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WELCOME TO THE 59TH 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 consider joining onsite. IMPI membership connects you to microwave and RF academia, researchers, developers and practitioners across the globe. Talk to an IMPI member today to learn more about the value of joining our outstanding organization!

Thank you for joining us. We hope you learn from the technical presentations, interact with your colleagues, and enjoy the atmosphere of the Symposium. And do take the opportunity to visit the many interesting sites in and around Edmonton, Alberta, Canada.

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Does it Make Sense to Use Microwaves and RF when Creating Ceramic-Based Materials for High Temperature Applications?

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Keywords: Sintering, chemical vapor deposition, joining, slip casting, commercialization success

ABSTRACT

This potentially controversial presentation will attempt to shed light on why the use of microwaves and radio frequency (RF) processing have not really ‘taken off’ for the processing of technical ceramics, despite still being a fairly popular research field. The presentation will review many of the areas in which electromagnetic (EM) processing has been investigated over the years, including sintering (the most popular application), chemical vapour infiltration, joining, slip casting, binder burnout, powder synthesis and drying, and attempt to draw conclusions about when it has a better chance of success. This is believed to be when specific advantage can be taken of the intrinsic nature of EM energy, rather than using it simply as an alternative energy source. EM offers many advantages, not least high coupling efficiencies under the right conditions, ‘inside-out’ heating and the ability to put the energy exactly where it is needed. However, it also brings a number of disadvantages, not least potentially high equipment and energy costs, and by no means is every ceramic material ideally suited to its use. Thus, a great deal of thought and care must be used to identify suitable applications and innovative approaches devised. Thus, for example, from a commercialization viewpoint hybrid processing can often be a better approach than the use of pure EM energy. The audience will not necessarily agree with everything that is said, but it is hoped to stimulate thought and debate.

Essential Aspects of Commercialization of Microwave Heating Technology for Foods and Beverages

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Keywords: Food processing operations, beverages, process uniformity, temperature, food quality

ABSTRACT

Microwave and radio frequency (RF) heating are promising advanced food processing technologies that have been developing for more than 70 years. Their primary advantages lie in their ability of rapid and volumetric heating that is desirable for delivering premium foods with higher quality, nutritional and sensory attributes. Any energy and other savings in microwave-based food processing operations can have a large positive impact on food processing sustainability.

The well-known commercial applications include tempering frozen products, precooking in foodservice and cooking sausages. Other processing operations and aids include post- and pre-process drying, cooking, pre-heating, extraction, disinfestation, pasteurization and sterilization. These processes are applied to liquid foods and beverages, prepared and cooked solid pre-packaged meals, and low and intermediate moisture products, ingredients, seeds and nuts.

This presentation reviews the commercial applications of microwave heating in food processing, emphasizing research efforts needed for broader acceptance of this technology. Key research areas include enhancing process uniformity, streamlining process validation, improving temperature measurement and control systems, and improving packaging and microwave equipment through broader use of solid-state power sources instead of magnetrons. The effects of microwave treatment on quality and nutrients, such as moisture, protein, carbohydrate, and vitamin retention, as well as chemical reactions, need to be analyzed across different product categories.

Additionally, computer simulations are essential tools to address the challenges of uneven microwave heating by aiding process designs that account for interactions between food products, packaging, and cavity. Collaboration between food technologists, processors, and microwave technology providers is essential to fully utilize the recent advances and capabilities of microwaves and RF in various food processing operations.

The History of IMPI and Its Role in Applications of Microwave and RF Power

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Keywords: Microwave, radio frequency, power applications, microwave associations

INTRODUCTION

Microwave technologies, and electromagnetics in general, are considered to be within the domain of electrical engineering. The first known professional association of electrical engineers was founded in 1871 in the UK as the Society of Telegraph Engineers [1]. Other associations soon followed, including the American Institute of Electrical Engineers (AIEE) in 1884 and Institute of Radio Engineers (IRE) in 1912 [2]. Practical uses of microwave energy began in the 1940s with the availability of suitable microwave sources [3]. Interest in microwave engineering grew rapidly, and in 1952 the Institute of Radio Engineers (IRE) formed the Professional Group on Microwave Theory and Techniques, which through a merging of AIEE and IRE became what we know today as the Microwave Theory and Technology Society of the Institute of Electrical and Electronics Engineers (IEEE/MTT-S) [4].

FOUNDING AND EARLY YEARS

Availability of high-power microwave sources generated great interest in the development of industrial applications in the late 1940s [5]. While the principal forum for technical presentation of microwave applications was the IEEE/MTT-S, its heavy focus on microwave theory and techniques was not conducive to presentation to non-microwave application specialists [6]. This led to the Symposium on Microwave Power (Edmonton, Canada) in 1966 and formation of the International Microwave Power Institute (IMPI). IMPI has since organized the Microwave Power Symposium annually and published the Journal of Microwave Power quarterly. Shortly after its founding, IMPI became heavily engaged with government authorities on development of standards for hazards and safety, electromagnetic interference, and equipment performance. In response to the rapid growth of sales of microwave ovens and the development of microwaveable foods, packaging materials, and microwave cooking accessories, IMPI formed the Cooking Appliance Section (CAS) to serve its growing membership more effectively. Soon after forming the Cooking Appliance Section, the Industrial, Scientific, Medical and Instrumentation (ISMI) section was formed to provide similar support to members from industry and academia.

WORLDWIDE INTEREST IN MICROWAVE POWER

As its name implies, IMPI was founded as an international organization to serve microwave applications professionals throughout the world. In its first 15 years IMPI organized the Microwave Power Symposium in four different European countries. As the worldwide market for microwave ovens grew, IMPI was largely perceived to be focused more on consumer and commercial microwave cooking and related industries than scientific research and application development. This prompted the formation of the Association for Microwave Power in Europe for Research and Education (AMPERE), and the Microwave Working Group (MWG), the Japan Society of Electromagnetic Wave Application (JEMEA), and the China Association for Microwave Power Applications (CAMPA).

These organizations and their activities clearly indicated a growing worldwide interest in microwave applications. To bring the worldwide community together, representatives from these regional associations met in Brussels, Belgium in 2006 to form the Federation of Associations and coined the acronym MAJIC to represent its founding organizations MWG, AMPERE, JEMEA, IMPI and CAMPA. The five associations have hosted the Global Congress on Microwave Energy Applications (GCMEA) every four years. In 2024, the Association of Industrial Microwave Heating and High Frequency Applications (AIMHHA) was formed in India and has become a member of the Federation of Associations.

PRESENT AND FUTURE

As the global market for consumer and commercial microwave foods and appliances began to saturate, IMPI seized opportunities with advances in solid state RF technology and applications based on environmental sustainability. In 2019 IMPI formed the Solid State RF Energy (SSRFE), and most recently established a partnership with IEEE/MTT-S to promote applications in climate change, electrification and renewable energy. IMPI is well positioned to serve its membership by playing a leading role in microwave and RF power applications.

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Microwave Debinding of Ceramics Produced by Additive Manufacturing

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Keywords: Ceramics, debinding, additive manufacturing, modeling, simulation

INTRODUCTION

Microwave-assisted debinding offers an economical approach to processing 3D-printed engineering ceramics [1]. Ceramic parts produced with photopolymer-based additive manufacturing techniques require thermal debinding to remove polymers that bind ceramic particles during the printing process. Microwave-assisted debinding significantly reduces processing times and offers energy savings over conventional thermal treatments due to higher heating rates and more uniform heating. Finite-element modeling of the debinding process allows optimization and prediction of temperature distribution, stress development, and potential defects, leading to improved process control and material quality.

METHODOLOGY

Microwave processing enables volumetric heating by directly transferring microwave energy to the 3D printed part, leading to efficient and rapid binder removal. This occurs at the molecular level through friction between molecules, caused by dipolar rotation and the movement of conducting ions in an electric field. After debinding the green parts, sintering is required to densify the ceramic material, enhancing its mechanical strength and structural integrity. Conventional debinding and sintering processes use standard furnaces and thermal treatments, typically resulting in long operating times and high energy consumption. Canillas et al. [2] conducted a comparative study in which alumina printed parts were debound and sintered using microwave and/or conventional heating in an electric furnace. They found that both debinding methods achieved similar relative densities and that microwave debinding did not introduce additional defects compared to conventional thermal debinding. However, microwave processing reduced debinding time by 70%. Microwave sintering resulted in lower densification due to the lower achievable temperatures compared to conventional thermal sintering and therefore is not used in our research.

The microwave source used in our research is a high-power, large format microwave oven operating at 2.45 GHz with a maximum power of 2100 watts (Model BP-210, Microwave Research Associates, Carol Stream, IL). Microwave energy enters the process cavity through four mode stirrers—two positioned above and two below the cavity—to ensure

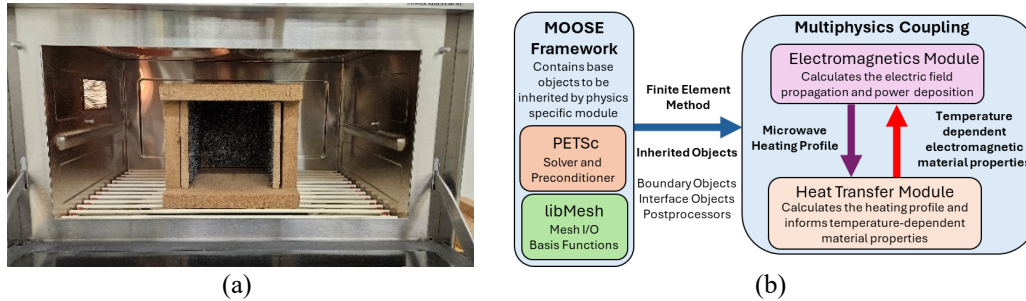


Figure 1. Microwave unit with SiC coated muffle (a) and structure of MOOSE application (b).

uniform heating. The standard low temperature floor has been replaced with a high temperature ceramic rod floor. Absorbent materials can be directly heated, while low loss (such as alumina) or reflective materials require a susceptor [3]. A susceptor, which is a microwave-absorbent material at room temperature, initiates heating until the sample's dielectric loss increases, allowing for direct microwave heating. Silicon carbide (SiC)-coated alumina/silicate composite muffles can be inserted within the internal cavity to provide hybrid heating of the samples (Figure 1a). Power can be controlled either manually or by a process controller. Regulating the incident power is crucial because uncontrollable heating rates can cause rapid decomposition of the photopolymer and produce a large volume of gas, potentially damaging the green ceramic body.

Idaho National Laboratory's Multiphysics Object-Oriented Simulation Environment (MOOSE) is an open source multiphysics framework based on the finite element method [4] that is employed to simulate debinding scenarios and offer insights to guide the optimization of microwave furnace parameters for improved process outcomes. Electromagnetic and heat transfer modules are internally coupled within MOOSE (Figure 1b), which can provide the electric field, power deposition, and material heat profiles [5]. The primary coupling mechanism between the two physics domains is the temperature dependent electromagnetic material properties, the conductivity and dielectric coefficients, in the two primary equations of:

$$\nabla \times (\nabla \times \vec{E}) = \mu_0(\omega^2 \epsilon_0 \epsilon_r - j\omega\sigma)\vec{E} \quad (1)$$

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-\kappa \nabla T) = \text{Re}(\sigma \vec{E} \cdot \vec{E}^*) \quad (2)$$

where $\vec{E}$ is the electric field, $\vec{E}^*$ is the complex conjugate, μ_0 is the permeability of free space, ϵ_0 is the permittivity of free space, ϵ_r is the relative material dielectric coefficient, ω is the angular drive frequency of the system, σ is the electrical conductivity, ρ is the sample density, C_p is the specific heat capacity, T is the sample temperature, and κ is the thermal conductivity. Equation 1 is the electromagnetic wave equation used with the assumption that the electric field propagation response occurs on time scales much faster than the temperature propagation of the sample. Equation 2 is the heat transfer equation, with the right-hand side term representing the power deposition into the sample by the microwaves. To represent the mode stirrers, a modified port boundary condition is employed.

On short time scales during the startup of the microwave system where the diffusion of the temperature in the material can be neglected, the temperature growth, power deposition, and magnitude of the electric field can be calculated directly by:

$$\frac{\rho C_p \partial T}{\partial t} = \frac{P}{V} = \omega \epsilon_0 \epsilon'' E_{RMS}^2 \quad (3)$$

where P is the power supplied by the microwave, V is the volume of the sample, ϵ'' is the complex component of the material dielectric coefficient, and E_{RMS} is the root mean square of the electric field. Assuming that the magnitude of the electric field is only determined by the power supplied by the microwave system, this calibration method provides a measure of the unique electric field magnitude per each microwave power setting of P . To account for inherent losses in the system, such as ohmic losses in the cavity walls and impedance mismatch, calorimetry measurements from inferred thermal readings of water are correlated to the applied power. These temperature measurements through inferred thermal readings, power measurements, and magnitudes of the electric field will assist in the validation of the model.

RESULTS AND DISCUSSION

Microwave debinding enhances ceramic manufacturing efficiency and quality, advancing high-performance component production for industrial applications. The MOOSE model under development predicts debinding behavior by considering interactions with temperature and electric fields, and accounts for the microscale evolution of the part over time when exposed to microwaves.

CONCLUSION

Microwave debinding produces ceramic parts faster and with significant energy savings compared to conventional thermal debinding, promising efficient production of customized components. Additionally, the development of an open-source modeling tool will benefit the microwave research community.

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Microwave-Assisted Gasification of Biomass and Plastics for H₂ Production: Plant-Wide Modeling and Techno-Economic Analysis

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Keywords: Gasification, process modelling, microwave reactor, TEA

INTRODUCTION

The demand for hydrogen is expected to rise sharply in the future, with an estimated consumption of 2.3 Gt/yr across sectors such as synthetic chemistry, transportation, power generation, and heating [1]. This increase in demand positions hydrogen as a key element in efforts to decarbonize energy-related industries, potentially reducing emissions from about 18% of these sectors and contributing to the global shift toward a fully renewable energy system [2]. At present, hydrogen is predominantly produced from fossil fuels, mainly through processes like steam reforming (76%) and coal gasification (22%) [3]. As energy demands continue to rise, coupled with growing concerns over climate change, resource depletion, and fluctuating fossil fuel prices, there is an urgent need to transition to more sustainable methods of hydrogen production. Biomass, municipal solid waste, and waste plastics are gaining attention as alternative feedstocks for producing hydrogen. However, the traditional process of gasification, which is widely used for these materials, has limitations, including the need for high operating temperatures and significant energy inputs.

A promising solution to these challenges comes from the emerging technology of microwave-assisted reactive systems. Unlike conventional methods for heating, microwave interacts directly with materials at a molecular level, causing them to heat up quickly through selective absorption. This process results in reduced energy consumption and potentially lower operational costs. Additionally, microwaves can minimize unwanted chemical side reactions due to selective heating, thus increasing the yield of the desired hydrogen products. In addition, microwave can have strong non-thermal effects, i.e., it can lead to higher hydrogen yield than a conventional gasifier operating under same

temperature and operating conditions. This study focuses on developing a detailed model of a microwave-assisted gasification process for hydrogen production from mixed feedstocks such as biomass and plastics.

METHODS

The model of a lab-scale microwave gasifier is developed. Feed flowrates to the lab-scale gasifier for each plastic component, biomass, and air are 0.043 g/min, 0.133 g/min, and 200 sccm, respectively. The model is validated with the data from an experimental setup at the National Energy Technology Laboratory in Morgantown. This lab-scale model is then scaled up to the commercial scale level that can produce 2,740 kg/h of H₂. The hydrogen production unit includes additional unit operations such as gasification, gas cleaning, sulfur removal, steam reforming, and hydrogen purification using pressure swing adsorption (PSA).

An economic model is developed and techno-economic analysis is undertaken. All reactors, flash vessels, compressors, blowers, heat exchangers are sized using Aspen Process Economic Analyzer. Equipment costs, including those for sulfur removal unit, steam reformer, high temperature and low temperature reactor, and PSA unit are estimated based on the data and cost correlations available in the literature. Operating and maintenance costs considered in the economic analysis includes raw material costs, utility costs, operating labor, and supervision, maintenance labor, operating supplies, laboratory charges, and general and administrative costs.

Capital and operating cost calculation of the microwave (MW)-assisted gasifier involves several steps. First, gasifier duty is calculated, second, number of magnetron (microwave generator) module is calculated, third, total magnetron cost is calculated, fourth, gasifier vessel cost is calculated, and finally MW-gasifier cost is calculated by adding magnetron cost and vessel cost. As the energetics from feed materials to the gasifier products are not known, an approach is developed by going through the paths for which the enthalpies are known. Such approaches are often adopted since enthalpy is state dependent and not path dependent.

RESULTS

The economic analysis highlights several advantages over conventional processes, including a reduction in capital expenditure and operating expenditure by 10-15%. The microwave-assisted process shows a 35% decrease in energy consumption and a 20% increase in net present value when compared to a gasification process that has the same hydrogen production rate and uses the same feed as the microwave-assisted gasifier, but does not use the microwave. Furthermore, sensitivity analyses are carried out to investigate how changes in feedstock costs (including processing, harvesting, transportation, and recycling), electricity prices, and carbon tax policies impact the overall economic performance of the process.

CONCLUSIONS

The study indicates that the MW-assisted gasification process is highly feasible if waste plastics and biomass are free of charge and transportation costs are negligible. Even when considering only transportation costs for biomass, the process remains viable. The study shows that plant capacity is an important decision variable for the economic viability of this process. The economic viability can be improved further by enhancing tar cracking and char gasification and improving product yield, especially by reducing methane yield.

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Microwave-Assisted Synthesis of Nanomaterials with Desired Properties

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Keywords: Microwave-assisted chemistry, nanomaterial synthesis, solid-state microwave source, closed-loop operation

INTRODUCTION

Microwave (MW) heating in chemistry is advantageous over conductive heating techniques not only because the temperature build-up is faster and more precise, but also because of the direct interaction of the electromagnetic field with the reacting molecules. This results in highly localized heating, leading to enhanced reaction rates and improved control over particle size, which is important for nanoparticle synthesis. Special MW reactors with precise temperature and power controls are required for reproducibility of nanoparticle's colloid. An experimental reactor was developed for a series of experiments on the study of the properties of different type of nanoparticles obtained with 5.8 GHz MW assistance [1, 2]. An example synthesis of mesoporous selenium nanoparticles (mSeNPs) under assistance of 5.8 GHz MW irradiation with different process settings was performed. The microwave-assisted method for the particle number concentration and size-controlled SeNPs synthesis using natural extract as a source of non-toxic reducing and stabilizing agents was also investigated.

METHODOLOGY

A crucial part of the dedicated reactor is the MW cavity, designed using 3D electromagnetic simulations with QuickWave-3D software [3]. The goal was to obtain maximally uniform vertical distribution of heating along the test tube's height. A block diagram of the reactor and a view of the numerical model of the cavity with resulting heating pattern is presented in Figure 1. The cavity is driven by a programmable 40-Watt 5.8 GHz CW GaN-based semiconductor source. An array of IR temperature sensors enables automatic temperature control by gradual changes of the output power. The field pattern inside the cavity can be adjusted with a help of the tunable electrical short connected to the output waveguide. An array of electric field sensors assist in its fine-tuning. Details are described in [1].

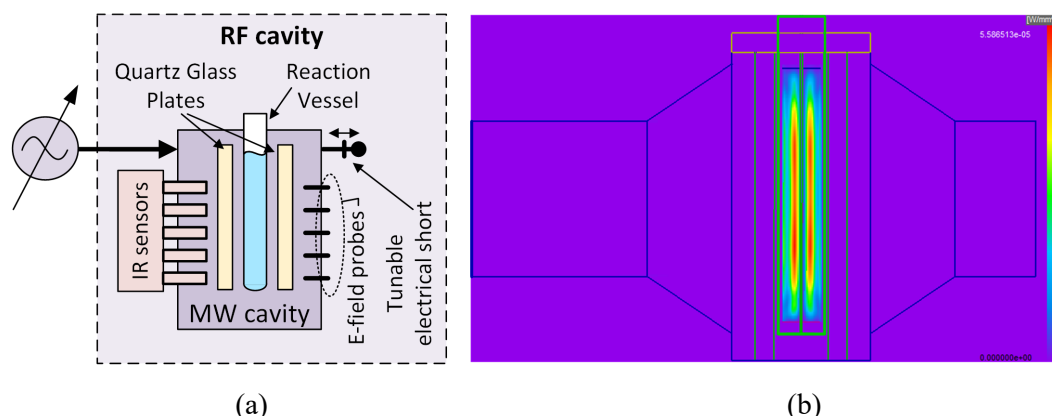


Figure 1. Block diagram of the reactor (a) and visualization of the MW cavity's simulation model with the resulting heating pattern in the center plane of the test tube (b).

Nanoparticles were synthesized using microwave-assisted approaches based on the one- and multiple- step reduction of selenite for non-porous and mesoporous SeNPs, respectively. In the synthesis of mSeNPs, ZnNPs were used as templates, ascorbic acid was the reductant, and cetyltrimethylammonium bromide (CTAB) acted as the dispersing and capping agent of the NPs. The synthesis was performed under MW heating at 5.8 GHz. Once the zinc template was removed, the resulting SeNPs feature a mesoporous structure. The entire protocol is thoroughly described in [2].

In case of the SeNPs synthesis, the selenite stock solution was obtained by dissolving selenium dioxide in water with an appropriate amount of NaOH. A specific amount of natural extract was placed in a glass tube and dissolved in a portion of water. The selenite stock solution was then added to achieve the desired Se precursor concentration in the reaction mixture. Finally, the tube was transferred to a microwave reactor. The formation of SeNPs was initially observed through visual inspection of the color change in the reaction mixture. After undergoing the microwave-assisted process, the reaction mixture turned red, signifying the formation of SeNPs. Characterization of nanoparticles was performed using single-particle inductively coupled plasma tandem mass spectrometry (SP-ICP-MS/MS) mainly. Their morphology was observed on SEM images.

SYNTHESIS RESULTS

It has been observed that the morphology of mSeNPs is modulated by controlling the temperature ramp parameters and the duration of microwave irradiation. At an early stage of synthesis, the formation is limited to nearly-spherical Se nuclei. However, an increased temperature ramp rate in the presence of CTAB micelles enhances the growth rate of particles, facilitating the development of nanorods and branched structures [2]. On the other hand, an increase in particle size accompanied by a decrease in particle number concentration of SeNPs was observed as the microwave temperature was elevated from 105 to 130°C during the 10-minute synthesis process. The higher temperature likely facilitated the continuous growth of the initially formed Se seeds, leading to the formation of SeNPs with a reduced particle number concentration. The accelerated nanoparticle

growth promotes rapid stabilization by natural extract compounds, which may contribute to minimizing the likelihood of agglomeration or aggregation.

DISCUSSION

A notable investigation examined the synthesis of mesoporous selenium nanoparticles (mSeNPs) under 5.8 GHz microwave irradiation. The findings indicated that this higher frequency (in comparison to classical 2.45 GHz) could enhance the nucleation and growth rates of mSeNPs, leading to improved control over particle size and porosity. This enhancement is attributed to the more efficient interaction between the microwave field and the precursor materials at 5.8 GHz, resulting in accelerated reaction kinetics and superior material properties.

The occurrence of the microwave effect was confirmed, characterized by the stimulation of molecular alignment, which enhances reaction efficiency, accelerates the process, and influences the size distribution of the resulting nanoparticles. Overall, by adjusting parameters such as MW frequency, reaction time, heating rates, solvent composition, and stabilizer concentration, MW-assisted synthesis provides a high degree of control over nanoparticle formation. This precision makes it a highly advantageous approach for fabricating nanomaterials with tailored characteristics, ensuring their applicability in diverse fields.

Despite enhanced heating efficiency, microwave irradiation can additionally offer non-thermal effects. In this synthesis, the formation of 1D and multibranched nanostructures is accelerated by so called lighting rod effect, due to the microwave-metallic nanoparticles interaction. Also, the localized microwave heating at the microscopic level is revealed as configurational temperature effect that improves the kinetics of the formation of seed particles.

CONCLUSION

Compared to 2.45 GHz method, the proposed method facilitates the production of nanoparticles that exhibit varying morphologies and size distributions, thereby demonstrating their potential application as a nanopesticide. This can be attributed to maintaining a stable reaction temperature and construction of the cavity optimized for the field uniformity. The influence of frequency itself is a topic of further research.

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Advanced Intermittent Microwave Convective Drying (IMCD) Method to Improve Energy Efficiency and Food Quality

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Keywords: Multiphysics simulation, three-dimensional modeling, bioactive compounds, moisture redistribution, power ratio (PR), tempering effect

ABSTRACT

Drying is one of the major processes in the food industry as it adds value to a product, reduces transportation and storage costs, increases its shelf life and reduces waste in the food chain. However, the traditional drying process is time-consuming and energy-intensive, and often leads to considerable quality deterioration. Intermittent application of microwave (MW) energy in hot air drying, can significantly reduce the drying time, enhance energy efficiency and attain better product quality. Microwave interacts with water molecules inside the food and heats up the samples volumetrically, thus increasing the moisture diffusion rate and significantly reducing the drying time and improving energy efficiency. We have established that about 80% of drying time can be reduced through the application MW in food drying. However, continuous application MW often deteriorates the product quality due to the uneven temperature distribution which creates hot and cold spots. Application of MW energy intermittently with convective drying can overcome this problem. Due to the unique advantages of intermittent microwave convective drying (IMCD), research in this field is gaining more attention. Dr. Karim's research group at Queensland University of Technology recently developed an advanced theoretical IMCD model based on multiphase transport during drying. This seminar will present details of the findings. Although the IMCD research has advanced significantly, a fundamental understanding of the transport process during IMCD has not been fully uncovered yet. Food materials have heterogeneous cellular structure, where multiscale transport (micro or macroscale) takes place during drying. Therefore, the micro level IMCD process needs to be well understood and eventually a multiscale IMCD model needs to be developed. A clear understanding of these transport mechanisms in IMCD will lead to the development of a drying process that improves food quality, energy efficiency, and optimization of the IMCD process. This invited talk will highlight the current status and future direction of this advanced research.

Microwave Baking of Biscuits; Towards the Next Generation of Biscuits with the ABCD Project

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Keywords: Biscuits, baking, microwave, volume, water content

INTRODUCTION

Biscuit baking is among the most energy demanding baking process. The ABCD project (Alternative Baking of Dry Cereal products – French ANR National funding) aims at exploring alternative baking strategies using microwave (MW) combined with a post baking infrared process to ensure optimal biscuit coloration. During baking, starch undergoes partial gelatinization, while protein denaturation remains negligible. During the first minutes, baking soda aids dough expansion. Sodium bicarbonate and ammonium bicarbonate are the most commonly used leavening agents, with their addition extending thermal degradation from ca. 30°C to 80°C. The major energy demand in biscuit baking is due to water loss, with a final water content expected to be below 4%. Ahmad et al. [1] used MW to mitigate biscuits checking, which was presented at IMPI52 in 2018 [2]. AL-Ansi et al. [3] studied MW baking of biscuits at 700 W for 90 s but did not specify the biscuit mass. Dong et al. [4] studied MW baking of biscuits, but did not include precise information about the specific energy used (baking time 2 - 3 min). Further work is thus needed to better optimize MW baking of biscuits.

METHODOLOGY

A MW cavity (based on a modified domestic microwave) connected to a solid-state MW emitter was used (SAIREM GMS 200-2450 MHz) with a ceramic resonator. The recipe used for preparing the dough is presented in Table 1. After 10 min. of mixing, the biscuit dough was laminated to reach a 3 mm thickness. The biscuits had a circular shape with a

Table 1: The recipe of the biscuit dough based on mass of 100 g of flour

Ingredient	Mass for 100g flour
Biscuit flour	100
Water	20.77
Sugar (sucrose)	31.85
Glucose syrup	2.23
Butter (16% water)	5.53
Salt	0.94
Ammonium Bicarbonate	1
Sodium Bicarbonate	0.64
Sodium Pyrophosphate	0.4

Table 2 : Selected power & baking times, specific power (SP) and specific energy (SE)

Power (W)	Time (min)	SP (W/gDB)	SE (kJ/gDB)
20	5	20	2.4
20	10	20	4.8
20	15	20	7.3
30	5	30	3.6
30	8	30	5.8
30	11	30	8.0

diameter of 3 cm and an average mass of 3.3 g; they were baked individually. Preliminary tests done with larger diameter (6 cm) showed a high risk of over-run. The temperature of the biscuits was recorded with optical fibers. The power was adjusted to different levels as shown in Table 2. The conventional baking was obtained in around 9 min. Attempts done to reduce this baking time in the case of MW yielded in over-run and non-acceptable biscuit expansion and final structure (uneven thickness and color). The specific power (emitted power in W / dry mater of biscuits in g) and the specific energy (emitted microwave power x time of baking / dry matter of biscuits in g) were considered as indicative values of the baking energy. The end of baking was fixed from the time at which the biscuit temperature reached around 130°C.

COMPUTATION OF THE BAKING ENERGY

The energy needed for baking concerns the specific heat needed to heat up the dough to the final baking temperature and the energy associated to water loss, which is divided in two parts; the evaporation energy of the free water of the dough (energy = mass of the free water x latent heat of vaporization L in J/kg water) and the desorption energy of the bound water (mass of the bound water x isosteric heat of desorption ΔH_{IS} in J/kg water). A calorimetry measurement allowed the determination of the amount of free water based on the energy measured during thawing of a frozen biscuit dough. The initial biscuit dough temperature was fixed at 30°C and the final biscuit temperature was fixed to 130°C. The final water content of the biscuit was fixed at 4%_{DM} in dry basis (%_{DB}) (usual value in industry). Based on our computation, the specific energy needed for baking is expected to be in the range of 1.15 kJ/g_{DOUGH DB} (0.87 kJ/g_{DOUGH}) with $\frac{1}{4}$ and $\frac{3}{4}$ of the energy being linked to the specific energy and water loss respectively.

RESULTS

Time temperature plots obtained during biscuits baking are presented in Figure 1. Two baking phases are evident: a rapid rise until 100°C-110°C, matching the boiling point of the sucrose syrup in the dough, followed by a more gradual temperature rise during the desorption phase. Figure 1 also shows a MW baked biscuit with optimal conditions in the range of 30-20 watts with ca. 10 min. baking.

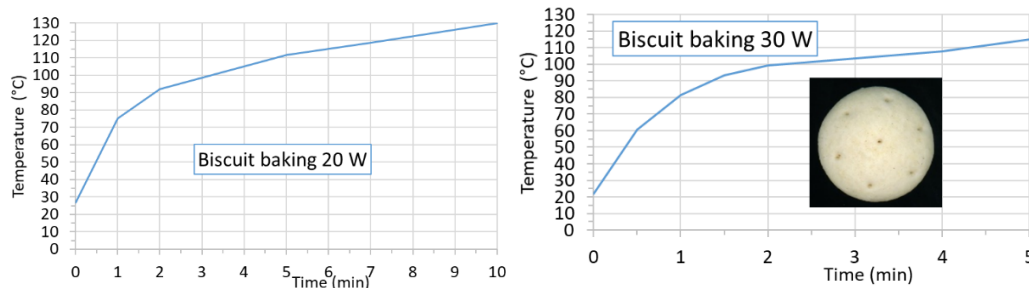


Figure 1. Time-temperature plots during biscuits baking using selected specific power and times. The picture shows an example of a 10 min - 30 W baked biscuit. All biscuits were white.

DISCUSSION

The specific energy observed during our baking tests with MW was in the range of 2.5 to 8 kJ/kg DOUGH DB as shown in Table 1, whereas the theoretical baking energy was in the range of 1.15 kJ/kg DOUGH DB. The difference may be due to the reflected energy and to some difference between the power of the solid-state generator and the power effectively emitted by the generator. The best conditions in terms of water loss, volume and uniformity of the biscuit's structure were 20 W with long baking time in the range of 10 min. or more.

CONCLUSION

Based on our results, baking biscuits by MW appears feasible. The baking energy for bread is in the range of 3 to 5 MJ/kg using conventional baking processes and it is expected to be even more for biscuits in which the water is fully removed. The estimated energy demand for biscuit baking (without coloring the surface) was 1.15 kJ/g DOUGH DB. Experimental baking energy is 3 to 7 times the theoretical energy; however, this result does not account for reflected energy and was obtained with a small amount of biscuit dough. Further tests with a continuous MW oven will be presented.

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Microwave Baking of Food Foams Under Selected Gas Pressure

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Keywords: Microwave, sponge cake, gas pressure, starch

INTRODUCTION

Snacking is an increasingly coveted mode of consumption, but which often has a negative image in terms of diet. The process used in this work enables the transformation of almost any type of food into a compact food, having the texture and appearance of sponge cake. Its principle was based on the emulsion and then expansion of a paste under the pressure of a gas, followed by coagulation in the microwave. This process has the advantage of being fast and inexpensive in energy compared to the traditional preparation method.

The objective of this research was to understand the phenomena which govern the transformations of raw materials during the different stages of manufacture: formulation, cooking, cooling and storage, from a vegetable sponge cake recipe. The goal is to gain in-depth knowledge of the material's texturing, enabling process optimization and development of a micronutrient-enriched sponge cake tailored for athletes or the elderly.

METHODOLOGY

The method of manufacturing sponge cakes and the associated experimental device are detailed by the various patents held by NBread Process, which describe a process in which an emulsion is pressurized under gas, followed by mechanical expansion through a pressure shock (Figure 1). The expanded foam is then quickly solidified by thermal coagulation.

The batter was propagated in a cylindrical stainless steel tank with a 2.5 L capacity, using a mixing paddle. The tank was equipped with a gas inlet connected to a pressure gauge at the inlet, and a double jacket to ensure that a constant temperature was maintained over time. Injection into the mold, described by patent [2], was carried out by a valve nozzle, topped with a preparation chamber with a volume fixed by the movement of a piston. The passage of a volume of foam into the preparation chamber was done via a ball valve.

Sponge cakes were baked in two different ways: in a microwave or in a conventional oven. The microwave used was the MenuMaster DEC14E2EL model, with a capacity of 17 liters

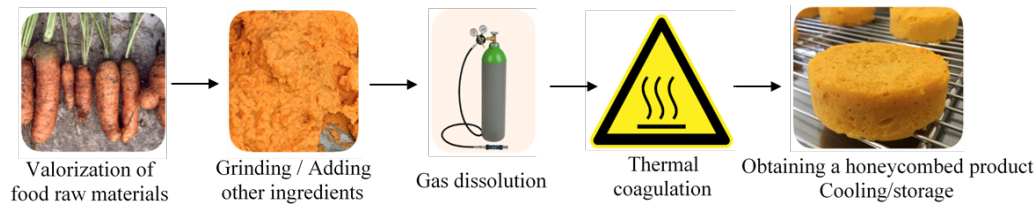


Figure 1: Diagram showing the steps of the NBread®, process, described by patent [1].

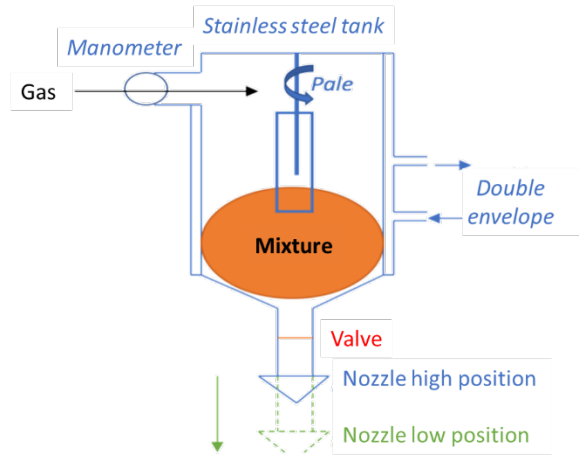


Figure 2: Simplified diagram of the dough mixing and injection device

and a power of 1400 watts according to the manufacturer. The oven was a Moulinex OX286810 with a power of 2200 watts and a capacity of 39 liters. The actual power of the Menumaster microwave was measured using the water heating method and was found to be 950 watts.

RESULTS AND DISCUSSION

The batters underwent two different cooking methods: the microwave oven inspired by the NBread process, and the conventional oven. The sponge cakes obtained were characterized after cooling. The results showed that the two cooking processes differed in terms of the overall water loss of the sponge cake, the homogeneity of cooking (water distribution and gelatinization rate between the center and the surface), and the expansion of CO_2 during cooking. The variations in the two manufacturing stages resulted in sponge cakes with different volumes, densities, porosity, colors, texture, and visual aspects of the crumb and surface. A statistical analysis highlighted the relationships between certain production parameters and the properties of the sponge cakes. The mixing stage was the most impactful factor on the density of the sponge cakes, their porosity, cohesion, and firmness. It also consequently influenced the visual appearance of the crumbs. The cooking stage was the most impactful factor on sponge cake moisture, the dough-to-crumb transition, and color. Controlling these parameters was an important factor in managing sponge cake quality. Further optimization could be achieved by integrating new gas injection parameters (pressure, gas type), or baking parameters (baking time, mixed baking mode).

This work also involved monitoring the aging of the sponge cakes during storage. The major parameters of product aging were measured during storage at 4°C. For both baking methods, the drying of the sponge cake (as a whole, in the crumb, and in the crust), the restructuring of amylopectin, and the firming of the texture were observed. Compared to the traditional process, sponge cakes made with the NBread® process had higher values for these criteria; which was a point of vigilance to maintain product quality during storage.

CONCLUSION

This study identified the strengths and weaknesses of the new process studied for the production of healthy snacks. The CO₂ injection mixing process, combined with rapid microwave cooking, produces sponge cakes with high alveolar content and low density. To further develop healthy products, or even products with health benefits, it would be interesting to study the impact of microwave cooking on the preservation of the nutritional properties of the initial raw materials compared to traditional cooking. In particular, the modification of protein functionality, starch digestibility, and the antioxidant effect of carrot carotene by microwaves could positively or negatively impact this objective.

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Greetings from IEEE MTT-S: A Society with Seven Decades of History and Rejuvenated Interest in Collaborations with IMPI

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Keywords: Microwaves, microwave heating, collaboration, synergy

ABSTRACT

From its inception in 1952, the IEEE Microwave Theory and Technology Society (MTT-S) has conducted a broad range of microwave-related technical activities (recently renamed from “microwave” to “MHz-to-THz”), grown its membership (13,000+ in 2024), and collaborated with other professional groups, as excellently reviewed in [1]. In particular, since the foundation of IMPI in 1966, MTT and IMPI shared interests in the public concerns about microwave safety and worked on this issue for about 20 years, contributing to the relevant standards and organizing joint events, e.g. at IMS 1978 and 1984 [2]. Then, their collaboration was frozen for about 25 years, until the workshops at IMS 2009 [3] and IMS 2023 demonstrated a significant overlap of new technical interests, which include computer modeling of field-matter interactions [4], material measurements, and solid-state power sources. Since 2024, a dedicated sub-committee invites IMPI-relevant contributions to IMS conferences. In January 2025, an MoU was signed between MTT and IMPI. This session aims to identify the most efficient and effective ways to implement the MoU for the benefit of the two societies.

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Microwaves in Climate Change

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Keywords: Climate change, microwave remote sensing, microwave environmental applications, microwave radiometry, microwave radar, microwave power beaming, microwave heating, microwaves in fusion

ABSTRACT

Climate change is arguably the single most important global challenge of the 21st century. Energy consumption is rising rapidly, especially in developing countries, and the continued use of fossil fuels is bringing the world closer and closer to the brink of an irreversible climate catastrophe attributed to greenhouse gas production and its role in induced global temperature rise. There has never been a time when global resource and climate monitoring were more necessary, and when every direct or indirect method for reducing fossil fuel dependence and/or the release of additional greenhouse gases was essential. This talk presents a broad look at some of the microwave techniques that have traditionally played a major role in the field of resource management and in activities related to documenting and understanding climate change or mitigating its impacts [1]. While acknowledging the importance of microwave communications and tracking in space-based and ground-based wireless technologies and transportation management, the focus shifts to the techniques and data that these systems use and provide. Some of the more unusual applications and ideas that are being enabled by both current and future microwave component and systems advances will be surveyed, including the impacts that they might have on processes that can assist in mitigating climate change. This talk intends to provide the listener with links and references to microwave technologies related to climate science and to encourage more researchers to seek out and collaborate on ideas and proposals that directly or indirectly bridge these often disparate areas of development. The overview is broken up into topics that highlight particular characteristics and general applications of microwaves: sensing, heating, power generation, power beaming, and propagation.

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MHz to THz: Emerging Systems, Applications and Networks

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Keywords: Microwave systems, microwave heating, terrestrial communications, 5G/6G networks, non-terrestrial networks (NTN), power amplifiers, phased arrays

ABSTRACT

MHz to THz frequency systems encompass a diverse array of emerging applications such as efficient industrial radio frequency (RF) heating, future 5G/6G Non-Terrestrial Networks (NTN), medical imaging, autonomous vehicles. Emergence of highly integrated monolithic microwave semiconductor technologies, high-efficiency power amplifiers (PA's) with advanced packaging and effective heat removal, have been critical to many of the emerging MHz to THz applications. Magnetrons have been the traditional high-power sources for RF heating in microwave ovens and for Industrial heating processes. The application of high-efficiency GaN power amplifiers with 60-80% power-added efficiency (PAE) is emerging in Industrial RF heating systems used for microwaves industrial applications, and for environmentally friendly waste management systems [1]. The last few decades have witnessed the emergence of multiple generations of terrestrial and space-based communications networks with future application extending to mm-waves and THz [2]. Non-Terrestrial (NTN) Networks using communication satellite systems are being deployed. Commercially deployed Geostationary (GEO) space-based network platforms, Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) currently offer global and regional fixed and mobile connectivity. Convergence between space-based and terrestrial networks with flexible, on-demand data transfers between satellite and terrestrial network nodes is a rapidly emerging trend in telecom networks. This talk will focus on the system drivers, key underlying MHz to THz technologies, flexible frequency/power allocations and frequency-reuse system applications.

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Design and Realization of a Solid-State RF System for Fluidized Bed Heating Experimentation

Pablo Santón and Klaus Werner

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Keywords: Radio frequency, resonant circuit, green hydrogen, induction heating, solid-state energy

INTRODUCTION

Within the industrial, scientific, medical (ISM) bands, radio frequency (RF) heating can offer benefits like deeper penetration, better uniformity, and higher selectivity than microwave heating [1],[2]. The work shown here details the design process of a 27.12 MHz applicator for a bench-scale fluidized bed heating process based on an RLC resonant circuit where the sample is placed inside a coil structure. The process comprises the theoretical study, the dielectric properties analysis, computer-aided electromagnetic simulations, preliminary tests, and optimization. The result is a compact, low-temperature (up to 300° C), lab-ready system for fluidized bed heating experiments powered by a 1.5kW RF generator.

METHODS AND MATERIALS

First, a theoretical analysis defined the operational requirements, including frequency of choice, power levels, and efficiency targets, supported by analytical models [3] to optimize impedance matching and energy transfer. The material used for the fluidized bed (a carbon-based powder) was characterized electromagnetically as a function of frequency and temperature using a novel system [4] developed by the Institute of Information and Communication Technologies (ITACA) of the Polytechnic University of Valencia, Spain.

The applicator was modeled using the Ansys HFSS (high-frequency structure simulator), which has coil height, pitch, and diameter as tuning driving parameters. The fluidized bed was made within a 2 mm thick, 25 mm outer diameter, and 250 mm height quartz tube. Prototype testing and fine-tuning with a VNA were then conducted to validate impedance matching and performance, with iterative adjustments ensuring minimal reflection and maximum power transfer.

Finally, the optimized applicator was constructed and integrated (see Figure 1 (a)) with the MPG1k5HF (pinkRF, Netherlands) RF generator. High power tests ensured compatibility and reliable operation for clean hydrogen production experimentation.

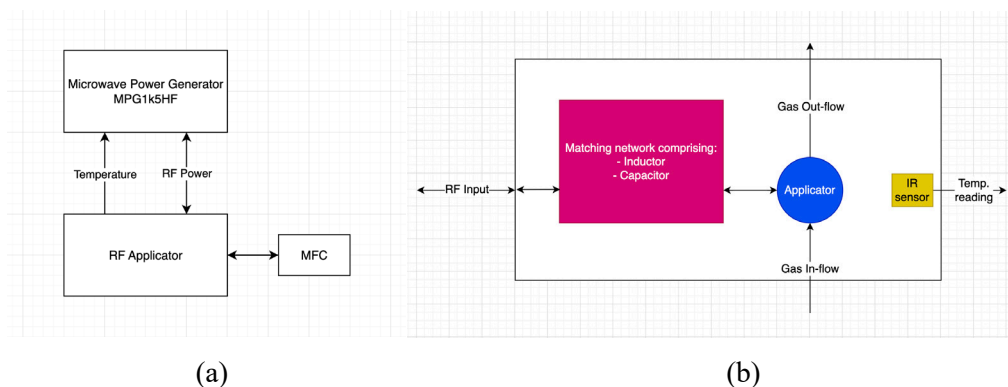


Figure 1. (a) Complete system and (b) applicator details schematics.

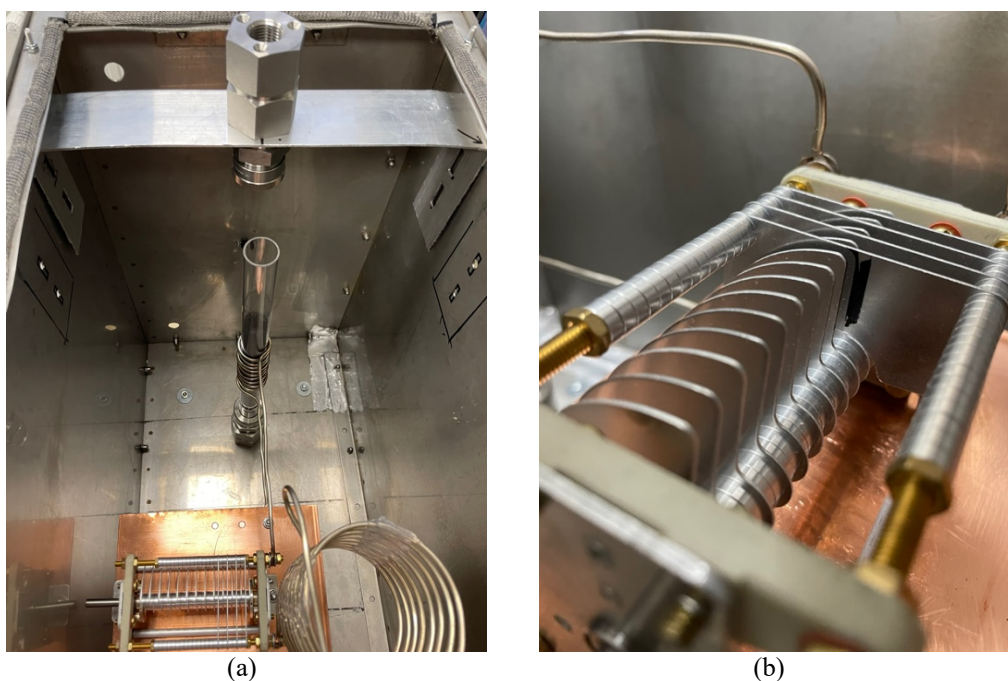


Figure 2. (a) Top view of the applicator's inside and (b) capacitor detailed view.

The fluidization was done with air and an EL-FLOW Select (Bronkhorst High-Tech, Netherlands) mass flow controller (MFC) operated from an external computer, while the temperature readings were done by the integrated MLX90641 (Melexis, Belgium) infrared sensor (see Figure 1 (b)).

RESULTS

The applicator was implemented in a 0.1 m³ stainless-steel box. The inner components are shown in Figure 2, with a detail of the most critical component, the tunable capacitor, which was modified to operate at the mentioned power level properly.

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Within the industrial, scientific, medical (ISM) bands, radio frequency (RF) heating can offer benefits like deeper penetration, better uniformity, and higher selectivity than microwave heating [1],[2]. The work shown here details the design process of a 27.12 MHz applicator for a bench-scale fluidized bed heating process based on an RLC resonant circuit where the sample is placed inside a coil structure. The process comprises the theoretical study, the dielectric properties analysis, computer-aided electromagnetic simulations, preliminary tests, and optimization. The result is a compact, low-temperature (up to 300° C), lab-ready system for fluidized bed heating experiments powered by a 1.5kW RF generator.

METHODS AND MATERIALS

First, a theoretical analysis defined the operational requirements, including frequency of choice, power levels, and efficiency targets, supported by analytical models [3] to optimize impedance matching and energy transfer. The material used for the fluidized bed (a carbon-based powder) was characterized electromagnetically as a function of frequency and temperature using a novel system [4] developed by the Institute of Information and Communication Technologies (ITACA) of the Polytechnic University of Valencia, Spain.

The applicator was modeled using the Ansys HFSS (high-frequency structure simulator), which has coil height, pitch, and diameter as tuning driving parameters. The fluidized bed was made within a 2 mm thick, 25 mm outer diameter, and 250 mm height quartz tube. Prototype testing and fine-tuning with a VNA were then conducted to validate impedance matching and performance, with iterative adjustments ensuring minimal reflection and maximum power transfer.

Finally, the optimized applicator was constructed and integrated (see Figure 1 (a)) with the MPG1k5HF (pinkRF, Netherlands) RF generator. High power tests ensured compatibility and reliable operation for clean hydrogen production experimentation.

Pushing the Limits: High-Power GaN Transistors Surpass 80% Efficiency

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Keywords: RF power, solid state, GaN HEMT

INTRODUCTION

For a long time it was deemed impossible to achieve efficiencies beyond 70% at S-Band frequencies using Solid state high power transistors, but with the introduction of GaN, we were able to solve this previously deemed impossible challenge in solid state radio frequency (RF) power. Further advancements and optimization in GaN device technology have now pushed efficiency even beyond 80%. This article reviews recent progress in GaN-based devices and provides an outlook on their future as an RF power source.

METHODOLOGY

GaN high-power transistors have been utilized in industrial, scientific, and medical (ISM) applications for the past decade; however, they traditionally lacked an internal (pre-) matching network at the output (drain) side due to inherent high losses and thermal challenges. Consequently, these devices exhibited low output impedances, making GaN-based RF power amplifiers highly sensitive to production spread. Additionally, the low impedance led to increased output bondwire currents, elevating their temperature and consequently increasing conduction losses.

A newly patented internal matching circuit integrated within high-power GaN transistor packages enables the generation of over 500 W at 2.45 GHz with an efficiency of 80%. This advancement is achieved by optimizing the transistor impedance while reducing internal electromagnetic coupling, thereby minimizing internal losses within the package. Additionally, the improved matching circuit enhances PCB design by reducing sensitivity to production spread and decreasing overall size. As a result, system-level efficiency exceeds 75%, further improving overall application performance.

RESULTS

The achieved load pull results are depicted in Figure 2a. The nose plot shows the achieved P3dB Efficiency and Gain at the load states measured, this shows the Drain efficiency exceeds 80% over a wide range of load states which vary in 3dB compression power between 200 and 400W.

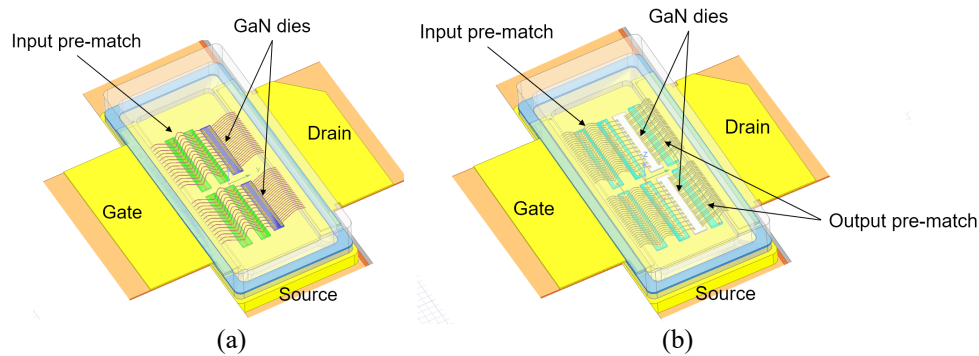


Figure 1. 3D image inside the package of an RF GaN transistor: Device without output pre-match (a) and a device with output pre-match (b)

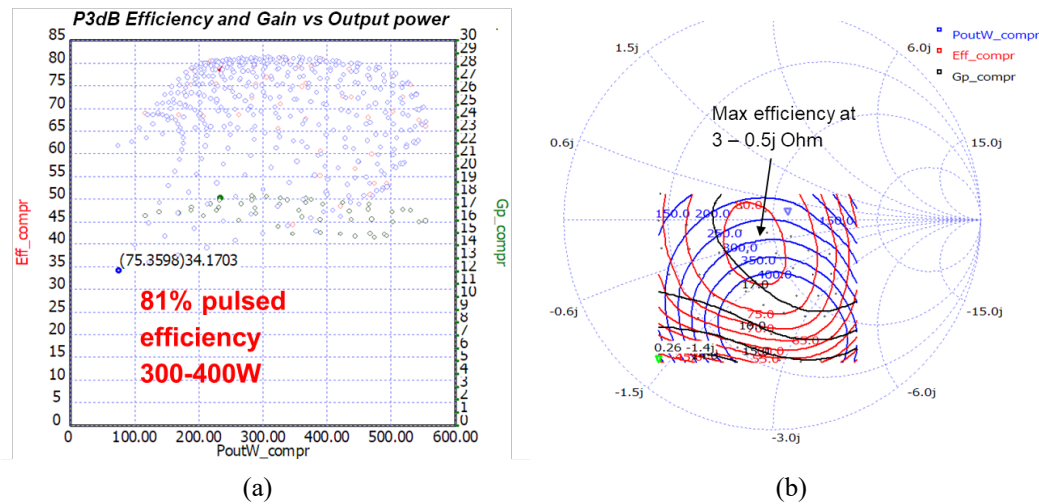


Figure 2. Nose plot of P3dB Efficiency and Gain vs output power for various load points measured during load pull (a) and plotted load contours of the same loadpull measurement session

The contour plot in Figure 2b. shows the sweet spot in efficiency at a very reasonable load impedance of $3 - 0.5j$, which is more than 3 times higher than what is achieved when we did not apply any output match. These lower impedances caused a higher output loss and resulted in a 6% drop in efficiency.

CONCLUSION

The long-promised efficiency benefits of GaN technology for RF power are now materializing, particularly in high-power devices, which are showing significant improvement due to advancements in device technology, internal matching, and harmonic terminations. Continued improvements are expected in future generations, positioning GaN RF power technology as the mainstream solution for high-power microwave amplifiers and generators.

Performance Study of a Solid-State Microwave Remote Plasma Source

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Keywords: Remote plasma source, solid-state microwave generator

INTRODUCTION

Microwave (MW) remote plasma sources (RPS) are used in various types of applications such as chemical vapor deposition, cleaning of plasma deposition chambers, photoresist or molding compound removal, waste gas cleaning, etc. Up to now, RPS are mostly based on magnetron-based MW generators. However, as solid-state technology is becoming more reliable, solid-state generators (SSG) can be utilized for RPS. The advantages of the solid-state technology can be thus transferred to the RPS, enabling the development of highly flexible and compact systems with extended life-time and reduced maintenance and downtime issues compared to magnetron-based technology. This work presents the integration of SSG into RPS system and investigation of physical parameters obtained for plasma generated with the RPS.

METHODOLOGY

A RPS based on 2.45 GHz solid-state generators feeding microwave (TEM mode, coaxial structures) into a plasma applicator is developed. The plasma applicator consists of a ceramic tube inside a metallic body forming a resonant structure. The SSG flexibility eases the plasma ignition and maximizes the power going into the plasma. Properties of several plasma generated by the RPS are investigated by means of optical emission spectroscopy (OES). Additionally, plasma ignition time and etching rate are studied. The tests are repeated with a magnetron based RPS (previous generation of plasma applicator) and the results are compared. Figure 1 shows a sketch of the measurement setup.

PRELIMINARY RESULTS

Figure 2 shows preliminary results for the evaluated plasma gas temperatures for both plasma sources as a function of power. The temperatures have been evaluated using the free software “massive OES” [1] which allows batch processing of spectra. For the evaluation, the C-B band system of molecular nitrogen in the range of 300-380 nm was

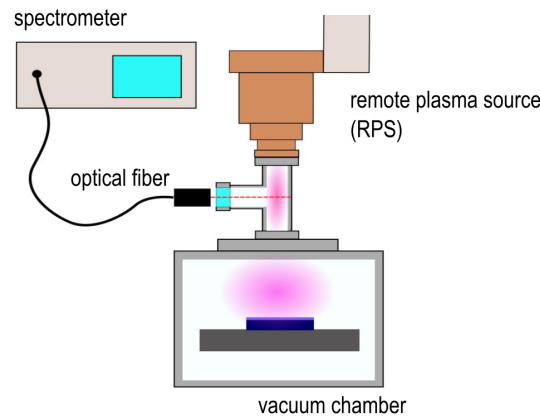


Figure 1. Sketch of the measurement setup used for OES, etching rate and ignition time studies. The RPS is mounted on a T-shaped vacuum component enabling OES. This component is fixed on a process chamber where to be etched substrates are lying on a plate.

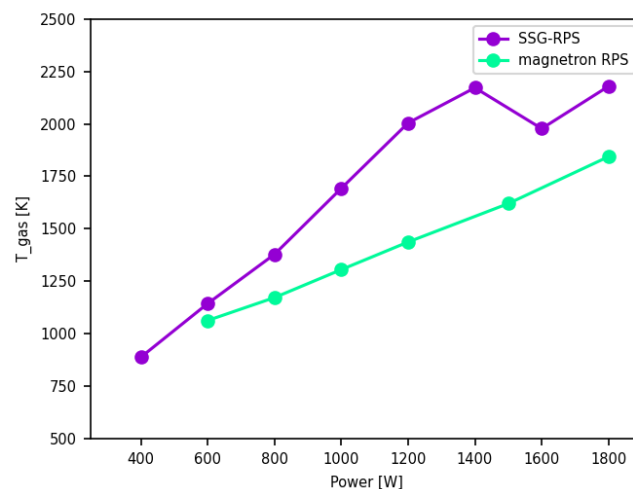


Figure 2. Evaluated plasma gas temperatures from optical emission spectroscopy for an air plasma. Displayed are the rotational temperatures of the molecules, which are comparable to the plasma gas temperatures.

used. In the investigated power region, the plasma gas temperatures for the SSG based RPS are higher than for the magnetron-based one.

Figure 3 shows the measured electron densities in the plasma. These values were obtained by comparing the spectral density of two nitrogen lines in the measured spectra, as described in [2]. Analogous to the plasma gas temperatures, the electron densities are higher for the plasma source using the SSG technology for all measured points inside the investigated power region. Note that those results are used to compare the two generations of plasma source (MW generators + plasma applicators), and not the solid-state and the magnetron technologies on themselves.

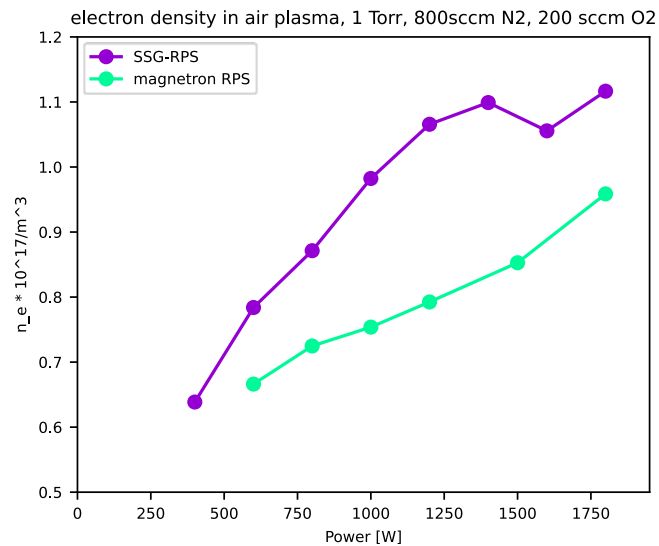


Figure 3. Measured electron densities in an air plasma. The values have been obtained by comparing the spectral line intensity of two nitrogen lines [2].

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Solid-State Generator Array for Dynamic Plasma Shaping

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Keywords: Solid-state, array, reactor, plasma, software

INTRODUCTION

Microwave (MW) driven plasma reactors are well-known tools that exploit the reactive behavior of high-energy charged particles for many applications, typically related to production or processing of high-tech materials and components. Most of these applications require high accuracy, high repeatability and guaranteed safety of operation, possible through a careful combination of engineering skills and understanding of the physics behind each application. This technology, still dominated by the use of magnetron-based MW generators, is currently experiencing a significant technological boost thanks to the progressive availability of reliable solid-state MW generators [1], allowing higher compactness, maximum flexibility of operation and extended life cycles with extremely low maintenance and downtime.

METHODOLOGY

An experimental MW array source composed of four 1kW 2450MHz solid-state generators [2], arranged in two 2kW combined pairs, was developed to drive an existing closed-chamber plasma reactor, previously powered by two 2kW magnetron sources. The aim of the experimental development was the assessment of the parametric controllability of the MW array and to check the capability of flexible dynamic shaping of the plasma volume. The developed experimental kit included a software platform allowing incoherent dual-frequency radiation or frequency-synchronized emission with fine relative phase shifting between the two generator pairs, in either case with operating frequency in the range 2400-2500MHz. Both CW and pulsed operation were possible, by software settings. Feedback from the system was generated by real-time measurement of RF and DC parameters of the array and by cameras pointing into the reactor showing the visible radiation from the generated plasma.

The main technological focus of the experimental development was to check the capability of the system to dynamically modulate the plasma intensity and shape, while minimizing overall power consumption.

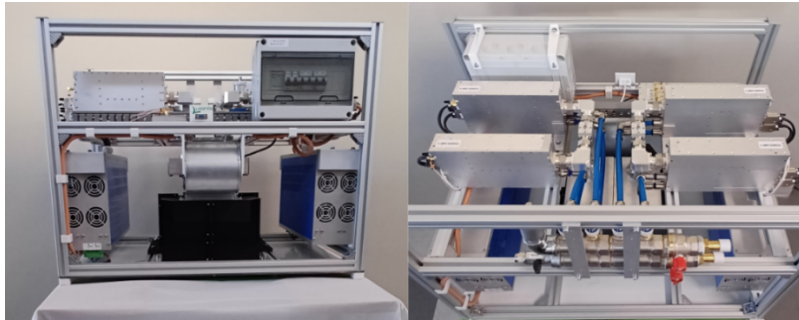


Figure 1. Experimental solid-state 4x1kW 2450MHz generator array

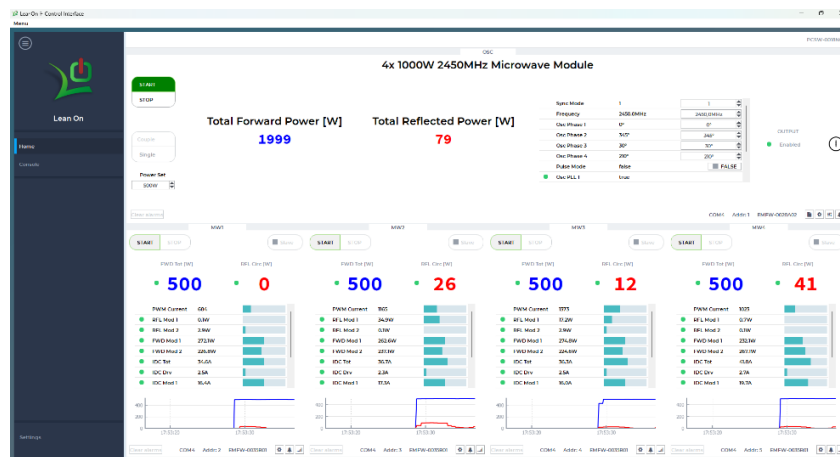


Figure 2. Screenshot of the control and monitoring software platform

The software platform was designed to allow fine tuning of frequency and power of each generator and, when operating in sync mode, also of the relative output phase. Each test run consisted of the following steps:

- selecting frequency, power and phase values;
- turning on the system and waiting for plasma ignition;
- re-tuning the parameters to minimize the reflected power level;
- setting the MW power to 4kW and progressively reducing it until plasma extinction.

When operating in the incoherent mode, the software platform forces generators 1 and 2 to be tuned to the same frequency, and the same applies to generators 3 and 4.

RESULTS

Solid-state generators allowed dynamic shaping of the plasma volume, both in intensity and spatial distribution, and higher controllability and repeatability of the ignition conditions, than with the previous magnetron feed. This flexibility gives the user the ability to switch dynamically and repeatably from a uniform spatial distribution to a concentrated intensity in a lower volume.

Tables 1 and 2 summarize the most relevant outcome of the experimental tests. The Left-Center-Right distribution in tests 9-12 is a relative value derived from three identical

Table 1. Outcome of the tests in Incoherent mode

Test #	Mode	f1 [MHz]	f2 [MHz]	f3 [MHz]	f4 [MHz]	Ignition [W]	Min Ref PW @4kW [W] ⁽¹⁾	Extinction PW [W]
1	CW - Incoherent	2440,0	2440,0	2460,0	2460,0	1050	238	260
2	CW - Incoherent	2449,0	2449,0	2451,0	2451,0	1010	304	360
3	CW - Incoherent	2449,5	2449,5	2450,5	2450,5	920	276	370
4	CW - Sync	2450,0	2450,0	2450,0	2450,0	980	248	290
5	CW - Sync	2454,0	2454,0	2454,0	2454,0	950	225	260
6	CW - Sync	2446,0	2446,0	2446,0	2446,0	1080	271	290
7	CW - Sync	2458,0	2458,0	2458,0	2458,0	890	186	240
8	CW - Sync	2456,0	2456,0	2456,0	2456,0	860	166	240

Table 2. Outcome of the tests in Sync mode

Test #	Mode	f[MHz]	Phase21	Phase31	Phase41	Left	Center	Right
9	CW - Sync	2456,0	345°	30°	210°	40%	40%	20%
10	CW - Sync	2456,0	345°	45°	225°	30%	40%	30%
11	CW - Sync	2456,0	345°	60°	240°	20%	40%	40%
12	CW - Sync	2456,0	345°	90°	270°	10%	40%	50%

(1) reflected power value after parameters re-tuning

cameras pointed at the left, middle and right parts of the plasma chamber. Photos were taken with identical ISO and exposure settings, and light intensity has been compared from average pixel values. Approximation to the nearest ten was used at the end.

Comparative analysis showed that the new system used 30% less microwave power for plasma ignition than the magnetron source and allowed maintaining the plasma active with minimum overall microwave power.

CONCLUSION

The use of a solid-state generator array allowed software-driven modulation of plasma intensity and different spatial distributions of its density within the reactor. Planned future developments involve introduction of temperature and light intensity sensors to implement reliable self-regulated processes aimed at subsequent industrial scale-up.

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An AI-Driven Complementary Frequency Shifting Strategy to Improve Heating Uniformity in a Solid-State Microwave System

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Keywords: Convolutional neural network, solid-state microwave, frequency shifting, heating uniformity

ABSTRACT

The complementary frequency shifting strategy has been reported to be effective in improving the heating uniformity of foods in solid-state microwave systems. However, two significant limitations need to be addressed before the strategy can be implemented in the real-time microwave heating process. First, the current complementary frequency-shifting strategy uses a time-consuming, orderly frequency-sweeping stage to prepare frequency-dependent thermal contributions for the essential complementary frequency-shifting stage. Also, the frequency-dependent thermal contributions are only prepared once without considering the change in food properties during microwave heating. This may hinder the effectiveness of the complementary frequency strategy in the real-time heating process. This study proposes a convolutional neural network (CNN) model to predict frequency-dependent thermal contributions. The CNN model was trained by using the multiphysics modeling results of frequency-dependent thermal contributions of seven representative food products (mashed potato, tuna flesh, egg white, lean beef, egg yolk, turnip, and fried chicken) and four package shapes (oval, square, rectangular, and curved rectangular) obtained from COMSOL. The trained CNN model was tested to predict new frequency-dependent thermal contributions of a food product with arbitrary dielectric properties. The predicted (from the CNN model) and ground truth (from multiphysics modeling) frequency-dependent thermal contributions showed a structural similarity index measure (SSIM) of about 0.9, indicating good prediction results. The trained CNN model was integrated with the solid-state microwave system for testing real-time dynamic heating process and demonstrated promising results.

Recent Development of Radio Frequency Systems for Postharvest Processing of Agricultural Products

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Keywords: Disinfestation, drying, pasteurization, uniformity improvement RF energy

ABSTRACT

Recent pathogen incidents, increased regulations on fumigants, and green technology requirements have forced the agricultural product industry to seek alternatives for effective postharvest processing of agricultural products. Radio frequency (RF) has been identified as one potential treatment method to replace chemical fumigations and other conventional thermal methods because it is relatively easy to apply and leave no chemical residues. RF equipment is commercially available today and is commonly used by the baking industry for final drying of crackers and by other industries. It involves the direct transfer of electromagnetic energy into bulk materials, initiating fast and volumetric heating. This presentation introduces the RF heating principle and systems, explores the difference between free running oscillator and 50 Ω systems, and finally demonstrates some recent developments and applications of RF systems for drying, disinfestations and pasteurization of agricultural products, including system safety, top electrode voltage determinations of the RF systems, industrial applications of RF disinfestations for walnuts and milled rice, new small scale RF system development and RF heating uniformity improvements using computer simulation.

A Review of the Benefits of Wave-based Heating for Processing Liquid Food Products in Vertical Vessels

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Keywords: Microwaves, wave-based process, food processing, jacketed vessels, conventional heating, steam heating, alternative heating

INTRODUCTION

In addition to more effective heating, the products that are heated by electromagnetic waves are rarely exposed to hotspots of conventional heating vessels, resulting in less oxidative damage to the product. The concepts present potential to produce more economical products across a broad range of applications. Combined with catalysts and nano particles, wave-based heating can deliver targeted reactions by careful attenuation of the waves to the dielectric property of target molecules. The presentation is designed to explain the theory as well as practical uses of wave-based processing and encourage development of newer processing techniques.

METHODOLOGY

This presentation is based on three patented concepts for applying industrial microwaves to a vertical vessel for heating products. The concept has been of practical use for reacting soap products to make machinery greases that often require temperatures in excess of 200 degrees Centigrade. Modified for use in food processing, wave-based food processing can improve energy efficiency by as much as 50% and reduce capital equipment costs significantly.

RESULTS

Comparison of jacketed vessels using heat transfer oils for process-heat and microwave heating has shown that energy efficiency is significantly improved when product heating is via direct electromagnetic excitation of product molecules instead of indirect heating of the vessel and via the hot vessel walls.

DISCUSSION

While processors are familiar with the use of household microwaves, the concept of using industrial microwaves for processing large volume products appears daunting. Practical



Figure 1: Waveguides deliver microwaves at 915 MHz frequency to top of a vertical vessel for processing products

uses of microwaves for batch processing large quantities of food products require comparative data and end user awareness.

CONCLUSION

Wave-based processing promises to save energy and improve processing efficiency as well as safety. While the amount of energy needed to heat a volume of products is the same regardless of the source of heating, microwave heating eliminates the need for jacketed vessels, hot oil or steam lines, insulations, and hot inside walls requiring scrape surface mechanisms. User education and comparative data will be the key to the growth of this processing technique that has the potential for significant energy saving and higher quality products.

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Numerical Simulation of a Microwave Applicator for the Treatment of Low-Moisture Food

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Keywords: 915 MHz microwave, modeling, electric field simulation, low moisture, food powder

INTRODUCTION

The understanding of the temperature distribution within microwave-heated food powders is crucial for homogeneous heat treatments to prevent risks of contamination by microorganisms. Temperature measurements inside the heated product can be obtained experimentally or predicted using numerical methods. However, the difficulty of making experimental measurements during microwave treatment has led researchers to increasingly rely on numerical techniques to better understand temperature and electromagnetic field behavior. For low moisture foods, limited scientific studies have compared experimental results with a computational approach. Some studies concerning the heating of low-moisture foods and the combination with simulation can be found in the literature, but they often use radiofrequency technology [1], [2]. Therefore, the main objective of the present study was to validate a model capable of predicting the microwave heating profile of a granular medium.

METHODOLOGY

A microwave system (displayed in Figure 1) operating at 915 MHz with power set to 200 W was used for the experiments. The quartz tube, filled with paprika, was positioned inside the cavity at the location of maximum intensity of the local electric field. The minimum reflected signal from the load was achieved by placing the tube with paprika inside the cavity, and then reaching the impedance matching by moving the iris (placed between the waveguide transition and the applicator) and the manual sliding short-circuit. The stubs shown in Figure 1 were not used to match the microwave cavity and were left in their default position. An optical fiber was used to precisely determine the temperature of a food powder (paprika) at two different locations along the axis of the material filling the tube (center and bottom positions). The three-dimensional representation of the electric field

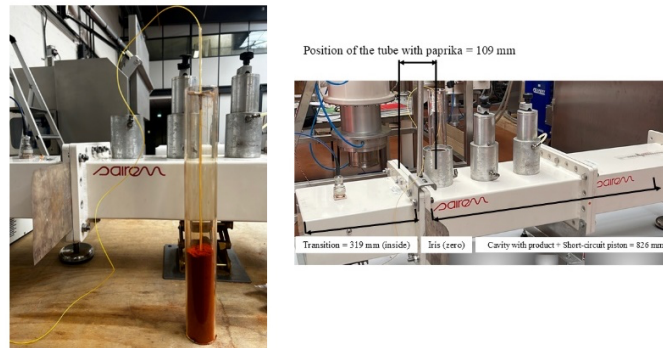


Figure 1. Experimental microwave system for paprika heating.

(norm of E-field) was compared with COMSOL Multiphysics and CST Studio Suite. The software COMSOL Multiphysics was also used to predict the temperature distribution within the sample and compare to the experimental data.

RESULTS

The three-dimensional representation of the electric field is shown in Figure 2. Figure 3 presents the simulated and experimental curves for the temperature evolution at the center of the paprika product, considering both a constant dielectric loss of 0.24 and a dielectric loss varying with temperature.

DISCUSSION

The representation of the electric field, shown in Figure 2, validates that both software produce similar results for the same model with identical inputs, confirming the consistency of their simulations. Since assuming constant dielectric properties for paprika the numerical model was unable to successfully predict the evolution of temperature obtained during experiments, a sensitivity study was conducted in COMSOL Multiphysics.

By assuming constant dielectric properties for paprika ($\epsilon' = 1.96$; $\epsilon'' = 0.24$), which were previously measured experimentally, the simulation did not follow the same trend as the experimental temperature evolution (see Figure 3). As previous numerical simulations revealed that the dielectric constant (ϵ') had less influence on the temperature profiles than the dielectric loss (ϵ''), an interpolation of the results of dielectric loss determined experimentally was performed to obtain a polynomial equation describing the variation of ϵ'' as a function of temperature. This step made it possible to evaluate the impact of the change in ϵ'' with temperature on the simulated temperature curves, getting closer to the experimental ones. The change in dielectric properties during heat processing was also reported by other authors [3].

CONCLUSIONS

The dielectric properties of low-moisture products are highly temperature-sensitive. In this study, only the dielectric loss was varied with temperature in COMSOL, but we

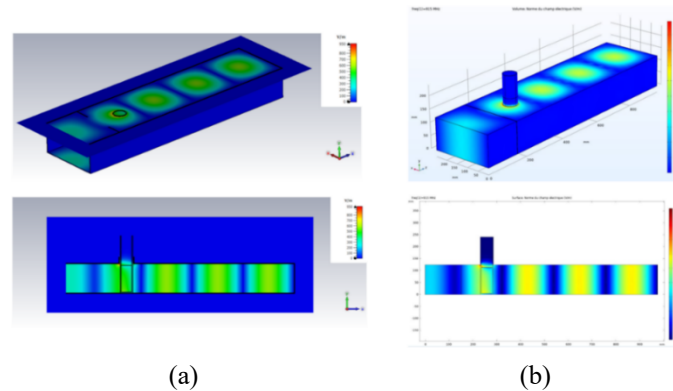


Figure 2. Three-dimensional representation of the electric field in the microwave cavity for paprika heating illustrated by (a) CST Studio Suite® and (b) COMSOL Multiphysics®.

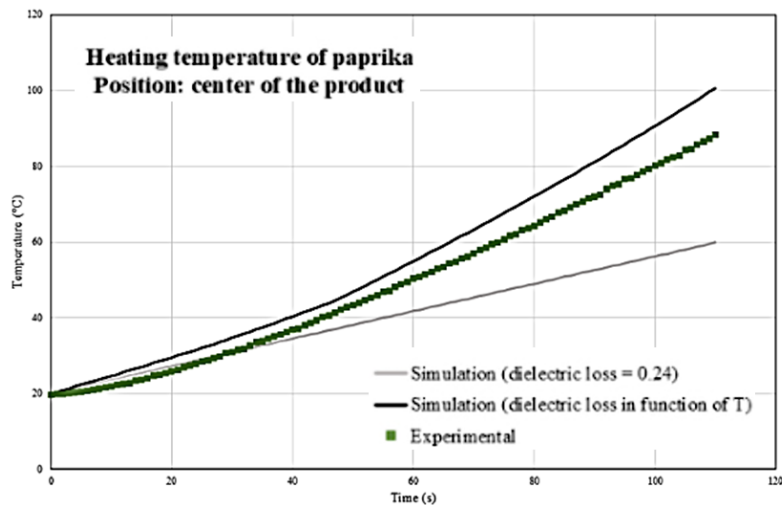


Figure 3. Simulated and experimental curves of temperature evolution over time of the center position of paprika powder. The dielectric loss remains constant or varies with temperature.

acknowledge that the dielectric constant should also be adjusted for more accurate results. Additionally, the positioning of the temperature acquisition tool is a factor to consider, as its slight variations could influence the results, making it challenging to simulate accurately.

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Microwave Process for Lunar Construction

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Keywords: Microwave power, microwave sintering, microwave vitrification, lunar regolith, lunar construction, in-situ resource utilization, high vacuum

ABSTRACT

One of the many challenges with lunar and Martian surface exploration is coping with dust that gets kicked up during landing or movement. Dust can be electrostatically charged with sharp edges, sticking to space suits and instruments and causing damage.

Dust mitigation for landing pads, berms, and roads has long been of interest to NASA. A study in 2010 highlights the potential for using microwave sintering [1]. In this earlier work, a method was developed where microwaves could be deployed from the lunar surface for top-down microwave paving [2],[3]. Feasibility was demonstrated with lunar simulant from the Mare region (basalt type regolith). This work was performed at atmospheric pressure, with the best results using a small quantity of microwave susceptible consumable material.

In 2020, NASA established the Microwave Structure Construction Capability team as part of the Moon to Mars Planetary Autonomous Construction Technologies effort led by Marshall Space Flight Center, with Dr. Shulman as the Microwave Sintering Lead. Sintering refers to the irreversible joining of particles, typically stimulated by heat and diffusion processes. Although sintering can lead to an increase in density, it can also occur with little to no change in the volume. With the goal of dust mitigation and making solid structurally useful products from a powder, there is a wide range for acceptable sintering or vitrification results. For landing pads, the surface must withstand a rocket plume, while for roads, a lesser degree of sintering can be acceptable.

Understanding dielectric and thermal properties of the feedstock is essential for developing microwave heating processes. Previous microwave sintering work used Mare simulants (basaltic). Highlands type simulants (anorthite rich) is the regolith predominantly found at the lunar south pole in the location water ice is available as a resource. Simulants were created and scaled up to offer better fidelity to the lunar Highlands regolith. This effort, led by Dr. Matt Creedon, resulted in the latest NASA Highlands simulant NUW-LHT-5M [4].

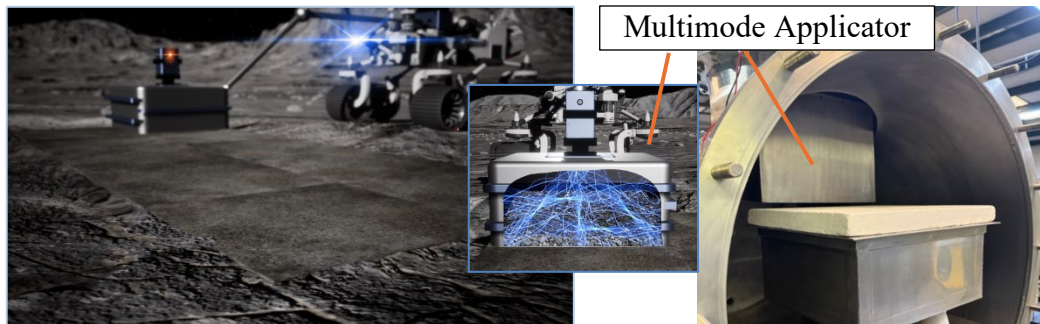


Figure 1. Concept rover using multimode applicator for top-down sintering at the lunar surface (left, center), and experimental set up for process development and feasibility (right).

Table I: Exploration of Microwave Power Time Profiles
Results from DOE: Mass (g) and figure of merit (Whr/g) of designed experiment

Variable : Level	MW Power: Low	MW Power : Med	MW Power : High
MW Energy : Low	N/A	340 g, FOM 3.5	600 g, FOM 2.1
MW Energy : Med	120 g, FOM 11.7	660 g, FOM 2.2	1020 g, FOM 1.4
MW Energy : High	1200 g, FOM 1.3	1480 g, FOM 1.1	N/A

Dielectric loss drives internal friction and can be measured with the cavity perturbation method as a function of temperature and frequency. Dielectric loss (ϵ'') is roughly an order of magnitude lower for the Highland simulant (NUW-LHT-5M) compared to Mare simulant (JSC-1AC) [4]. This translates to less vigorous heating until higher temperatures are achieved. From previous microwave sintering work with Mare simulant, it was clear that a hybrid approach was necessary, with a radiant heat source to start the process from the top surface.

For 100% in-situ resource utilization (ISRU), a process was developed with no consumables. And the system design required the ability for continuous microwave paving. Figure 1 (left, center) gives a rendering of the concept design, and Figure 1 (right) shows the experimental set-up in a high vacuum chamber with a multimode microwave horn for top down application. This equipment (MMT101) has also been modified to allow a moving stage for demonstration of continuous microwave sintering. A radiant heat source is provided by a proprietary susceptor design, but further development is underway to use other sources such as solar or electric.

Temperature was extremely difficult to use for feedback in the development stage, therefore a methodology using power time profiles to achieve a known energy input regime was applied. Using a fast DoE in argon (Table I), target conditions were found and applied to subsequent high vacuum microwave experiments.

Figure 2 shows examples of Highlands lunar regolith top- down microwave sintered. Note that at atmospheric pressure in argon, fine porosity was present, while in vacuum large macroporosity occurred. The likely cause is related to outgassing from non-lunar materials

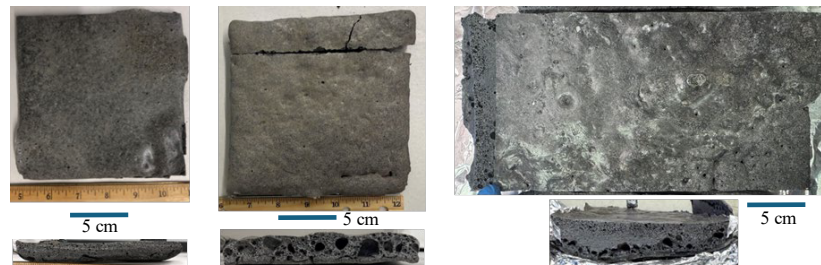


Figure 2. Microwave sintering results, top and cut side views: (left) argon, 1080 g, 2.1 Whr/g, (center) vacuum, 820 g, 1.2 Whr/g, (right) high vacuum, 2260 g, 0.7 Whr/g.

in the simulants. With further process development, utilizing an outgassing phase in the high vacuum chamber, improvements in microstructure were achieved (Fig. 2 right).

A driver for using microwaves is their ability to penetrate deeply and heat volumetrically. This offers extremely high energy efficiency. Figure 2 (right) shows the best figure of merit at 0.7 Whr/g and largest microwave sintered Highlands lunar regolith sample to date, produced with the highest fidelity simulant (NUW-LHT-5M) and lunar conditions (high vacuum).

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Advancements in Mining Applications Using Solid-State Microwave Power

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Keywords: Solid-state, mining, microwave systems, process development and validation

ABSTRACT

This presentation will cover non-proprietary updates on several new and ongoing system process developments for the mining industry, emphasizing the role of solid-state microwave sources. Featured developments including, but not limited to, ore comminution trials with a mine owner/operator, the creation of ruggedized microwave systems for extreme comminution environments, Direct Reduced Iron (DRI) process development and validation, and advancements in ore reduction and concentration for enhanced magnetic separation yields.

Microwave Heating for Minerals Drying: Experimental and Numerical Study

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Keywords: Microwave heating, minerals drying, finite element analysis, moisture removal, electrification.

INTRODUCTION

Transitioning from natural gas-burning kilns commonly used in minerals drying to electricity-driven technologies such as microwave heating powered by renewable energies, can cut dependence on fossil fuels [1]. The present paper evaluates the application of microwave systems for minerals drying through conducting laboratory experiments and numerical modeling. Drying tests were conducted in a commercial microwave oven, with samples exposed to energy dosages of up to 150 kWh/t aiming at reducing moisture content to below 1%. The loss tangent, heat capacity and thermal conductivity were evaluated at various temperatures and used to develop numerical models coupling electromagnetic and heat transfer. The drying rates and temperature profiles of samples were predicted using a numerical model and compared to experimental measurements where strong agreement was found. It was found that providing a minimum of 15 kWh/t microwave energy dosage initiates evaporation. Evaporation remains the dominant mechanism in expensing microwave energy, removing water at an approximate rate of 0.31 gram per kWh/t of material until moisture content of approximately 2% is reached.

METHODOLOGY

The thermal conductivity of wet and dry samples was measured using a KD2-Pro thermal properties analyzer. The heat capacity of the samples was measured only for fully dried samples using differential scanning calorimetry with Discovery 2500 from TA Instruments. The effect of latent heat was incorporated into models using an apparent heat capacity approach [2]. Samples were thoroughly analyzed for their electromagnetic properties using cavity perturbation technique at frequency of 2467 MHz across temperatures ranging from 25 °C to 120 °C, with incremental steps of 20 °C.

Drying experiments were conducted in a commercial microwave oven from Amana (model RC30S2) (Figure 1(a)) with a nominal forward power of 3 kW, equipped with 3 magnetrons in separate rectangular TE₁₀ waveguides, 3 stirrers, and 2 fans [3]. The actual forward power of microwave was measured following IEC 60705:2010 + A1:2014 standard [4] through energy absorption study on water.

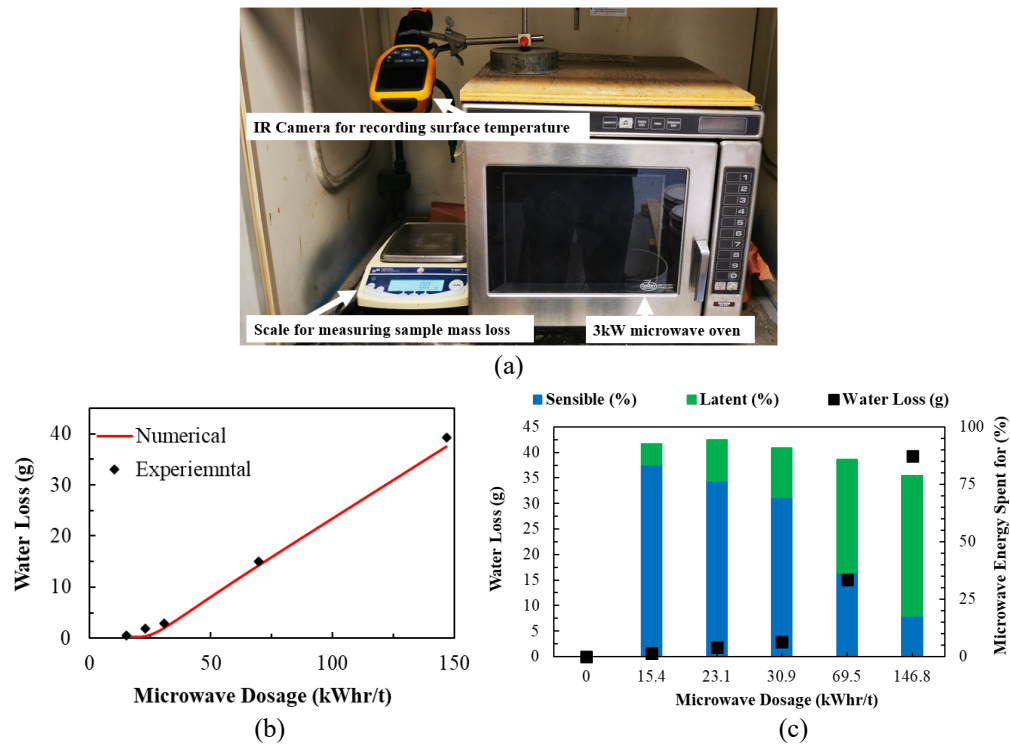


Figure 1. The 3 kW microwave oven together with IR camera and benchtop scale (a). The numerical mass loss is compared to experimental measurements (b), with respective contribution of sensible energy and latent energy energies in expensing microwave energy (c).

The generators' ramp-up time and actual power draw from electrical grid were measured where changes in temperature, mass and electrical current were recorded using a thermometer, benchtop scale and power analyzer, respectively.

Samples weighing approximately 275 g with 25% initial moisture content were exposed to microwave energy for durations of 9, 12, 15, 30, and 60 s. Mass and temperature changes were measured and used to calculate the total thermal energy absorbed by the samples i.e. sum of sensible and latent energies.

A finite-element based numerical model was developed in COMSOL Multiphysics coupling electromagnetic physics with heat transfer bi-directionally. The transient revolution of stirrers was incrementally incorporated and the sequence of electromagnetic physics and heat transfer were solved iteratively. The electric field were solved in frequency domain at respective temperature profiles, and the corresponding resistive losses were used as heat source in solving heat transfer in time domain. Following a mesh dependency analysis taking into account the respective computational costs, meshes as small as 5 mm were given satisfying numerical errors below 1% in both calculated electromagnetic resistive losses and heat transfer power balance. The optimal mesh was

used to perform numerical simulations to compute changes in temperature and mass of samples exposed to microwave radiation.

RESULTS AND DISCUSSION

The dielectric measurements at various moisture contents showed that decreasing the moisture content of samples decreases the tangent loss significantly. For instance, the dielectric loss of wet samples with 25% moisture content drops two orders of magnitudes upon drying, from 0.240 to 0.014 when moisture content dropped to 5%. Once fully dried, samples show minimal interaction with the applied electromagnetic field. This observation was further examined by performing and comparing drying tests experimentally and numerically. An excellent agreement was found between measured and numerical moisture mass loss as shown in Figure 1(b). Once the material reaches the phase change threshold (at 100 °C), evaporation becomes the dominant mechanism in expensing microwave energy, as seen from the sharp change in mass loss trend as well as in latent energy contributions in Figure 1(c). Higher microwave dosages (longer exposures) result in higher moisture losses. At lower microwave dosages (shorter exposures), the microwave energy is mostly spent to rise and maintain materials volumetric temperature, leading to lower moisture losses. At low dosages, 0.04 grams of water can be removed per 1 kWh/t energy dosage given to the material, and by increasing the energy dosage, up to 0.31 gram of water can be removed per 1 kWh/t energy dosage given to material.

CONCLUSION

Through dielectric measurements over temperatures ranging from 25–120 °C, it was found that water has the dominant role in expensing electromagnetic energy of wet mineral samples, with wet samples showing dielectric loss factors two order of magnitude larger than those of dry samples. The mass and temperature changes from developed numerical model and experimental measurements were concordant. It was found that a minimum of 15 kWh/t microwave energy dosage must be provided to initiate evaporation. By retaining energy dosages above 30 kWh/t of material, a consistent evaporation rate of 0.31 gram per kWh/t of material can be sustained.

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Computational Analysis of Electron Density Effect on Power Absorption in Microwave Plasma Applicators

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Keywords: Electromagnetic modeling, electron density, microwave plasma applicators

INTRODUCTION AND METHODOLOGY

The last several years have seen an increased use of microwave (MW) plasma for hydrogen production, nitric acid synthesis, surface processing of semiconductor components, decomposition of CO₂ and other innovations [1]. When scaling up the plasma-based technologies into industrial processes, the designers inevitably face the constraint for the level of MW power. The rise in power raises electron density, which increases plasma's electric conductivity, worsening the coupling of the microwaves with the plasma, reducing power absorption, cutting the energy efficiency of the system, and limiting the potential for scalability.

In this paper, we suggest addressing this conceptual challenge by a focused computational analysis of the electromagnetic (EM) processes in the MW system in question. The recently proposed approach for the characterization of microwave plasma for EM modeling [2], [3] has laid groundwork for use of the FDTD technique to determine the operational bounds of MW applicators with plasma and assist in the CAD of such devices. To demonstrate the benefits of this approach in dealing with the electron density related challenges, we designed the model of a 2.45 GHz system resembling certain plasma applicators and simulated it using the FDTD approach, adjusting the electron density parameter to account for changes induced by the variation of MW power. The model was implemented in the FDTD simulator *QuickWave* [4]. Our computations show an anticipated increase in reflections from the system that is caused by the increase in input power. At the same time, they reveal that some alterations in the system design could take advantage of the resonant properties of the system and lead to improved coupling and increased energy efficiency.

COMPUTATIONAL RESULTS

In the considered MW device (Figure 1), the plasma is ignited in a gas enclosed in a cylindrical quartz tube positioned inside a metal cylinder connected with an exciting rectangular waveguide (whose wide wall is parallel to the y -axis) and a larger cylindrical

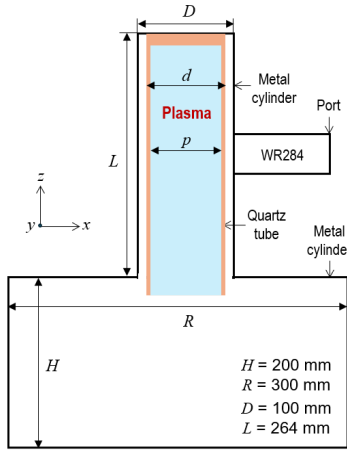


Figure 1. Layout of the microwave plasma system.

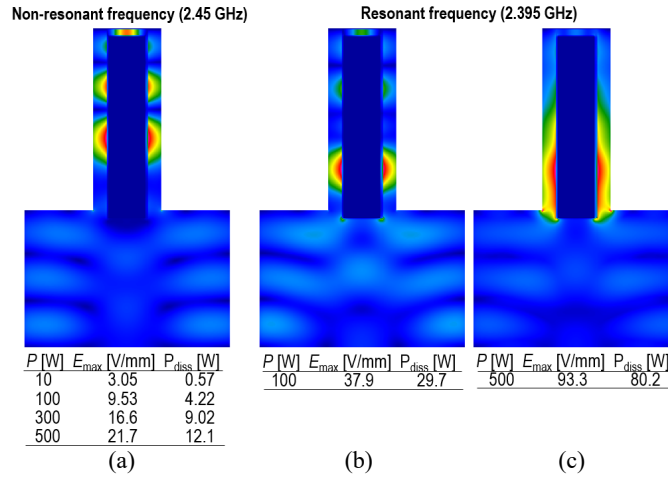


Figure 3. Relative patterns of the electric field in the central yz -plane at the non-resonant (2.45 GHz) (a) and resonant (2.395 GHz) (b, c) frequencies; $p = 54$ mm; max values of the field and absorbed power for different P are tabulated.

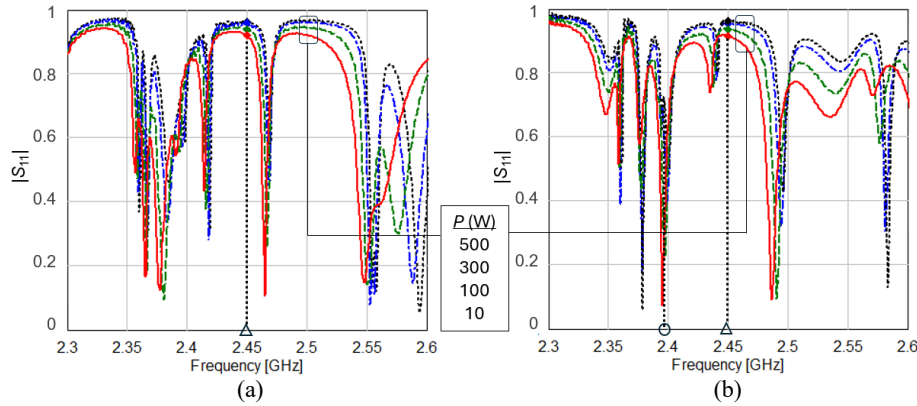


Figure 2. The reflection coefficient $|S_{11}|$ in the system in Figure 1 for MW power P in the range from 10 to 500 W; $d = 58$ mm; $p = 38$ mm (a) and 54 mm (b); plasma is ignited in argon at low pressure (with the neutral gas density $n_g = 1.94 \cdot 10^{-24} \text{ m}^{-3}$ [3]); $\gamma = 0.33$ GHz [3]; non-resonant (2.45 GHz) and resonant (2.395 GHz) operating frequencies are marked by o and Δ .

cavity which serves as a reactor for the intended application. To single out the impact of plasma, the processed material is not included in the model. The input data representing the plasma medium is compiled in accordance with the approach outlined in [2], [3]. The electric conductivity of plasma σ is conditioned by electron-neutral collision frequency γ and plasma frequency f_p . The latter depends on electron density N (and can be approximated as $f_p \sim 8.97N^{1/2}$ [3]) which is a system-specific function of MW power P . According to the experimental data in [5], [6], the dependence $N(P)$ is close to linear. Here, we define $f_p(P)$ using the slope of $N(P)$ in [5], $N \cdot 10^{-23} [\text{m}^{-3}] = 1.12 \cdot 10^{-3} P [\text{W}] + 2.57$, such that then $f_p [\text{GHz}] \sim 0.22 P [\text{W}] + 89.5$. The increase of MW power is therefore accounted for by the growth of the plasma frequency input parameter.

Simulated frequency responses of the reflection coefficient $|S_{11}|$ obtained for different f_p (determined by MW power) (Figure 2) suggest that, in applicators similar to the device in Figure 1, the level of power absorption strongly depends on whether the operating frequency f_0 is near or at one of the resonances of the system. The curves imply that, at non-resonant frequencies, the coupling is normally very low regardless of the level of power. At a resonance, however, the decrease in energy efficiency resulting from increased electron density may be insignificant; in some cases, the coupling may even improve. The positioning of resonant frequencies depends on geometrical parameters of the system. For the system in Figure 1, the diameter of the plasma cylinder and thickness of the quartz walls are especially impactful. This suggests that the decline of energy efficiency because of increased power can be addressed instead by simply choosing a design that matches f_0 with one of the system's resonances.

As a supplementary result, the model also estimates the evolution of the electric field for the growing MW power. When P varies from 100 to 500 W, the range chosen for the present study, the resulting change in N produces an increase of σ from 111 to 323 S/m. It is seen from Figure 3 that when the system is excited at a non-resonant frequency, the absorbed (dissipated) power (P_{diss}) is very low for any level of power, and the field distributions are nearly the same. However, the field pattern may change with MW power when f_0 is tuned at a resonant frequency due to corresponding variation of plasma conductivity.

CONCLUSION

The presented computational results suggest that while the increase of electron density with the growth of MW power poses a fundamentally natural challenge, FDTD modeling of the EM processes in the considered device may inform the design such that it could help mitigate the negative effects of this phenomenon. Certain combinations of geometrical characteristics of the device and physical parameters of the plasma medium may help tune the operating frequency to the system's resonances, improve energy coupling, and increase energy efficiency for scalable MW power.

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From Renewable Energy to Valuable Chemicals: Plasma-Process Innovations in Power-to-X Applications

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Keywords: Power-to-X, plasma process, high power microwave source

ABSTRACT

The conversion of industrial processes to *all-electric* power is widely accepted as a solution for transition toward clean energy [1]. Power-to-X technologies that convert surplus grid and/or renewable electricity into carbon-neutral synthetic fuels and/or raw material for the chemical industry will be central to this shift, with plasma being a key contributor.

Plasmas can be applied to chemical processes at high and low gas pressures, offering several advantages. They are on-demand processes, as plasma can be started and stopped instantly. Plasma solutions can also be implemented in modular plants for decentralized production. Microwave plasma offers several advantages over other plasma technologies, including higher ionization efficiency, higher electron temperature and reduced risk of contamination and damage, since not based on electrodes. Moreover, microwave plasma sources can be operated in a wide range of process parameters, and their use is also economically attractive, as microwave sources and generators are commercially available at 2.45 GHz up to 15 kW and 915 MHz up to 100 kW. Their energy efficiency is high [2], allowing both low electrical energy costs and high productivity.

For those reasons, technologies based on microwave plasma processes are rapidly gaining acceptance in the industry, with their implementation across various types of applications. Prominent examples among others include [3]: (1) the dissociation of carbon dioxide into carbon monoxide, an important feedstock in bulk chemicals manufacturing, (2) the biogas, natural gas or generally hydrocarbons into hydrogen and coproducts (black carbon at atmospheric pressure, acetylene and ethylene at moderate pressure), and (3) the production of fertilizer from nitrogen and oxygen contained in air.

This work presents how the MUEGGE products, and in particular its high-power microwave plasma sources and generators contribute to these plasma-process innovations.

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Scaling Up Microwave Plasma Technology with Solid-State Generators: Overcoming Surface Limitations for Enhanced Performance

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Keywords: Microwave, plasma, solid-state, GaN, automatic frequency tuning, plasma uniformity, high density, multisource

ABSTRACT

In response to the growing demands of nanotechnology industries, particularly in microelectronic component manufacturing, innovative self-matched plasma sources driven by microwave solid-state generators have been developed. These innovations address the challenges associated with plasma surface coverage and ion density. Through the integration of patented automatic frequency tuning, the need for an impedance matching system has been eliminated, greatly simplifying operations and enhancing reliability [1].

One significant drawback of traditional microwave plasmas is their limited volume, which restricts their applicability in large-scale processes. To overcome this limitation, two distinct plasma sources were developed to operate across a broad pressure range: the Aura-Wave source, functioning between 10^{-2} Pa and a few Pa, and the Hi-Wave source, covering from 1 Pa to several tens of Pa [2–4]. This work focused on multisource configurations, where each source is independently powered by its own microwave solid-state generator, enabling precise control of transmitted power in 1-watt increments. This approach effectively expands the plasma volume and enhances uniformity across larger surfaces.

A Langmuir probe was utilized to analyze plasma density, and custom simulation software was developed to optimize surface uniformity by adjusting source distribution and power distribution. This software also predicts plasma density outcomes for multisource configuration, with probe measurements validating the simulations. Key plasma parameters, such as gas type, operating pressure, microwave power, and working distance, were systematically investigated.

For example, a nitrogen plasma at 1 Pa, generated using a 16-source Aura-Wave matrix with a lattice parameter of 110 cm, yielded a high-density plasma of $1.2 \times 10^{11} \text{ cm}^{-3}$ with

5% uniformity over a 410 mm diameter at a 10 cm distance from the source plane [5]. Similarly, a 16-source Hi-Wave matrix operating with argon plasma at 0.5 Pa achieved a plasma density of $1.2 \times 10^{12} \text{ cm}^{-3}$ with 5% uniformity over a 440 mm diameter.

Moreover, a new generation of solid-state generators is currently in development. This upcoming generation promises to deliver even higher performance and greater stability, further enhancing the scalability and applicability of microwave plasma technology across various industrial sectors with high levels of demand.

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Microwave Energy to Effectively Electrify Process Heat in the Fluidization Industry: A Particle-Scale Insight

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Keywords: Electrification, microwave heating, fluidized beds, microwave penetration, uniform heating

INTRODUCTION

Fluidized beds, widely used in industries like chemical processing, energy production, and pharmaceuticals, are traditionally heated by fossil fuel combustion. They offer advantages such as efficient heat and mass transfer, uniform mixing, and continuous operation. Electrically heated fluidized beds, powered by renewable electricity, are emerging as a promising solution for industrial electrification, enabling significant CO₂ emission reductions and improved overall energy efficiency [1]. In this regard, microwave heating offers an exciting opportunity to decarbonize process heat in the fluidization industry. However, microwaves are known for their limited penetration depth, posing a significant challenge to achieving uniform heating in industrial processes. The evolution of microwave penetration depth and the interaction of microwaves with a dense set of fluidized particles remains poorly understood to date [2].

Detailed modeling efforts are essential to bridge the gap and promote the broader adoption of microwave technology for commercial and scientific applications. However, numerical studies on the interaction between microwaves and fluidized beds remain unexplored, primarily due to computational resources and the complexities of such heterogeneous systems, which involve simultaneous fluid flow, particle dynamics, and microwave interactions [3]. Here, we develop a detailed particle-scale modeling of microwave interaction with a bed of 10,000 micron-sized particles in a fluidized state. The model is applied to enhance the understanding of microwave energy absorption in fluidized beds containing particles of varying sizes, including Geldart A (100 μm), B (350 μm), and D (2 mm), which are commonly used in fluidized beds.

METHODOLOGY

We model the interaction of microwaves with a set of fluidized particles by only solving Maxwell's equation in the frequency domain based on the Finite Element Method (FEM).

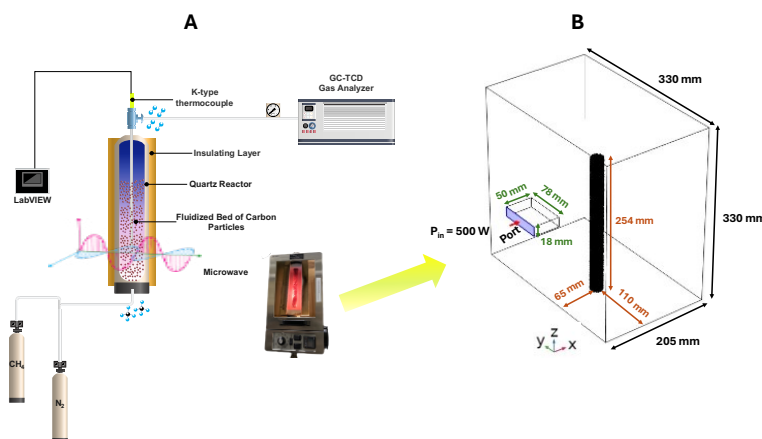


Figure 1. (A) Schematic of the bench-scale microwave experiment for methane pyrolysis. (B) Simulated geometry of the cavity, waveguide, and the 1-inch diameter fluidized bed reactor.

The computational domain consists of a multimode microwave cavity, a waveguide, and a fluidized bed, as depicted in Figure 1B. A fluidized bed is generated by randomly distributing particles confined in a cylindrical bed based on the bed dimension, particle size, and bulk solid volume fraction. A collision detection is also defined by calculating the distance between the particle centroids to preclude particles from having contact points, resulting in a fluidized state for all the particles.

RESULTS AND DISCUSSION

Figure 2 shows that for all particle groups, particle regions exhibit low electric field intensity, indicated by blue regions confined within each particle, whereas the surrounding air shows significantly higher electric field intensity by several orders of magnitude. Moreover, several resonances of the electric field are observed and highlighted as reddish regions in the narrow gaps between closely spaced particles, with field intensities exceeding 10^5 V/m in these regions. For Geldart D particles, the electric field plot in Figure 2 clearly demonstrates that individual resonance modes can interact and combine, forming new resonance patterns that spread throughout the bed, as illustrated with smooth reddish regions in the electric field contour.

For Geldart A and B particles, the magnetic field penetrates the fluidized bed with minimal attenuation. Two factors likely explain this phenomenon: (1) these particles have a small or comparable ratio of $d_p/2\delta$, where d_p is the particle size and δ is the skin depth, which mitigates the skin depth effect, and (2) the non-magnetic nature of both particles and the air gaps between them further contributes to this minimal attenuation of the magnetic field. This suggests the independent formation of eddy currents within each particle, leading to Joule heating. Within the scale of our interest, no evidence of exponential attenuation is observed in the power absorption density across the fluidized particles, as can be seen in the distribution of power absorption density, particularly for Geldart A and B.

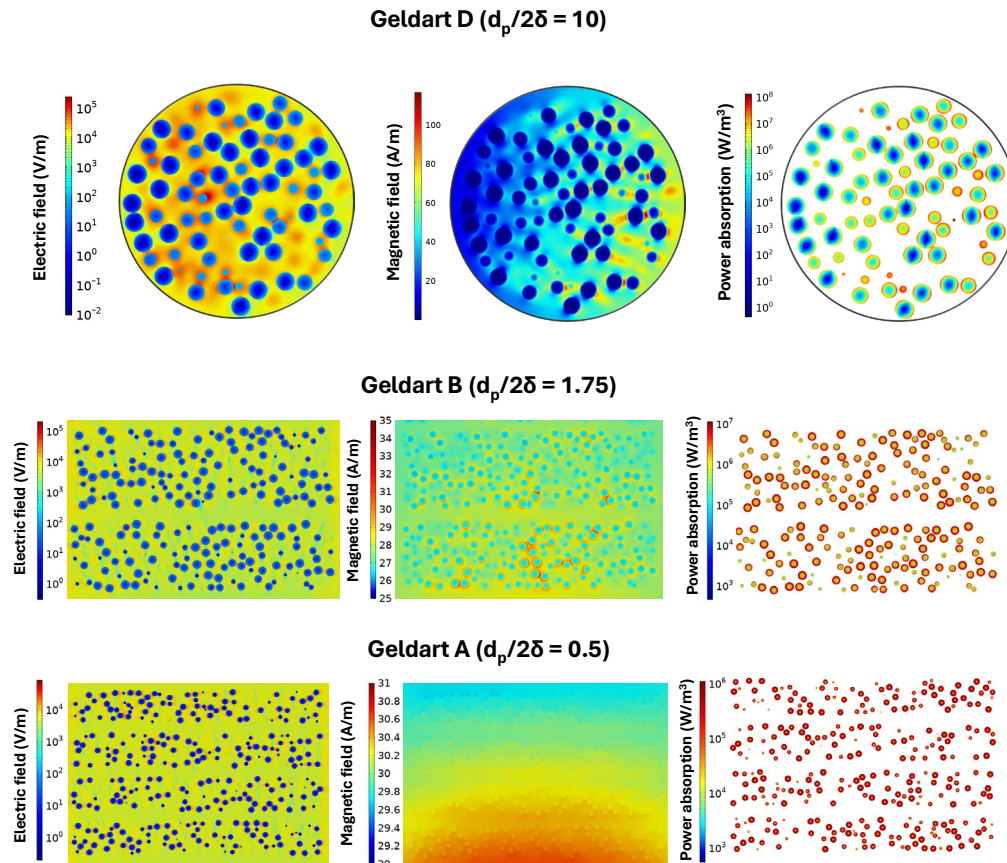


Figure 2. Power absorption density and interaction of the electric and magnetic fields with the fluidized bed of particle groups Geldart A, B, and D. For Geldart D particles, the plots present the top view of the middle layer, while the side view of the middle layer is displayed for Geldart A and B particles.

CONCLUSION

The present study reveals two key findings on microwave heating of fluidized beds: (1) The alternating magnetic field fully penetrates the reactor, inducing eddy currents and heating each particle. (2) The power absorption density for Geldart A and B particles is uniform across the bed, with no evidence of exponential attenuation, demonstrating unexpected penetration depth.

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Inclusion of Thermal Dependent Material Relations for Modeling Microwave Ablation Antennas

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Keywords: FDTD, computational electromagnetics, microwave heating analysis, microwave ablation, cancer therapy

INTRODUCTION

When designing antennas for cancer therapy using microwave ablation (MWA), it is worthwhile to use simulations to optimize the design process. Heating modeling is faced with many challenges due to the phenomena that occurs during heating, for instance the change of material properties with the temperature. In QuickWave Basic Heating Module (QW-BHM) [1], by using an external file users can set material properties for a given temperature. This paper examines the impact of temperature-induced changes in material properties on heat propagation within a liver model subjected to an applied electromagnetic field by an antenna model for MWA. A comparison between the simulation and experimental results [2] is also presented.

METHODOLOGY

All parameters of the antenna model were based on previously published data [2]. Simulations were performed using Bodies of Revolution Vector 2D (BoR V2D) method in QuickWave and three different QW-BHM setups were applied: Neumann Boundary Condition (NBC) without Heat Flow (HF); NBC with HF; NBC with HF and added temperature-dependent (TD) material parameters. With the external file, as shown in Fig. 1, users are allowed to set material properties such as permittivity, enthalpy, density, thermal conductivity or specific heat for each value of the temperature.

For each setup the same antenna was simulated by heating the sample (liver model) for the same time of 15 minutes and with excitation power of 20 W. The QW-BHM workflow and another examples of its application were presented in the NanoBat project [3].

RESULTS

The results for all setups and the experimental results are presented in Table 1. Using the heat distribution, ablation zones (AZs) were determined which correspond to area within the sample with a temperature of at least 60 degrees Celsius [4]. In the case of setting NBC

DATA FROM -20 C to +80 C, dH/dV in J/cm3 reversedEnth/Temp column

!Temperature # Data deg C	Enthalpy J/cm3	EPa	SIGa S/m	SpecHeat	Density	Ka
-20	0	4.9	0.064	2.21	1.041	0.0051
-15	14.0	5.5	0.093	2.21	1.041	0.0051
-10	34.4	6.1	0.153	2.21	1.041	0.0051
-5	71.4	12.3	0.573	2.21	1.041	0.0051
-3	110.4	22.0	1.118	2.21	1.041	0.0051
-2.2	144.4	30	1.636	2.21	1.041	0.0051
-1.6	192.4	42	2.113	2.21	1.041	0.0051
-1.3	240.4	46	2.385	2.21	1.041	0.0051
-1.1	274.4	48.9	2.426	2.21	1.041	0.0051
-1.0	288.4	49.2	2.440	2.21	1.041	0.0051
10	327.9	48.9	2.317	2.21	1.041	0.0051
20	382.9	48.2	2.194	2.21	1.041	0.0051
35	450.4	46.9	2.072	2.21	1.041	0.0051
50	517.9	45.5	1.949	2.21	1.041	0.0051
65	585.4	43.6	1.922	2.21	1.041	0.0051
80	652.9	41.7	1.908	2.21	1.041	0.0051

Figure 1. An example of external file with the material data.

Table 1. Ablation Zones Dimensions.

	Length x Diameter (mm)
NBC+HF	36 x 35.48
NBC	— x 31.28
NBC+HF+TD material parameters	25 x 23.08
Experiment	38 x 31

without HF it is impossible to determine the length of the AZ caused by its irregular shape; usually AZ takes the shape of a sphere.

CONCLUSION

For each setup case, the AZ dimensions are close to the experimental results [2] in terms of order of magnitude. The largest AZ and the closest to the experimental result was obtained in the case of using NBC with HF and the smallest in the case of adding the TD material parameters. Taking TD materials parameters into account reduced AZ by more than 30 percent. When comparing the results one must also take into account that the methods for determining AZ in the experiment are inaccurate. In the future this work can be developed by extending the QW-BHM to include the Bio-heat equation and by performing a more detailed experiment.

As can be seen, taking into account the change of heated liver parameters can change the results significantly. The difference between the simulation and experimental results may

be due to the differences in the parameters of the real liver and those assumed in the model shown in Fig. 1 and the not very accurate experimental method of determining the AZ.

ACKNOWLEDGMENT

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Theoretical Average Power Handling of Circular Waveguide

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Keywords: Circular waveguide, electromagnetic modeling, power handling, thermal modeling

ABSTRACT

The power handling capability of rectangular waveguides (WG) is well known, with peak limits well into the tens of megawatts for a WR975 WG [1]. As power is continuously transmitted, conductive losses in the WG cause heating, limiting practical power transmission to hundreds of kilowatts [2]. Information on the average power handling capability of circular WG is not as available but is of interest as industry leaders innovate toward higher power delivery. Circular WG are suitable for high pressure applications (i.e., pressure vessels) due to having no stress concentration points [3], and where polarization may be required.

An analytical approach for the average power handling of rectangular WG is reconciled with existing literature [4], then the same technique applied to a 9.314-inch-diameter circular WG. This WG size was chosen considering a 915 MHz operating frequency, its availability as a 10" schedule 100 pipe [5], and the operating frequency falling within the acceptable frequency region for TE₁₁ propagation [6]. Important parameters considered in the analysis are the WG dimensions, material conductivity, internal surface roughness, external surface convective and radiative heat transfer, and ambient conditions.

Analytical results are compared with numerical methods simulated in Ansys High-Frequency Structure Simulator (HFSS) and Ansys Mechanical. In HFSS, a surface roughness boundary condition (BC) is applied to the inside faces of a 1 m segment of WG. Input powers from the analytical results are applied in HFSS, resulting in surface losses that are imported into Ansys Mechanical. To solve the mechanical model, radiation (including emissivity) and convection (temperature- and geometry-dependent) BCs are applied.

The analytical approach for a rectangular WG takes the well-known attenuation equation for the TE₁₀ mode [7] and modifies the surface resistance with a surface roughness factor [8]. Radiation and convection losses are also considered, where external WG wall and ambient temperatures are correlated to an average power. Fig 1 shows the convection

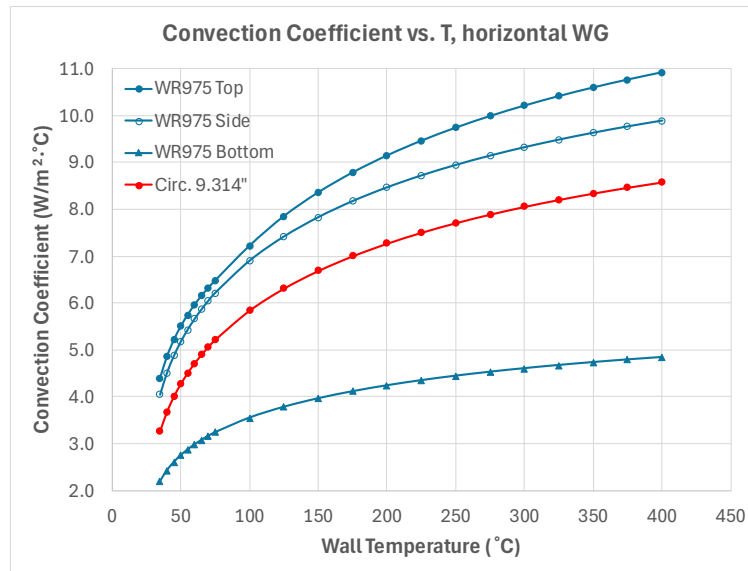


Figure 1. Calculated convection coefficients for a horizontal aluminum WG. $T_{amb} = 25\text{ °C}$.

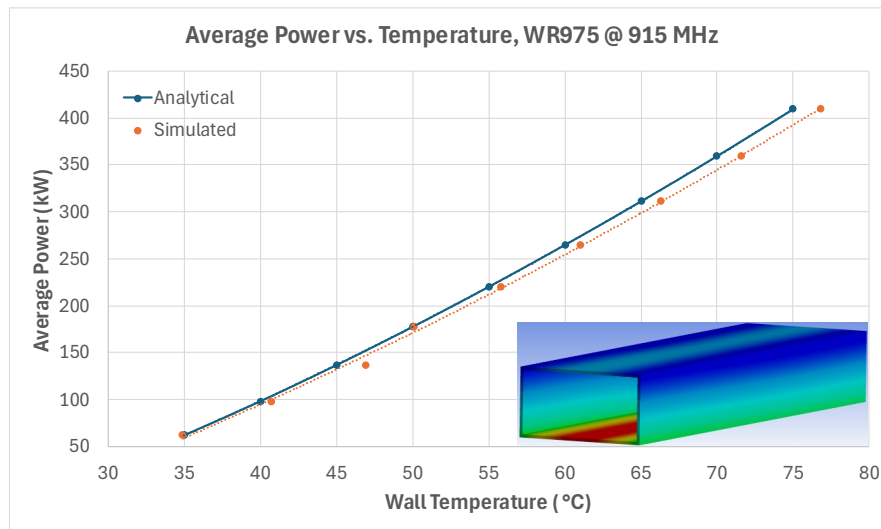


Figure 2. Analytical and simulated average power handling as a function of temperature for a horizontal aluminum WR975 WG. Emissivity = 0.95, surface roughness = $1.6\text{ }\mu\text{m}$, $T_{amb} = 25\text{ °C}$.

coefficients used for analysis and simulation. Fig. 2 compares the analytical average power handling versus temperature for analytical and simulated results.

With good agreement between analytical and simulated results for the WR975 case, a similar approach is applied for a 9.314" circular aluminum WG using the attenuation equation for the TE₁₁ mode [7]. The convection coefficients are different for a horizontal cylinder (red trace in Fig. 1). Fig. 3 compares the analytical average power handling versus temperature for analytical and simulated results.

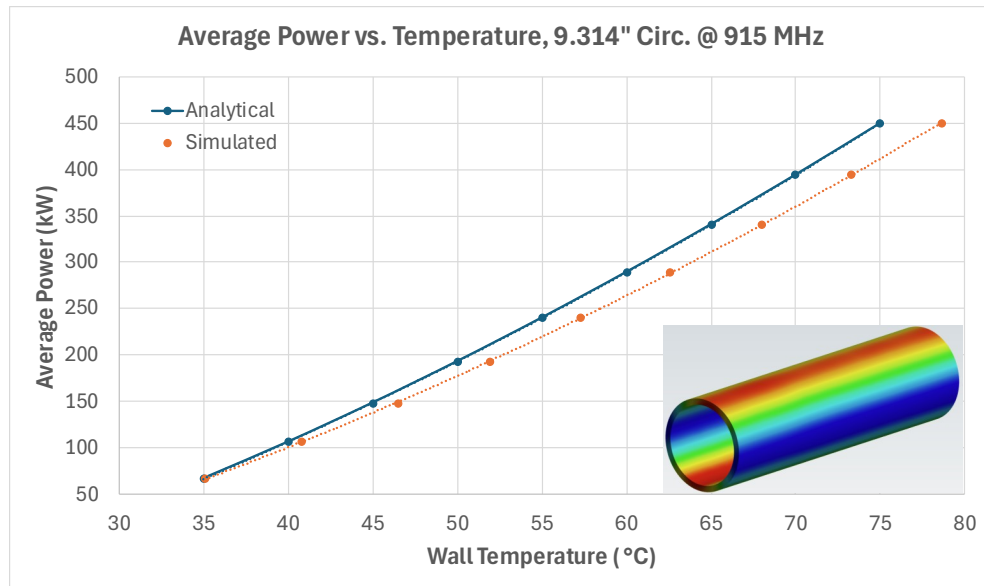


Fig. 3. Analytical and simulated average power handling as a function of temperature for a horizontal aluminum 9.314" WG. Emissivity = 0.95, surface roughness = 1.6 μm , $T_{\text{amb}} = 25^\circ\text{C}$.

In both cases, there is increasing error between analytical and simulated results. It is suspected that this is due to the analytical model assuming constant wall temperature and convection coefficient, whereas simulations result in thermal gradients and treat these parameters iteratively. The results presented are preliminary and will be further refined.

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Facts and Misinformation about What is “Microwave-Safe” and What is Not

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Keywords: Microwave ovens, microwave cookware, microwaveable plastics, stainless steel

INTRODUCTION

Consumers often ask, “Is it safe to use in a microwave?” Or, “How do I know if it is safe?” When searching online for answers to these questions the advice offered is generally correct and helpful. But quite often the answers apply only to plastic, ceramic, glass and other non-metallic cookware, as though the inquirer has already been taught to avoid putting metal in a microwave. Although that may be a safe assumption, it avoids a more comprehensive answer and can lead to a misunderstanding about what is microwave-safe and what is not.

The terms “microwave-safe” and “microwaveable” are found ubiquitously on many forms of reusable ceramic, glass and plastic cookware (e.g. Figure 1). With very few exceptions, consumers can be confident that cookware labeled as such is safe to use in a microwave oven. Some cookware items lacking such labeling might also be microwave-safe, but it is up to the consumer to make that determination by following the advice found online.

DEFINITION OF “MICROWAVE-SAFE”

A clear, concise and generally accepted definition of “microwave-safe” may not exist. The Society of the Plastics Industry (now Plastics Industry Association) defined microwave-safe as “A description of utensils made from materials transparent to microwave energy that is not harmful to the microwave oven or harmed by it or the heat of the cooked food” [1]. While this particular definition may be applicable only to non-metallic cookware, it specifies two important criteria applicable to all cookware: 1) it will not harm the microwave oven, and 2) it will not be harmed by the microwave oven or foods being cooked. The primary concern is overheating and causing damage to either the cookware or the microwave oven itself.

This definition neglects any harm that may be caused by the cookware to the food being cooked. Regulations and standards for food contact materials (FCMs) vary widely from one country to another [2]. In the European Union, Commission Regulation (EU) No. 10/2011 on plastic materials and articles sets out rules for the composition of plastic FCMs and establishes a list of substances that are permitted for use in the manufacture of plastic

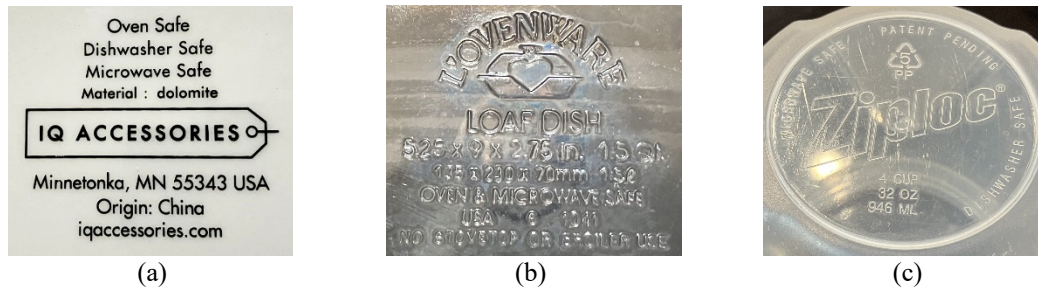


Figure 1. “Microwave Safe” labels found on ceramic (a), glass (b) and plastic (c) cookware.

FCMs [3]. Migration into the food of harmful compounds, such as bisphenol A (BPA) [4], is more likely to occur at elevated temperatures, which for microwave cookware is a particular concern as the food temperature during cooking can easily exceed the safe operating temperature of many plastics [5].

While these regulations and standards may help to establish a generally accepted definition of “microwave-safe,” a legal definition remains elusive. Two relevant definitions of the English adjective “safe” are found in The Oxford English Dictionary [6]:

- 1) Not exposed to danger; not liable to be harmed or lost; secure, and
- 2) Presenting no risk of physical harm; posing no threat, not dangerous.

These definitions are consistent with the above requirements, specifically that “microwave-safe” cookware will not harm or be harmed by the microwave oven or the foods being cooked.

“MICROWAVE-SAFE” TESTING

European Standard EN 15284:2007 is a test method widely used to determine the suitability of non-metallic cookware for use in a microwave oven [7]. This method assesses the “resistance” of articles to microwave heating and specifically excludes articles that could damage or be damaged by the microwave oven. Furthermore, it cautions against articles containing metal which, of course, include cookware made entirely of metal.

Several metallic cookware products described and promoted as “microwave-safe” are currently available to consumers in the retail marketplace (Figure 2). Such products are also promoted by professional associations representing the stainless steel industry, one of which claims “The safe use of these products is now guaranteed by many research organizations” [8,9]. No standard test method is known to exist for validating these claims, while the identity of research organizations making such guarantees remains a mystery.

While metal has been demonstrated to be safe for use as a packaging material for microwaveable consumer packaged goods (CPGs), the use of such materials is done only with careful product development and testing along with providing instructions for their use to ensure safety [10]. However, this applies only to single-use CPG packages and not reuseable cookware.



Figure 2. Stainless steel cookware products promoted as “microwave-safe.”

CONCLUSION

Non-metallic reusable cookware products labeled “microwave-safe” do not require special instructions to ensure consumer safety. Metallic reusable cookware can be “microwave-safe” when accompanied by adequate instructions for their safe use by consumers. Stainless steel cookware currently promoted to consumers as “microwave-safe” provide these instructions not on the product itself but on the product packaging. Unless consumers retain the product packaging and refer to it whenever the cookware is used, these metallic reusable cookware products are inherently not “microwave-safe.”

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Temperature-Dependent Dielectric Measurements of PAN Fibers During Stabilization Process

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Keywords: Dielectric measurements, PAN fiber, stabilization, carbon fiber production

INTRODUCTION

Carbon fiber composites are highly attractive in applications where the strength-to-weight ratio is critical. However, widespread adoption is hindered by production costs. Among various precursors, polyacrylonitrile (PAN) fibers are the most commonly used for carbon fiber production. The production process involves several stages, each inducing specific chemical, mechanical, or morphological changes. Initially, fibers are drawn from a polymer solution, followed by stabilization and carbonization stages. Each stage is characterized by distinct temperatures. Despite not occurring at the highest temperatures, the stabilization stage is the most energy- and time-consuming. Additionally, it plays a crucial role in producing high-quality carbon fiber. Therefore, modifications to this step, such as microwave heating, have been proposed [1], [2]. Understanding the dielectric losses in PAN fiber can optimize the stabilization process and provide insights into the chemical reactions over time. This study describes the application of a measurement system for real-time, continuous, and non-contact monitoring of the dielectric properties of PAN fiber during stabilization, depending on temperature.

METHODOLOGY

A microwave cavity perturbation method was used to measure the dielectric properties of PAN fiber as it was heated by hot air. The dielectric parameters were calculated using the following equations [2]:

$$\begin{aligned}\varepsilon_r' &= \frac{1}{A} \frac{f_{ref} - f_s}{f_{ref}} \frac{V_C}{V_S} + 1 \\ \varepsilon_r'' &= \frac{1}{B} \frac{Q_{ref} - Q_s}{Q_{ref} Q_s} \frac{V_C}{V_S} \varepsilon_r'\end{aligned}$$

where ε_r' is the relative dielectric constant, ε_r'' is the relative dielectric loss factor, f_{ref} and f_s are the resonance frequencies of the unperturbed and perturbed cavity, respectively. Q_{ref}

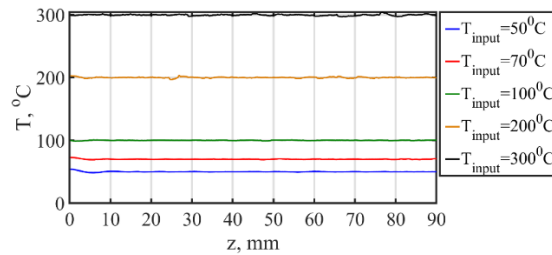


Figure 1. Air flow temperatures along the length of the cavity.

and Q_s are the corresponding quality factors, V_c and V_s are the volumes of the cavity and the sample, respectively. The calibration factors A and B depend on the cavity and sample geometries, the sample permittivity as well as on the final cavity wave pattern. The calibration of A and B is done with the help of CST Microwave Studio within the range of expected dielectric properties.

The measurement system included a cylindrical TM_{010} -mode cavity with a frequency around 2.5 GHz and a quality factor of about 11000. The cavity's height and radius are 45 mm. An N-Type port with a pin antenna was used as the input, and an SMA port with a pin antenna as the output. A PAN fiber, representing a bundle of 6000 filaments, was placed in a quartz tube along the maximum electric field of the TM_{010} -mode. The quartz tube was fixed using a Teflon insulation ring. A HP 8720D Network Analyzer measured the system's resonance frequency and quality factor.

Hot air was heated using a MK-45R heater from Zinser GmbH, Germany. It was modified for analog control. Temperature was measured with a NI-9211 thermocouple input module using type K thermocouples. Two thermocouples were placed at the quartz tube's entry and exit points to measure airflow temperature, while a third and fourth thermocouple measured the cavity and quartz tube temperatures, respectively.

Accurate dielectric constant measurement heavily relied on the precision of the resonance frequency measurement, which was improved by stabilizing the cavity temperature at 20°C using a 106 W Peltier element. PID controllers were developed and tuned to manage the heater and Peltier element power.

RESULTS

The first test measured the air flow temperature along the cavity length to ensure temperature uniformity within the cavity. Figure 1 shows the temperature profiles along the longitudinal axis for different input air temperatures. The temperature shift inside the cavity stays under 10°C and the process temperature is assumed to be constant in the following. Subsequently, the temperature measured by the thermocouple at the cavity input was considered the final temperature and used as a controllable heating parameter.

During the stabilization stage, the precursor was heated to between 200 °C and 300 °C, where chemical reactions of dehydration, cyclization, and oxidation occurred, forming a non-flammable fiber. This fiber could then be heated to up to 1000 °C during the carbonization stage. Figure 2 shows the dielectric property measurement results for a heating rate of 30 °C/min.

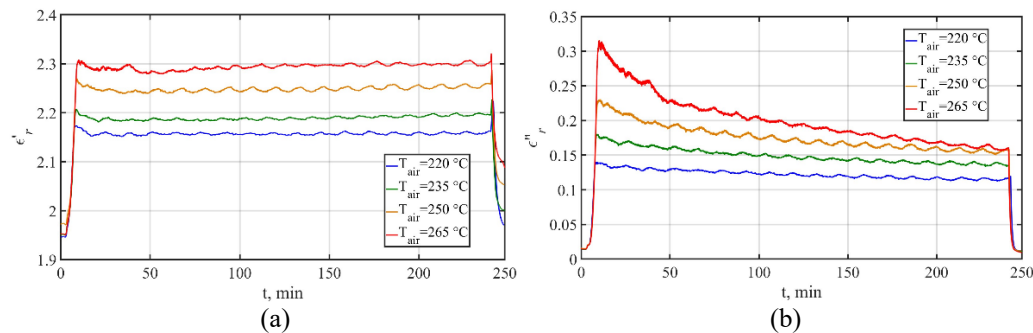


Figure 2. Dielectric properties for different air flow temperatures: dielectric constant (a) and dielectric loss (b) versus time.

DISCUSSION

The dielectric properties exhibited a strong temperature dependency during the heating process. The virgin PAN fiber started with a relative dielectric constant $\epsilon_r' \approx 1.9$ and a dielectric loss factor $\epsilon_r'' \approx 0.015$. The loss factor increased by one order of magnitude with rising temperature, while the dielectric constant increased by approximately 1.19 times, from 1.93 to 2.3. The loss factor decreased with ongoing chemical reactions, whereas the dielectric constant remained nearly constant. During the cooling stage, the dielectric loss further decreased, ending at 0.0092. The dielectric constant also decreased during cooling to about 2.09, 1.07 times higher than the initial value.

CONCLUSION

The measurement system demonstrated changes in the dielectric properties of PAN fiber during the stabilization stage. The measurements indicated a significant temperature dependency of the dielectric properties. The results provide insights into the chemical processes during stabilization, as evidenced by the reduction in dielectric loss and dielectric constant, even after reaching and maintaining the final temperature. The findings can be used to optimize the PAN fiber stabilization process and improve subsequent carbon fiber production stages.

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