G., et al., *Effect of thermal and high pressure processes on structural and health-related properties of carrots (Daucus carota).* Food Chemistry, 2011. **125**(3): p. 903-912.

Comparison of Microwave and Conventional Thermal Pasteurization of Frozen Green Beans

Zhi Qu[1], Fang Liu[1], Zhongwei Tang[1] and Juming Tang[1,*]

[1]Department of Biological Systems Engineering, Washington State University, Pullman, WA, United States

Keywords: Microwave pasteurization, conventional pasteurization, green beans, color, chlorophyll

INTRODUCTION

Consumer's desire for high quality food and convenience has been a major driver for advancements of processing technologies. Microwave pasteurization can provide more rapid heating and better heating uniformity compared to conventional thermal pasteurization [1], thus holds potential to produce better quality vegetable products, such as fresh appearance and texture [2]. But little has been reported on direct comparison of the quality of vegetables processed with microwave and conventional pasteurization methods. The objective of this research was to study the influence of microwave and conventional thermal pasteurization on quality of green beans during storage at various cold chain temperatures.

METHODOLOGY

Thawed frozen green beans were vacuum sealed in 8 oz polymer trays, processed in a pilot-scale 915 MHz Microwave Assisted Pasteurization System (MAPS) and conventional water bath (WB) to achieve thermal lethality of 90 °C 10 min for 6 log reduction of nonproteolytic C. *botulinum*. The processed samples were stored at 10 and 2 °C. Color value was quantified using computer vision system and MATLAB R2019b. Spectrophotometer (V-5000, Metash Instruments, Shanghai, China) and HPLC (Agilent Technology, Santa Clara, CA) were employed to quantify chlorophyll and Vitamin C, separately.

Before pasteurization MAPS pasteurized WB pasteurized

Figure 1. Typical picures of green beans before and after thermal treatment.

RESULTS

Figure 1 shows typical pictures of green beans before and after pasteurization. Table 1 summarizes the quality parameters of the samples. MAPS processed green beans had significant lower a* value, total color change and higher chlorophyll a content after processing. Figure 2 depicted chlorophyll degradation during the storage at 10 and 2 °C. The degradation of chlorophyll a and b followed fractional conversion model and the reaction rate decreased as the storage temperature decreasing. the MAPS processed samples showed lower reaction rate compared to the WB processed ones

Table 1. Color and chlorophyll parameters of green beans before and after pasteurization.

	Before pasteurization	After pasteurization	
		MAPS	WB
L*	51.01±2.11[a]	50.55±0.52[a]	49.63±1.48[a]
a*	-29.52±0.08[a]	-13.94±0.71[b]	-9.39±0.29[c]
b*	44.06±1.24[a]	41.88±0.12[a]	43.45±0.37[a]
ΔE		15.82±0.44[a]	20.27±0.52[b]
Chlorophyll a (μg/g db)	751.09±10.78[a]	538.43±12.29[b]	496.31±13.95[c]
Chlorophyll b (μg/g db)	353.92±18.56[a]	196.39±13.26[b]	178.96±17.25[b]

Means in rows followed by different letters differed significantly ($p \leq 0.05$).

DISCUSSION

The lower a* value of MAPS processed green beans indicated better retention of green color and appearance attractiveness. For green beans, chlorophyll suffered greater degradation when pasteurized using WB. Microwave pasteurized green bean can not only be preserved for a longer time than WB heated one (with no gas formation inside the package, but also comparable chlorophyll content.

CONCLUSION

From the viewpoint of appearance and nutrition, microwave pasteurization led to less degradation after processing and greater degree of quality retention during cold temperature storage compared with conventional WB pasteurization. This implicates that microwave pasteurization might be a potential alternative to produce safe, high-quality vegetable products and preserve the quality during storage.

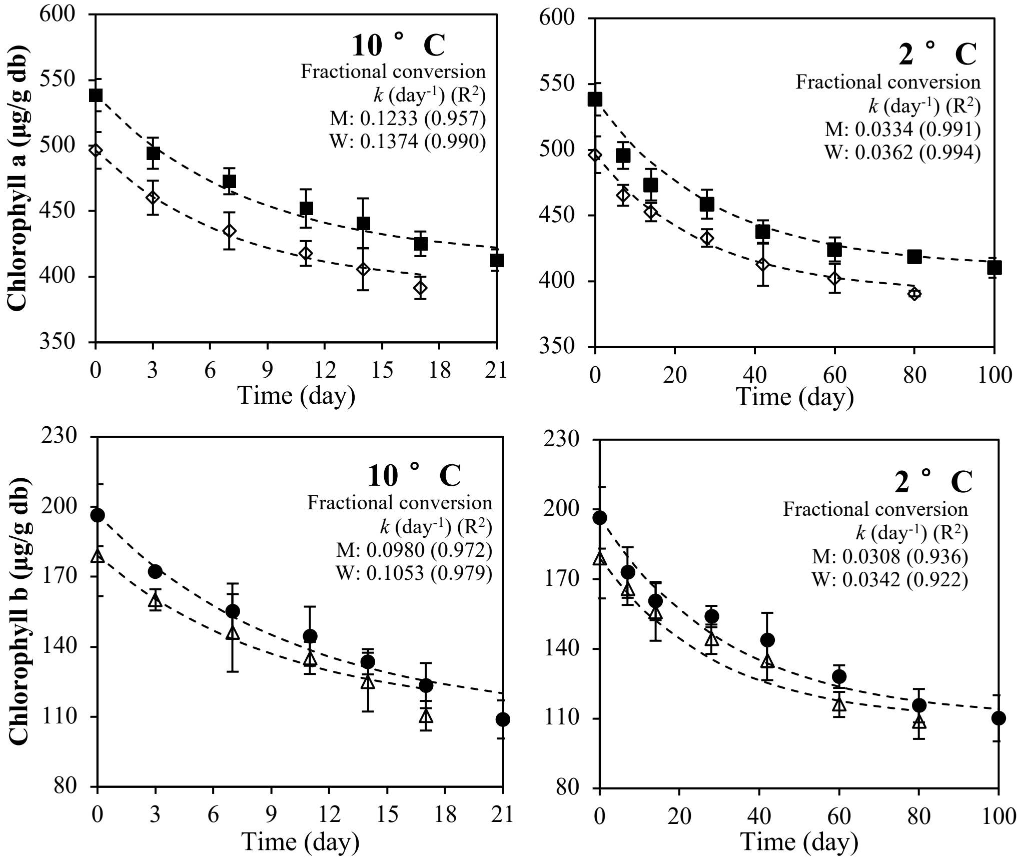


Fig. 2 Degradation of chlorophyll during storage.

REFERENCES

[1] J. Tang, Unlocking potentials of microwaves for food safety and quality. JFS Special Issue: 75 Years of Advancing Food Science, and Preparing for the next 75. *J. Food Sci.,* vol. 80 issue 8, pp. E1776-1793, 2015.

[2] M.H. Lau and J. Tang, 2002. Pasteurization of pickled asparagus using 915 MHz microwaves. *J. Food Eng*., vol 51, pp. 283–290, 2002.

Antimicrobial Effect of Microwave Treatment on Beef Jerky Inoculated with Salmonella and Listeria monocytogenes

Darvin Cuellar[1], M.Sc., Don Stull[2], PE, Ayodeji Adeniyi[1], Remio Moreira[1], Alejandro Echeverry, Ph.D.[1]

[1]Texas Tech University, Lubbock, TX, USA
[2]MicroZap, Inc., Lubbock, TX, USA

Keywords: Microwave, Salmonella, Listeria, Food-Safety, Intervention, Recall

INTRODUCTION

Salmonella and *Listeria monocytogenes* are dangerous pathogens that can cause costly recalls and severe illness with millions of dollars in related-public health costs [1], [2]. These pathogens have the ability to produce life-threatening illness in children, elderly, and other susceptible populations. Furthermore, *Salmonella* can survive for long periods of time even in dry conditions. This makes beef jerky, a dehydrated beef product, an environment where survival is possible even though the conditions would normally seem impossible for survival. A new intervention using microwave technology has shown positive results in other food products [3].

METHODOLOGY

Three types (Flavor 1 – 3) of beef jerky were evaluated: The study used two different treatment parameters. (Treatment A and Treatment B, each with different microwave treatment parameters and power levels) and one negative control. Treatment A and Treatment B utilized different overall parameters and different energy levels (Treatment A at 101.7kJ and Treatment B at 170.1kJ). For each treatment and control, 15 individual samples of 25g were analyzed. The samples were first inoculated under an air hood with 50µl of either *Salmonella* or *Listeria* cocktail (~8 Log10 CFU/ml). They were allowed to dry for 10 minutes, assigned to microwave treatments, and treated in a custom-made machine on a conveyor belt, comprised of six 2.45GHz magnetrons, see Figure 1. After treatment, each sample was diluted in 225ml of Buffered Peptone Water (BPW) and homogenized at 230RPM for 2min. Serial dilutions were made and spread plated on Rifampicin Tryptic Soy Agar for Salmonella and Modified Oxford Agar for *Listeria*.

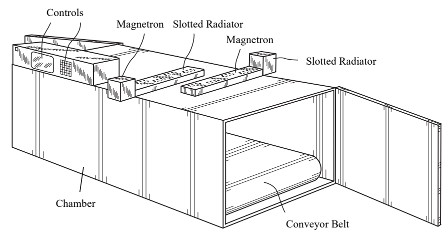
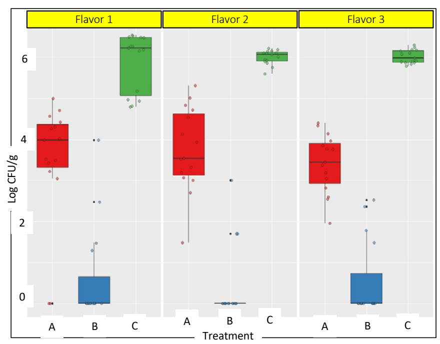
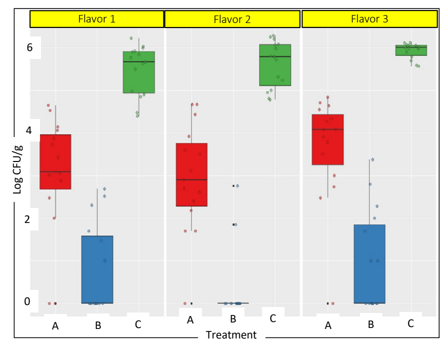


Figure 1. Microwave system diagram (Ref. Fig. 5 US Patent 8.675,401)

RESULTS

The results showed that treatment A can reduce ~ 2 Log CFU/g of *Salmonella* and *Listeria*, and Treatment B can reduce ~ 5 Log CFU/g with high statistical significance *(P* <.001).





(a) (b)

Figure 2. Effects of microwave treatments A & B vs. Control (C) on *Listeria monocytogenes* (a) and on *Salmonella* (b).

DISCUSSION

The results demonstrate the effectiveness of microwaves to eliminate *Salmonella* and *Listeria* in beef jerky. This technology can be implemented in a continuous production line as an effective food safety intervention on product prior to packaging and even post-packaging, which will eliminate cross contamination. Such a new intervention would provide vastly improved food safety, reduce illnesses and death and avoid costly food recalls.

CONCLUSION

Microwave treatment showed to be effective on reducing *Salmonella* and *Listeria monocytogenes* on inoculated beef jerky.

Although drying, smoking and high salt concentration usually prevents pathogens from growing in this type of product, microwaves could be used as a pre or post packaging antimicrobial intervention on new, chewable beef jerky products with higher moisture content.

REFERENCES

[1] Centers for Disease Control and Prevention (CDC). 2018. *Salmonella.* Accessed 10 January, 2019. Available at: https://www.cdc.gov/salmonella/index.html.

[2] Centers for Disease Control and Prevention (CDC). 2018. *Listeria.* Accessed 10 January, 2019. Available at: https://www.cdc.gov/listeria/.

[3] Lakins D. G., C. Z. Alvarado, L. D. Thompson, M. T. Brashears, J. C. Brooks, and M. M. Brashears. 2008. Reduction of *Salmonella* Enteritidis in shell eggs using directional microwave technology. *Poult. Sci*. 87:985-991.

Gentle Microwave Preservation and Production of Prepared Foods

B. Wäppling Raaholt[1]

[1]RISE Research Institutes of Sweden, Göteborg, Sweden

Keywords: microwave processing, one-step microwave cooking & preservation, microwave pasteurization, microwave sterilization, prepared foods.

INTRODUCTION

Applications for microwave pasteurization and sterilization include both in-pack preservation of packaged foods (e.g. ready-to-heat meals), heated continuously on a conveyor belt or batch-wise, as well as tubular in-flow preservation of semi-fluid pumpable foods. The latter include the type of microwave high-temperature short-time (HTST) processing which is further described and studied in Wäppling Raaholt et al (2016, 2017). Microwave in-pack sterilization of foods is described and evaluated in e.g. Zhang et al (2019), Patel et al., (2019).
Microwave heating uniformity is important particularly in systems intended for preservation purposes. A homogeneous temperature distribution is crucial to ensure that microbiological requirements are fulfilled, without unnecessary overheating of the food. Good heating uniformity requires appropriate design of the microwave system, including wave guide system, applicators, and cavities. Modelling tools can be used to predict the location of 'cold spots' for appropriate designs and configurations of the system. However, the developed processing units and products always have to be validated by measurements in order to confirm sufficient heat treatment.

Microwave processing can be used for efficient and rapid heating of foods, including applications for microwave pasteurization and sterilization. The main advantages of microwave processing for these applications are short come-up times (reduced time to reach the required target temperature in the coldest spot of the food), quality advantages related to volumetric heating, but also time savings, increased throughput and process flexibility. For a well-designed tubular process there are also other advantages, e.g. increased degree of heating uniformity over the cross section (Wäppling Raaholt et al, 2016). The high heating rates and uniform heat distribution in e.g. particulate foods (between particulates and the surrounding continuous phase in microwave HTST treated particulate foods, as described in Wäppling Raaholt et al, 2017) also offers minimized loss in food product quality due to heating. In this presentation, the microwave HTST concept developed by RISE will be discussed and results will be exemplified.

Among other types of microwave preservation systems for foods are conveyorized systems for microwave preservation of ready meals. These are industrially implemented worldwide. An example is a microwave pasteurization line for continuous heat treatment of ready meals as illustrated in Figure 2. (www.micvac.com). An example will be given where quality was evaluation for a microwave in-pack pasteurized soup with pieces of root vegetables and seafoods. The results will be presented together with the corresponding results for conventional processing of the soup at the corresponding shelf-life criteria.

METHODOLOGY

Figure 1 illustrates schematically the tubular microwave-assisted HTST system evaluated in Wäppling Raaholt et al, 2017. A microwave pasteurization tunnel for production of prepared meals is shown in Figure 2.

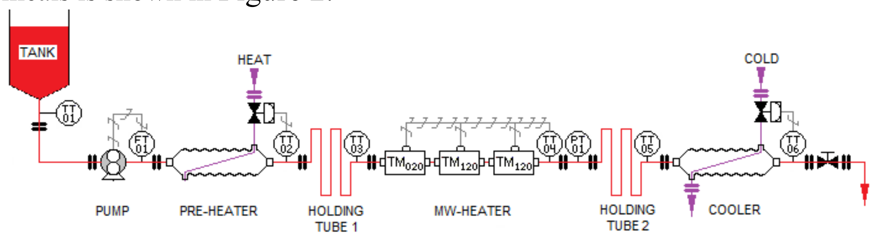


Figure 1 Schematic view of the microwave-assisted HTST system, including tank, pump, pre-heater, holding tube at the inlet, microwave heating unit, holding tube at the outlet, cooler, and product outlet.

Figure 2. Microwave pasteurisation tunnel, for production of ready-to-heat meals (Source: www.micvac.com, Reproduced with permission).

RESULTS AND DISCUSSION

High temperature-short time (HTST) processing of food products should give product quality benefits with maintained microbiological safety for sterilization of such foods, as manifested by the correlations reported between time, temperature, inactivation of enzymes, microorganisms and spores, as well as sensory and nutritional losses (Ohlsson and Bengtsson, 2002). Microwave heat treatment of foods enables HTST-like processing in a way that can be obtained also for solid foods of relatively large size (many centimeters). Crucial constraints to this type of microwave heat treatment are the minimum spread in temperatures that can be established, but also the fact that the cooling rate will rely on conventional cooling technologies and also on thermal properties of the food (Ohlsson & Bengtsson, 2002).

In a previous EU project (EU-AIR, 2000), the benefits of microwave sterilization in terms of sensory and nutritional quality were demonstrated and compared to conventional retorting (Sundberg, 1994 and 1997). Numerical modelling of microwave heating, in order to predict heating effects of food (Wäppling Raaholt, 2015, Wäppling Raaholt et al, 2002, Malafronte et al, 2007, Geedipalli et al, 2007), has in the latest years developed into increasingly more realistic models. Validation of such models is performed by experiments, where real product temperature distributions are measured or established. This is particularly important in pasteurization or sterilization applications. Multiphysics modelling (e.g. Wäppling Raaholt and Waldén, 2011, Malafronte et al, 2007, Lespinard et al, 2019) can be used to predict combined heating with microwave and convection or other heating means but need to be developed further to meet validation purposes. Movements of the food during heating and/or use of a small rotating mode stirrer could improve heating uniformity, as well as control the resulting microwave power distribution during processing. Conveyorized ovens with moving belts are developed specifically for industrial microwave treatment of foods. Tubular in-flow systems involve movement of the food during industrial heating and could be designed to achieve a more uniform and gentle heating than conventional technology can offer (Wäppling Raaholt, 2015; Wäppling Raaholt et al, 2016).

Among industrial examples of microwave pasteurization of foods are pre-packaged foods like ready meals and yoghurt (Micvac, 2015; Decareau, 1986, Rosenberg and Bögl, 1987b). For several years, industrial equipment for commercial pasteurization of ready-made meals (Figure 2.) is commercially offered and installations are available world-wide. Applications for microwave sterilization of packaged foods have been investigated for many years (e.g. Ohlsson, 1991; Sundberg, 1993, Tang et al, 2008) and were noted for packaged foods in the US already in 1971 (Kenyon et al., 1971, O'Meara et al, 1977). It is also used commercially, e.g., in Europe (Top's food, 2015). The demands for temperature control are even more rigorous for sterilization, with apparent requirements of process validation (Wäppling Raaholt, 2015, Ohlsson, 1991), assisted by advanced modelling tools to predict 'cold spots'.

CONCLUSION

Microwave HTST processing as described by Wäppling Raaholt (2017) offers a gentler way to preserve particulate soups, where texture of root vegetables as well as nutritional quality is better maintained. Microwave in-pack pasteurization shows quality advantages in perceived quality compared to prepared soups that are heat treated conventionally in its packages, when keeping the processing criteria to reach the same level of shelf-life from a microbiological and processing point of view. However, the studied in-pack microwave heating system does not give the same level of heating uniformity as the microwave HTST system. A pressurized version of the in-pack system is therefore regarded as a complementary system to the microwave HTST-like system.

REFERENCES

[1] B. Wäppling Raaholt, L. Hamberg & S. Isaksson (2017) Continuous tubular microwave heating of particulate foods at high temperatures, J. MW Power & EM Energy, 51 (4), pp 259-285.

[2] B., Wäppling Raaholt, S. Isaksson, L. Hamberg, L. (2013) A tubular microwave sterilisation process for pumpable foods, AMPERE conf. on MW & HF Heating, UK, Sep, 2013, pp 80-83.

[3] B. Wäppling Raaholt, S. Isaksson, L. Hamberg, A. Fhager & Y. Hamnerius. (2016) Continuous tubular microwave heating of homogeneous foods: evaluation of heating uniformity, J. Microwave Power & Electromagnetic Energy, 50 (1), pp. 43-65.

[4] Zhang, H, Patel, J, Bhunia, K, Al-Ghamdi, S, Sonar, C.R, Ross, C.F, Tang, J. & Sablani, S.S, Color, vitamin C, β-carotene and sensory quality retention in mw-assisted thermally sterilized sweet potato puree, Food Packaging & Shelf Life. 2019:21

[5] Patel, J, Al-Ghamdi, S, Zhang, H, Queiroz, R, Tang, J. Yang, T. and Sablani, S.S, Determining Shelf Life of Ready-to-Eat Macaroni and Cheese in High Barrier and Oxygen Scavenger Packaging Sterilized via MATS, Food & Bioprocess Technology. 2019:12;1516-1526.

Design of a Small Heating Cavity Intended for Insertion into a Vending Machine to Heat Ready-to-Eat Meals

C. De Massari[1], F. Dughiero[2] and A. Marconi[2]

[1]InovaLab, Padua, Italy
[2]University of Padua, Padua, Italy

Keywords: design, cavity, ready meal, vending machine.

INTRODUCTION

The goal of this work is to design a combination MW (microwave) and IR (infra-red) heating system which can be completely integrated into a vending machine to allow for the heating of ready-to-eat meals and sandwiches. The main foci of this machine include speed, food quality and sustainability. This machine will allow a user to phone order by App, thus requiring that the heating time be very fast so it can heat quality Italian foods, such as those found in ready-to-eat meals and sandwiches. All packaging used in this system must be compostable. Because of these requirements, the oven system must be small, efficient and operate at a relatively low temperature (less than 160°C, which is the degradation temperature of the packaging material).

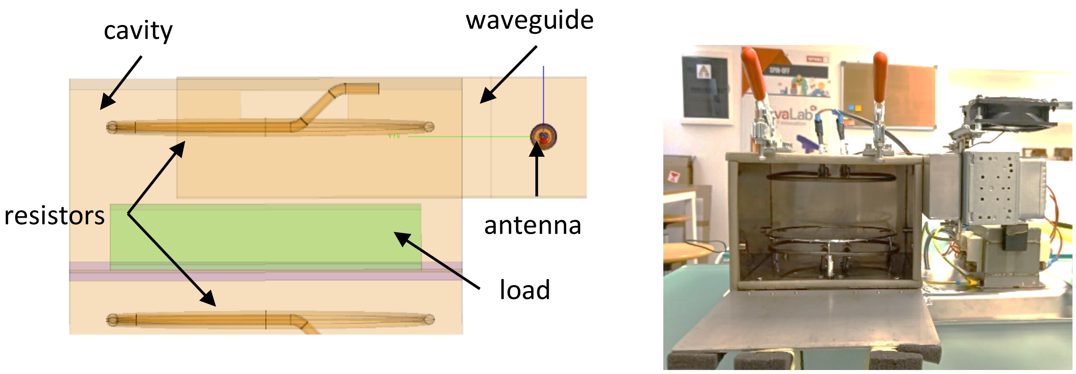
NUMERICAL MODEL AND EXPERIMENTAL TESTS

In order to fix the maximum feeding power (3kW: 1kW of MW at 2.45GHz, 1.5kW of IR resistors, 0.5 kW of handling systems) and optimize the size of the heating system (while also taking into consideration internal component design of the magnetron, transformer and capacitor), the different mechanical structures of the system were designed using numerical models based upon simulation studies, using FEKO).

The power transmission in the waveguide was maximized by using geometric optimizations. Then the system, including waveguide, cavity, IR resistors (top and bottom) and load were studied using parametric numerical simulations. Considering all the metal components inside the cavity, the goal was to maximize the power in the load and to verify that the power uniformity was good.

The sizing of the system was done using a large load from a ready-to-eat meal. Next, smaller loads were tested using sandwiches. The system will need to perform well with both types of foods, but sandwiches need a lower MW contribution because the heating time depends on IR, while ready-to-eat meals only need to be heated by MWs.

Based upon the numerical model, efficiency and the uniformity desired for the different food typologies, a first prototype was produced. Using this prototype we ran first, water efficiency tests and later food tests using ready-to-eat meals and sandwiches.



(a) (b)

Figure 1. Numerical model of the system (a) and first stand-alone prototype used for tests (b): external overall dimensions 282mm x 318mm x 175mm.

RESULTS

Efficiency tests on water were done with loads of different weight (300-1000g) and geometries (different shapes, different heights). The efficiency mean value is 75%. During tests on water, the best position for the load support was investigated and determined.

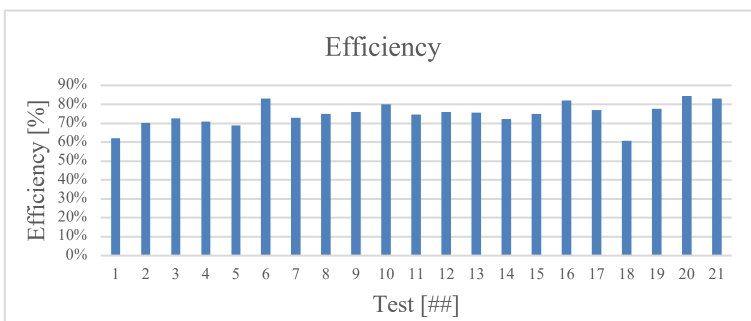


Figure 2. Efficiency tests on water in the first prototype.

Tests using ready-to-eat meals (different recipess) gave good results in terms of time (heating time ≤90s for 300g), uniformity and temperature (ΔT_mean=51°C). Tests using sandwiches (height≥50mm) gave good results in terms of time (≤50s), crispness and temperature (ΔT_mean=60°C). Because of the number of parameters analyzed (temperature, uniformity, flavor, crispness of bread, …) and personal preferences, different tasters were used and most foods received a good score (≥2.5).

DISCUSSION

Efficiency tests were performed using water to simplify the evaluation. Different loads were simulated in order to guarantee the correct operation of the cavity under different conditions.

Foods were heated using the vending machine cavity along with competitors' machines that are available on the market in order to compare results. The vending machine cavity heated in a shorter time, due to its smaller cavity size which allows for it to produce higher quality results.

CONCLUSION

This study allowed us to identify the most important geometrical parameters in the system design and the good modelling of the magnetron antenna and a small cavity. Experimental measurements confirmed numerical simulations and results were very close in terms of efficiency and quality.

Some improvements have been identified to get better performances, like replacing the magnetron with solid state generators: this modification allows a better control of the process and new algorithms can be developed especially for MWs.[1][2][3]

REFERENCES

[1] Microwave heating device and method for operating a microwave heating device, Inventors: F. Gambato, M. Bullo, C. De Massari, N. Lanza, F. Dughiero, A. Baccara, Publication Number 2019306937, Publication date 2019-10-03

[1] [2] Efficiency optimization of a two-port microwave oven: a robust automated procedure – Dughiero F., Bressan F., Bullo M., Di Barba, P. – COMPEL – Vol. 34, Issue 4, 6 July 2015, pp. 1213-1228.

[2] [3] Mechanistic understanding of plasma arcing in food processing – Chemical Engineering Science, Vol 195, pp. 141-158 - 2019