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Building a Microwave Community for a Decarbonized Future

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Keywords: decarbonization, electrification, microwave commercialization

ABSTRACT

To achieve the aggressive climate global goals, we will need technologies focused on energy efficiency, electrification, alternative chemistries, and innovative integration strategies for industrial decarbonization. Microwaves can play a large role in the decarbonization of many sectors through these pathways, but it will take a broader more integrated community approach to achieve these goals. There are tremendous achievements happening in academia, the national labs, and industry but are often siloed into their respective topic areas or industries. We learn of these achievements through publications, news releases, and sparse interactions at conferences. Those of us in research are often unaware of the pain points of industry and can get lost in our science. Those in industry are not often connected with the innovative work going on in labs and startups across the globe. How can we build a community to foster the acceleration of microwaves into industry?

This talk will be an interactive forum to discuss our experiences and individual pain points for the development of microwave technologies in new applications (e.g. chemical conversion). We also want to identify the needs within the community and how we can take a better collaborative approach involving academia, labs, industry and hardware developers to realize the full potential of microwaves. We hope this will set the stage for a potential road mapping workshop that can house a collective discussion of these needs and provide a pathway for informing stakeholders for research gaps and forming integrated teams that are prepared for funding opportunities.

Microwave & RF Process Solutions to Deliver Positive Food Choices for Consumers

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Keywords: microwave, food, health, nutrition, labeling, industrial processing

ABSTRACT

Food manufacturers are increasingly faced with regulatory and competitive pressures, as well as strategic opportunities, to increase healthier food choices for consumers. These drivers include front-of-pack labelling systems [1] (e.g. Guideline Daily Amount, Traffic Lights, Nutri-Score, and positive enforcement logos), regulatory frameworks like the UK “High Fat Salt & Sugar” [2], [3], the Ultra Processed Food concept [4], and publicly declared food manufacturers healthy food commitments [6], [7], [8]. This current and emerging context has driven renewed interest and evolving success criteria for evaluation of non-traditional food processing technologies to deliver healthier food options.

Historically, disrupting incumbent, well understood and highly cost optimized technologies (such as frying, hot air, extrusion, retorting, pressure expansion) has been very challenging. Industrial microwave food processing has found limited success outside notable exceptions (bacon cooking, tempering, and many small scale installations of vacuum microwave drying, pasta and vegetable drying, and a handful of pasteurization and sterilization systems). RF is widely used to finish-dry food (e.g. crackers, cookies) as well as tempering.

Case studies will be presented of several microwave & RF process development projects aimed at delivering positive food choices for consumers (e.g. nutrient-retentive, consumer-credible ingredient claims, lower fat/salt/sugar) along with some of the challenges commercializing such processes from the perspective of large food manufacturers.

Potato Chips (or Crisps in the UK) are made from sliced potato and are traditionally fried. The fryer time-temperature profile determines texture (along with potato variety and slicing), and can range from light/crispy to hard-bite/crunchy. Delivering the same consumer-preferred texture and flavour through a non-fried process has been the subject of much research since the 1960's. One case study describes a microwave-based process that delivers a 50% less-fat chip with equivalent consumer liking to fried (in concept led testing). This is contrasted with a process where the product transformations experienced by a sliced potato in a fryer were not replicated, negatively impacting consumer liking, but resulted in a simpler process which met with limited commercial success.

The same microwave-based process principles can be applied to deliver formulated snacks made from fresh vegetables/fruit/roots/tubers/herbs, which deliver consumer-credible clean-label on-pack ingredient declarations which meet high regulatory bars for low fat, salt and sugar, without comprising taste. Case studies include market-place testing.

Microwave or RF finish-drying par-fried potato chips have been shown to have very different technical and commercial success. Whilst benefits include reduced undesirable process contaminants (such as Maillard reaction products) and throughput increases, commercial viability depends as much on process control as well as material properties.

Microwave vacuum drying is increasingly used to make snacks and food ingredients from portions of whole fruit, vegetable and cheese [9]. Case studies are presented.

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Microwave Technology for Solid Waste Treatment and Aerosol Disinfection

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Keywords: microwave pyrolysis, solid waste utilization, aerosol treatment, grain disinfection

ABSTRACT

Microwave technology has gained prominence in various industries, such as chemical engineering, materials science, and food engineering, due to its unique ability for rapid and selective heating. This abstract highlights the utilization of microwaves in two key areas: solid waste treatment and aerosol disinfection.

In the realm of solid waste utilization, our team has successfully developed and scaled up an advanced catalytic microwave-assisted pyrolysis/gasification system. This innovative system, featuring a mixing SiC ball bed and a downdraft design, demonstrates superior performance with a cold gas efficiency of 73.3% at 800 °C and an electrical energy consumption of 7.2 MJ per kg of wood pellets. Notably, this system has been effectively employed for converting plastic waste into valuable products, reaching a commercial pilot demonstration stage (1-5 tons per day). Through the use of specially developed structured catalysts, high-quality naphtha or monomers are produced, contributing to a circular economy and reducing greenhouse gas emissions. With a remarkable total energy efficiency of 89.6%, our catalytic microwave pyrolysis/gasification system achieves energy self-sufficiency. Techno-economic analysis suggests a net annual profit of USD 50,000 and a 4% return on investment at a scale of 5 tons per day, with the potential for further improvements at larger pilot scales.

In the domain of aerosol disinfection, we have designed an experimental apparatus capable of effectively disinfecting virus-containing aerosols. By incorporating microwave-absorbing ceramic foam filters made of silicon carbide, we achieved remarkable results in

capturing and disinfecting Avian Influenza Virus (AIV) aerosols. Our lab-scale Microwave Assisted Disinfection of AIV Aerosols (MADA) device demonstrated complete inactivation of low pathogenic Avian Influenza (LPAI) H5N2 virus aerosols (10^5 - 10^6 PFU/m³ air) with an exit air temperature of 60°C and a residence time of 0.48 seconds, consuming 175 J/liter of treated air. The addition of a zeolite coating onto the SiC foam structure significantly reduced energy input, enhancing filtration effects. Compared to conventional systems, our microwave treatment achieved complete inactivation at a lower exit temperature, with a maximum reduction in E. coli up to 3.3 log.

Additionally, our research extends to grain disinfection, where microwave-treated kernels exhibited a notable increase in germination rate from 74% to 90%, while the fusarium infection rate decreased significantly from 23.75% to 4%. The combination of microwaves and fluidized bed processing for contaminated wheat kernels achieved a remarkable reduction in E. coli of up to 5.22 log in just 30 seconds, without compromising quality.

These findings underscore the versatility and effectiveness of microwave technology in diverse industrial processes, with significant implications for sustainability and efficiency.

Decontamination of Wheat Grains by Continuous Flow Microwave System

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Keywords: wheat, decontamination, continuous, microwave

INTRODUCTION

Microwave technology has gained significant attention as an effective method for eliminating contaminants and pathogens from food products due to its rapid and efficient characteristics. Specifically for wheat grains, this technique involves exposing them to microwave in a continuous system, controlling the power and residence time to ensure a homogeneous treatment and uniform decontamination. Traditionally, chemical fumigation has been the conventional treatment choice owing to its affordability, rapid processing speed, and user-friendly application. However, the concerns regarding the health risks associated with chemical pesticides and environmental pollution led to the research of alternative methods. Microwave technology stands out among the various treatment methods for the selective heating capacity, the fact that it is environmentally friendly, and its ability to maintain similar or superior quality while minimizing energy consumption. Some previous studies explored grain or nuts decontamination using microwaves, comparing also to other techniques in terms of quality of treated grains [1–4].

METHODOLOGY

Wheat grains were fed into the microwave system through a hopper and a peristaltic pump (scheme shown in the Figure 1). Microwave energy is sent to a rocket containing a quartz tube inside (intern diameter of 80 mm and length of 1500 mm). Upon arrival at the rocket, a temperature sensor measures the incoming grain temperature. Inside the microwave cavity, an infrared sensor records the surface temperature of the tube, and there is also a temperature sensor at the outlet. After passing through the rocket, the grains were removed and packaged in big bags. The rocket system was connected to a microwave generator and an isolator. Adaptation was promoted by a short-circuit piston and three stubs. The operational frequency was set at 915 MHz, and the maximal power supplied by the generator was 54 kW. The optimal product's flow was determined by weighing the amount of grain that exited the rocket within a specified time. This step facilitated the calibration of the pump responsible for feeding grains into the rocket. Once the grain flow was established, the microwave generator was activated at low power, and the adaptation elements (short-circuit piston and stubs) were adjusted to limit the reflected power.

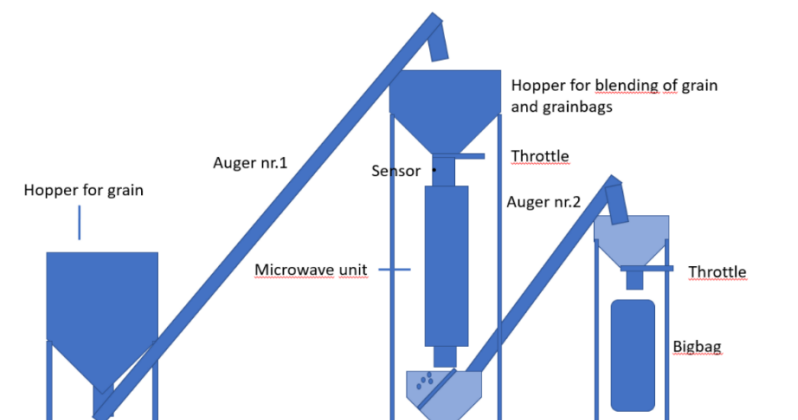


Figure 1. Schematic diagram of the microwave continuous system with feeding and removal of the grains.



Figure 2. Microwave continuous system.

RESULTS

The optimal conditions for wheat treatment were achieved with a flow of 1015 kg/h and 54 kW of power (which led to 1.1 kW of reflected power). The grain temperature at the inlet into the rocket was 24 °C, the temperature of the tube's surface during treatment was 112 °C, and the outlet temperature was 109 °C. The temperature of the treated wheat inside the big bag was of 92 °C. The test proceeded for 40 min (although the residence time inside the microwave cavity was only a few seconds). Microbiological tests were performed in

Table 1. Moisture content, Total bacterial count (UFC) and Enterobacter count for control and treated wheat grains.

Sample	Moisture content (%)	CFU (mg/kg)	Enterobacter (mg/kg)
Control	6.21 ± 0.99	137000	12800
Treated	5.53 ± 0.58	<100	<100

the control and treated samples. The results of moisture content, total bacterial count (Colony-Forming Units, CFU) and Enterobacter count are shown in Table 1.

DISCUSSION

Even at high temperatures, water loss was minimal, and no color change was observed. It was noted that the type of packaging after treatment is a crucial factor. If the grains are not adequately cooled before being placed inside the big bags, condensation may occur due to the high temperature, potentially leading to mold formation. Additionally, a lower product flow resulted in increased sticking of the grains inside the tube.

CONCLUSION

The continuous treatment of wheat grains by microwave was efficient in considerably reducing the initial microbiological count, besides significantly reducing the time required for the treatment compared to traditional processes and avoiding the need for chemical products in the treatment process.

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Solid-state Microwave Technology for Pathogenic Tissue Ablation

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Keywords: solid-state, medical, ablation, ex-vivo, tissue, cancer

INTRODUCTION

Microwave (MW) ablation is a minimally invasive technology [1] that uses local temperature increase - by means of the dielectric heating effect - to produce denaturation of the cellular membrane proteins, causing the membranes to rupture and inducing coagulative necrosis after having exceeded specific thermal thresholds. This technology is suitable for cancer treatment, heart rhythm disorders, benign tumors and other clinical needs. The momentum of this technology is mainly pushed by the availability of solid-state generators, that allow accurate parametric controllability and are smaller, lighter, more robust, and ensure a much longer lifespan – with unaltered performance - than tube-based ones.

METHODOLOGY

A prototypal solid-state hybrid radiofrequency and MW generator was developed for the experimental test of tissues ablation using water-cooled laboratory probes equipped with thermocouple (TC) sensors and with ex-vivo tissues as targets. The MW section of the hybrid generator is based on Leanfa's LEANGEN-2450M-250-M generator module, delivering up to 250W in the 2400-2500MHz ISM band both in CW and in pulsed mode by means of a dedicated software platform for real-time control and monitoring of all the operating parameters.

Leanfa's Hybrid Generator can deliver up to 250W on 50 Ω at 2450MHz and up to 50W on 100 Ω at 450kHz. In RF mode, the device manages the output power delivery as a function of the measured tissue impedance and temperature profile. In MW mode, the generator manages its power delivery according to the reflected power feedback and to the measured tissue temperature. A peristaltic pump was used to cool the laboratory probes with saline solution while the energy was delivered to the ex-vivo tissues in CW mode.

The RF probe is composed of two cables running through the applicator down to two electrodes, whose size and distance determine the shape of the ablation volume. The MW probe is composed of a micro-coaxial cable and a coaxial termination, that behaves as an antenna from an electromagnetic point of view, as a needle from a clinical perspective. Both laboratory probes integrate a micro-hydraulic cooling circuit to prevent unwanted

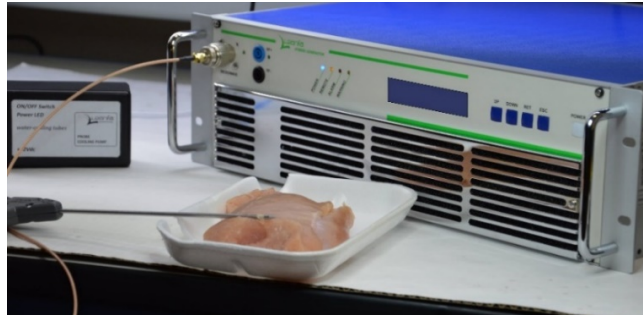


Figure 1. Leanfa Hybrid Generator in an experimental setup

heating of tissue portions outside the target volume, caused by Joule effect related to conductor losses. The probes also feature a TC positioned near its tip for ablation temperature monitoring and one immediately outside the ablation zone, to monitor unwanted hot spots in healthy tissues that are not in the target volume.

The main technological focus of the experimental ablation treatments was to check the capability of the system to confine the therapeutic thermal profiles within the pathogenic tissues, thus avoiding damage to healthy tissues located near the diseased ones. Experimental procedures were performed, with bovine liver and chicken breast, using a temperature-controlled algorithm, performing a constant-slope rise to reach the target temperature followed by a flat profile for a pre-defined time. Since protein denaturation starts at around 60°C [2] and the water boiling temperature is around 100°C, a suitable target temperature was 95°C, to heat the tissue as much as possible without generating bubbles that could mismatch the load in terms of MW coupling.

RESULTS

The results were analyzed using the clinical approach of looking for maximally large ablations and with the highest Roundness Index (RI). In fact, the regular spherical shape, without the so called tail effect, perfectly fits the need of hitting only the target tissue, maximally safeguarding the nearby healthy ones. The RI is a value between 0 and 1, calculated as ratio between two ablation diameters, i.e. Size B/Size A in figure 2.

The RI value was evaluated at the end of each experimental procedure: the ex-vivo samples were sectioned along the probe axis to evaluate the shape and extension of the ablation pattern. Each heat pattern around the probe showed a hotter region close to the probe axis where, at the end of the treatment, the tissue became particularly dried. Just outside this central region, the ablated tissue was white and less dried than in the central region, leading to an overall ellipsoidal ablation pattern. Experimental results recorded that the central region kept slightly lower than 100°C while the surrounding tissues reached temperatures in the 60-65°C range.

The ablations performed on bovine liver tissues produced patterns with RI from 0.78 to 0.83, the ones performed on chicken breast tissues yielded RI values in the range from 0.86 to 0.91, using MW radiation in CW mode for 10 minutes. The two diameters sizes were

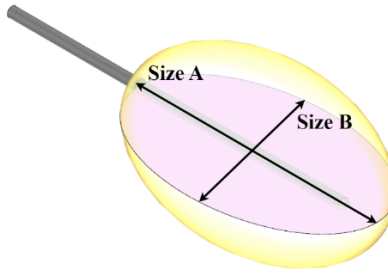


Figure 2. Parameters for Roundness Index calculation

bigger for chicken breast, due to the different dielectrical properties and the less uniform composition of bovine liver, featuring a denser vascularization that limits heat propagation.

DISCUSSION

The results obtained are consistent with those documented by literature [3] and data provided by the main players in the cancer ablation market. Obviously, the procedures performances can be significantly improved if the solid-state technology is associated with probes designed with advanced technologies and simulation systems. An optimal combination of this technology with state-of-the-art probes could significantly reduce surgery times, exposing the patient to less risk, and maximally safeguarding healthy tissues.

CONCLUSION

Solid-state microwaves were demonstrated to be a powerful enabler technology for accurate minimally invasive treatments, allowing the accomplishment of efficiently confined ablation patterns, safeguarding healthy tissues surrounding the pathogenic ones. Promising future developments, allowed by the extreme flexibility of the parametric control of solid-state generators, include advanced volumetric control with multi-probe applications and self-regulated treatments powered by sensorized probes that can allow greater customization of the ablation shapes. The problem of the resulting higher costs is certainly compensated by a reduction in hospitalization times and of the metastasis recurrence probability. These improvements can be combined to get the best out of each of the two RF and MW technologies, thanks to the use of hybrid generators that allow, depending on the case, providing a specific therapy.

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Boosting Reverse Water Gas Shift Reaction over Microwave-excited Metal Cations in Zeolite Nanocavity

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Keywords: microporous materials, hot spots, CO₂ utilization, reverse water gas shift reaction

INTRODUCTION

Microwave (MW)-driven catalytic processes are now gaining attention of its high efficiency compared to conventional heating (CH) method [1]. MWs can directly and selectively heat the catalysts, resulting in rapid heating of catalysts. In addition to the energy efficiency of the heating, various effects of MW irradiation for enhancing the catalytic reaction have been reported. These ‘MW effects’ should be explained by a heating mechanism based on ‘selective heating’, which cannot be achieved by CH. The selective heating occurs in various scales. Therefore, the deep insight into the selective heating which is caused by MW provides important guidelines for catalytic reactions driven by MW irradiation. Recently, our research group reported atomic-scale selective heating of alkali metal cations in FAU zeolites. This atomic-scale selective heating achieved a lower apparent reaction temperature (catalyst bed surface temperature) and improved selectivity in methane oxidation reactions with alkali metal cations as catalytic active sites [2].

This study investigated the influence of zeolite framework and metal cation species on the atomic scale selective heating of metal cations in zeolite micropores. Zeolites of various structures were introduced with metal cations and the atomic-scale temperature gradients between the zeolite framework and metal cations were investigated, mainly based on microporous size and electronic state etc. The hydrogenation of carbon dioxide was demonstrated using this atomic-scale, microwave-heated cations as the active sites, proposing the unique reaction field provided by atomic-scale local heating.

METHODOLOGY

Various metal cation-exchanged zeolites were prepared via liquid phase ion exchange method: NH₄⁺-type MFI (Si/Al = 11.5) was stirred in a metal nitrate solution for three times. Consequently, metal cation exchanged MFI was obtained. In⁺ incorporated zeolites were prepared via a reductive solid-state ion-exchange (RSSIE) method. In₂O₃ was supported on zeolites through impregnation method using indium nitrate solution with NH₄⁺-type zeolites, which were ion-exchanged by H₂ treatment at 500 °C.

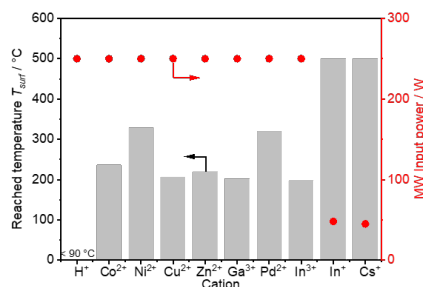


Figure 1. Reached temperature for incident wave power of each MFI zeolite.

MW heating tests were carried out using a GaN semiconductor microwave oscillator (900-930 MHz, Ryowa Electronics Co). MWs were irradiated through an impedance matcher into the cavity of the TM₀₁₀ mode. The temperature of the catalyst layer was measured by an IR thermometer which was calibrated on basis of the emissivity of the catalysts.

The CO₂ hydrogenation reaction was performed using a plug-flow reactor. The catalytic reaction was carried out with a gas composition of CO₂: 5-20 kPa, H₂: 10-40 kPa (N₂ balance, $P_{total} = 101$ kPa) and the contact time between the reaction gas and the catalyst was controlled by varying the flow rate from 10-100 mL min⁻¹. The outlet gas was analyzed using a microGC (INFICON) equipped with a TCD. Under CH condition, catalyst bed temperature was measured by a K-type thermocouple inserted into the electric heater.

RESULTS AND DISCUSSION

MW heating tests were conducted on various metal cation-exchanged MFI zeolites as shown in Figure 1. All heating tests were conducted under N₂ flow to avoid the change in oxidation state of metal cations. The heating behavior significantly depended on the metal cation species, indicating that the metal cations were directly excited under MW irradiation. Among the metal cations, In⁺-MFI reached 500 °C under MW irradiation with below 50 W input power.

In situ high energy total X-ray scattering (HEXTS) measurements under MW irradiation were performed to gain further insight into the selective heating of In⁺ cations in the zeolite framework at the atomic level. Figure 2 shows the temperature dependence of the pair distribution function of the In⁺-CHA obtained by Fourier transformation of total X-ray scattering factor $S(q)$. The peak attributed to In-O was specifically reduced only under microwave irradiation, while the peak height was almost constant under CH. X-ray scattering intensity decreases with increasing temperature according to the thermal scattering factor (Debye-Waller factor). Thus, the specific reduction of the In-O peak under microwave irradiation indicates local selective heating of In⁺ cations by microwaves.

CO₂ hydrogenation reactions was performed over In⁺-CHA, In⁺-MFI, and In⁺-FAU under MWs. Here, CO selectivity via RWGS reaction was 100 % (below detection limit for the other products). Since no activity was observed for the H⁺ type zeolite, the In⁺ cation acts as the active site for this reaction. The H₂ and CO₂ partial pressure dependence were not affected by MW irradiation, indicating that the reaction mechanism was not changed under MW. Figure 3 shows the Arrhenius plots of the RWGS reaction over each zeolite. Note

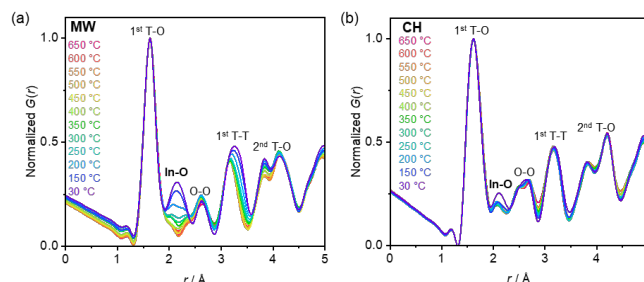


Figure 2. Pair distribution function of In^+ incorporated CHA zeolite obtained by in situ HEXTS measurement at various temperature under (a) MW and (b) CH.

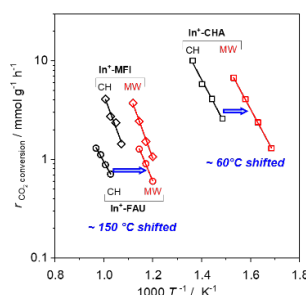


Figure 3. Arrhenius plots for CO_2 hydrogenation of In^+ -CHA, In^+ -MFI, In^+ -FAU. (P_{CO_2} : 10 kPa, P_{H_2} : 30 kPa, P_{tot} : 101 kPa)

that the temperature was the surface temperature of the catalyst bed measured by IR thermometer. The plots shifted toward lower temperatures under MW heating compared to CH method. Thus, the temperature of the catalyst active site, In^+ , was higher than the catalyst bed surface temperature. The temperature gradient in the local high-temperature field was dependent on the zeolite structure, with larger pore size FAUs producing larger thermal gradients in the atomic-scale local high-temperature field.

CONCLUSION

This study investigated the formation of atomic-scale temperature gradients of In^+ exchanged zeolites. MW heating tests on In^+ -zeolites with different frameworks showed that the smaller the zeolite pore size, the higher the heating efficiency. The RWGS kinetic analysis also showed that the catalytic active sites of In^+ are locally heated by MWs, which enhances the catalytic reaction. This study proposes an atom-scale strategy to input heat with high energy efficiency into endothermic RWGS, a reaction that contributes to the process of synthesizing various chemical products from CO_2 .

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Generator Technology Options for Microwave Driven Methane Pyrolysis

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Keywords: cost, efficiency, generator, heating, magnetron, microwave, solid state

ABSTRACT

There are numerous challenges associated with scaling up a process from lab to pilot scale and beyond. Material selection and feasibility are one such challenge, while power generation is another: practically and considering economies of scale [1]. In the context of microwave heating, magnetron and solid-state technologies compete in areas of cost, safety, power, efficiency, life, and signal purity [2]. As Aurora Hydrogen scales up in design, so do power requirements. A sensitivity analysis of efficiency is performed as it relates to absorbed power for solid state and continuous wave magnetron-based technologies. Associated costs of each technology are compared at selected scaling levels.

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Development of a Field Deployable Microwave Assisted Pyrolysis System

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Keywords: microwave assisted pyrolysis, waste management, scale-up, deploy ability

INTRODUCTION

Organic and recalcitrant waste materials, like plastics, are becoming significant environmental and human health problems [1]. Pyrolysis, which involves heating of carbon rich materials in low oxygen atmospheres to induce thermal degradation of the materials, has proven to be a viable alternative to conventional waste disposal methods, such as disposal to land fill, composting, animal feed (for some food scraps), or incineration [2]. Pyrolysis yields char, oil, and gas [2-3]. Microwave assisted pyrolysis has significant advantages over conventional heating methods, including faster processing, better energy efficiency, better process control, more porous biochar, and greater oil and gas yields [4-5]; however, scale-up of microwave systems has always been challenging. This paper presents some milestones on the journey towards microwave assisted pyrolysis of waste at a usable scale.

THE JOURNEY TO THIS POINT

The journey towards a useful system has involved several steps. Initial experiments were conducted in a one-litre, single mode chamber, operating at 2.45 GHz, using stabilized sewage sludge as the pyrolysis feed stock [5]. The one-litre chamber, shown in Figure 1 (a), allowed small samples (approximately 100 g) to be processed and was fed with microwave energy from a rectangular to circular wave-guide transition. Vacuum and nitrogen gas was applied to the chamber through the lid and vapour was extracted from the chamber using the vacuum pump. Condensers were used, between the chamber and the vacuum pump, to trap condensable components of the vapour stream. A microwave susceptor, mixed into the waste material at ratio of 10 % by dry weight, was necessary to initiate the pyrolysis reaction. Activated carbon was used to absorb the microwave energy and transfer heat to the feedstock until pyrolysis of the feedstock began, because the dielectric properties of dry organic materials and plastics are very low [5]. Biochar from previous experimental batches proved to also be a good microwave susceptor. The results

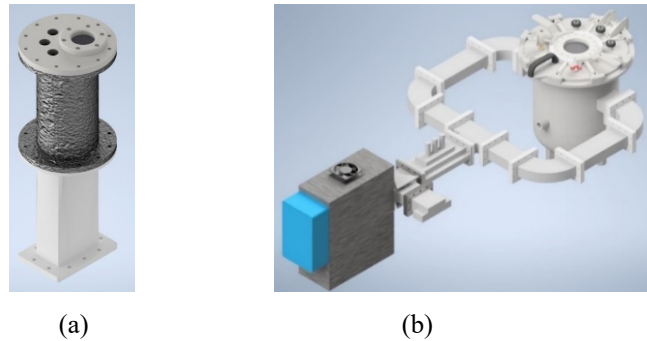


Figure 1. Experimental microwave chambers used to explore the potential for microwave assisted pyrolysis of organic wastes (a) the single mode microwave chamber with rectangular to circular wave-guide transition and (b) the 30-litre multimode chamber with microwave generator, circulator, and wave-guide arrangements.

were very promising [4-5] and led to the design of a 30-litre multimode chamber, also operating at 2.45 GHz (Figure 1 (b)).

The 30-litre chamber was fed from a 3-kW variable power generator, operating at 2.45 GHz. It featured a split feed to achieve more even distribution of the electromagnetic field through the chamber. The chamber had a hinged lid and quick action rotor clamping system to allow ready access and easier loading and unloading of the test samples. Samples of 2 to 3 kg of feedstock were regularly processed in this chamber, demonstrating that the concept of microwave assisted pyrolysis could be up scaled to some degree. Nitrogen, vacuum, and volatile extraction were applied through the lid. Samples of food waste, plastics, uncontaminated surgical waste (drapes, gowns, and gloves etc.), and stationery (paper and cardboard) have been processed in the 30-litre chamber. Experimental results, using this chamber, have also been very promising [2]. Extensive electromagnetic modelling, using FDTD techniques (Remcom Xfdtd), was used throughout the design phases of all the chambers to evaluate the distribution and propagation of microwave energy throughout the chamber and load materials. The dielectric properties of the various feedstocks were measured experimentally in most cases.

THE CURRENT SYSTEM

Based on the promising outcomes from the previous research, an opportunity to scale-up the concept from 30-litres to approximately 1,000-litres came from a request and accompanying funding from the Australian Department of Defence. They desired a system that could be used to process a variety of carbon-based wastes (food waste, surgical waste, plastics, and stationery) during military field deployments. The system needed to fit into a shipping container in order to be considered deployable. It is fed from one 5 to 54 kW microwave generator, operating at 922 MHz. The chamber is fed by splitting the output from the generator into four wave guide feeds, with two polarizations. Two of the chamber input feeds are vertically polarized and two are horizontally polarized. The feed ports are also at two different heights (Figure 2) to avoid resonances as much as possible. As with the 30-litre chamber, the purpose of this feed design is to achieve a more even field distribution inside the chamber.

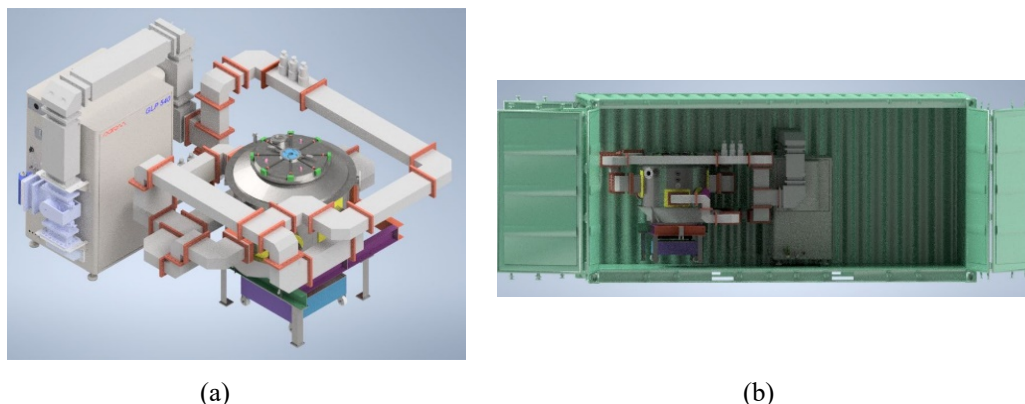


Figure 2. (a) Prototype 1 m³ microwave pyrolysis chamber showing wave-guide arrangements and microwave generator and (b) showing how the system fits into a shipping container for transport and deployment in the field. Space is available in the container for controllers and oil condensers.

The chamber has a loading lid with a quick action rotor clamping system at the top. There is a mechanical mixer inside the chamber, which stirs the material before or during microwave heating to ensure there is a more even distribution of heat through the larger samples. This stirrer should also act as a mode-stirrer to excite a wider range of electromagnetic modes inside the chamber as well. There is a trapdoor at the bottom of the chamber for rapid dumping of the biochar from the chamber after processing. Application of vacuum, nitrogen gas, and extraction of volatiles is through the walls of the chamber rather than through the lid. The bottom section of the chamber has forced air cooling to help dissipate heat from the pyrolysis process. Programmable Logic Controllers control the system and an extensive array of sensors have been incorporated into the system to capture and store data for further analysis. The system is a work in progress and is currently undergoing extensive commissioning tests to ensure that it is performing as expected. Some issues have been identified and rectified during these ‘shake down’ tests. It is anticipated that preliminary experimental data should be available for presentation at the upcoming symposium.

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Investigation of the Capabilities of a 5.8 GHz Microwave Plasma Source for Microchip Decapsulation

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Keywords: microwave induced plasma (MIP), microchip decapsulation, microwave frequency, 5.8 GHz plasma source

INTRODUCTION

Decapsulation of microchips aiming at revealing the contained components for visual inspection can be carried out by plasma etching the microchip cover, and microwave induced plasma (MIP) sources can be used in that context. In that case, the microchip is placed downstream a microwave source producing the gas radicals required for the chemical reactions responsible for the etching process. MIP sources can work at different frequencies, the most common being 2.45 GHz. Both the size of the MIP source and the maximal amount of radicals that it can create depend on the microwave frequency (electron density being proportional to the square of the plasma frequency [1] – wavelength being inversely proportional to the microwave frequency). An increase in microwave frequency seems thus advantageous in terms of compactness and efficiency. Therefore, this work compares the capabilities of a MIP source working at 5.8 GHz to those of a reference source working at 2.45 GHz in the context of material etching.

EXPERIMENTAL SETUP AND PROCEDURE

Preliminary experiments are conducted using the 5.8 GHz MIP source visible in Figure 1(a) for etching one or several graphite cubes that are placed in a chamber consisting of an ISO-K63 instrument cross (see Figure 1(b)). The gas fed into the MIP source consists of a mixture of O₂ and N₂, while the pressure in the chamber is maintained at 2 mbar. The mass of each graphite sample is measured before and after 30min of plasma processing and the etch rate in mg/min is computed from the measured loss of mass. This experiment is repeated by varying the microwave power supplied to the MIP source from 225 W to 675 W.

The same experiments are also conducted with a 2.45 GHz MIP source mounted on another processing chamber. While the chamber sizes are different, the distance between the graphite sample(s) and the plasma source is the same, thus enabling the comparison of the

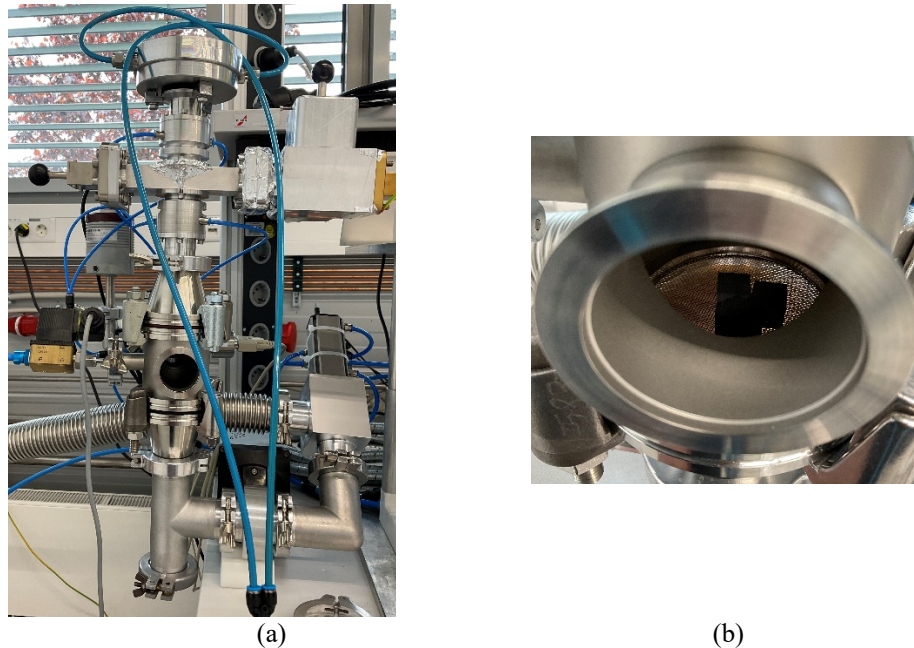


Figure 1. View of the experimental setup with the 5.8 GHz MIP source: global view (a) and view of the processing chamber (b).

obtained etch rates. In this case, the supplied microwave power varies from 500 W to 2 kW (higher power required when working at lower frequency).

RESULTS AND DISCUSSION

Figure 2 shows the etch rates obtained by etching one graphite cube with the 2.45 GHz and the 5.8 GHz MIP sources (gray circles and black squares, respectively) for several supplied power levels. For the 5.8 GHz MIP source, the etch rates obtained by processing two and three samples simultaneously are also depicted (black triangles).

Comparing the results obtained for a single sample, the etch rate increases with the supplied power in a similar way for the two working frequencies, both evolutions depicting a slower increase zone followed by a faster increase zone separated by a “jump” (at 375 W and 750 W for 5.8 GHz and 2.45 GHz, respectively). For 2.45 GHz, the etch rate seems to go into saturation as the power increases above 1.5 kW. Moreover, a loading effect is highlighted when comparing the results obtained for a single sample and for several samples, as the etch rate increases not linearly with the number of samples (same amount of radicals available to react with more material). Finally and most importantly, for the same supplied power, the etch rate obtained for the MIP source working at 5.8 GHz is (much) higher than the one obtained at 2.45 GHz (by a factor of 13 at 700 W in the slower increase zone of the 2.45 GHz MIP source, and by a factor of 2 to be expected in the higher increase zone of both sources).

These results confirm that a much lower power can be supplied to the 5.8 GHz MIP source compared to the source working at 2.45 GHz for reaching the same etch rate (because of

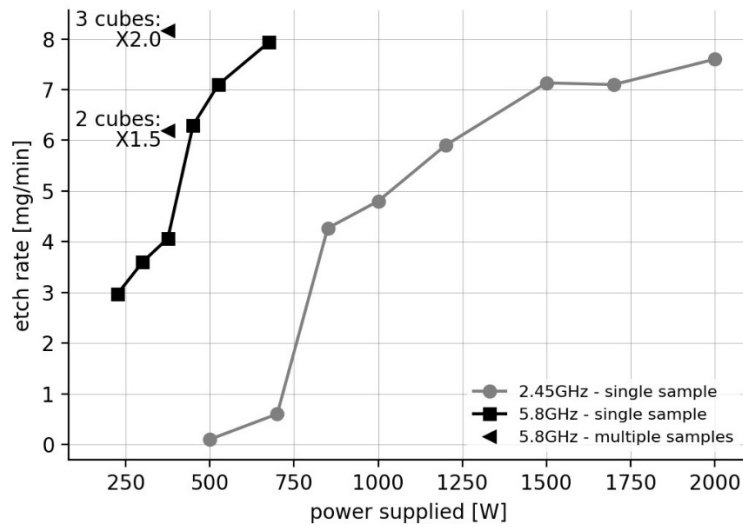


Figure 2. Comparison of graphite etch rates obtained with a 2.45 GHz and a 5.8 GHz microwave plasma system.

the higher electron density of the plasma generated at this higher frequency). This paves the way for the development of a compact microchip decapsulation tool working at 5.8 GHz.

CONCLUSION

Plasma etching tests were conducted using two MIP sources, one working at the commonly used frequency 2.45 GHz, and one working at 5.8 GHz. The results demonstrate that a lower supplied power can be used to reach the same etch rate when using a 5.8 GHz MIP source. This confirms that a 5.8 GHz MIP system for decapsulation of microchips can be advantageous in terms of process efficiency and compactness.

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Effect of Radio Frequency Based Thermal Processing on the Volatile Flavour Chemistry of Peas

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Keywords: volatile organic compounds, gas chromatography/mass spectrometry (GC-MS), headspace solid phase microextraction (HS-SPME), plant-based protein

INTRODUCTION

Peas are an abundant source of sustainable plant-based proteins. They have good protein content (20 to 30%), low in fat and their consumption is associated with health benefits. Peas belong to the legume family and are grown as rotation crops to promote soil health because of their association with nitrogen-fixing bacteria and ability to enrich soil nitrogen [1]. Protein rich pea seeds are processed by removing their seed coats and milling them into fine flours. They are further processed either by air classification to yield protein-rich concentrate and starch-rich fractions or by wet extraction to yield high-protein isolates. This results in a variety of ingredients, such as whole seeds, dehulled split cotyledons, flour, protein concentrate, starch and protein isolates, that find various applications in the food industry. However, the widespread consumption of plant-based ingredients from peas is limited by their poor sensory properties, techno-functional characteristics and presence of anti-physiological factors. Many of these negative attributes could be overcome by using novel processing technologies. Radio Frequency (RF) treatment has been applied for processing foods to achieve reduction in microbial and pest content, as well as for drying of materials [2]. We had previously evaluated and reported the effects of RF based thermal treatment on the molecular composition and functional properties of plant proteins [3]. Here, we present the effects of RF based thermal processing on the composition of volatile organic compounds that affect the flavour profiles of the pea-based ingredients.

METHODOLOGY

Whole yellow peas (variety CDC Lewochko) with a protein content of $27.35 \pm 0.5\%$ (dry weight) and a moisture content of $13.86 \pm 0.15\%$ was used. Two batches of 40kg of seeds were treated with RF using the GP-15 continuous-flow RF equipment (QMTI, Prince Albert, SK, Canada). The RF equipment works at a frequency of 27.12MHz and is capable

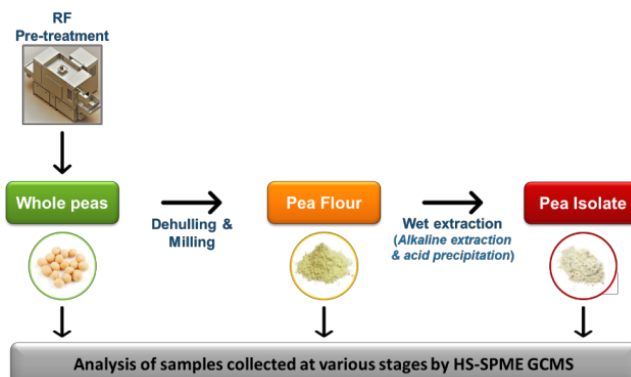


Figure 1. RF process flow for whole pea seeds followed by de-hulling, milling and wet extraction.

of a maximum power output of 15kW. The equipment parameters, such as electrode gap, anode current and belt speed were adjusted to attain an approximate temperature of 85°C for the first batch of seeds named ‘RF Low’ treatment and an approximate temperature of 115°C for the second batch of seeds named ‘RF High’ treatment. The temperature of the seeds was measured by IR sensors at the outfeed and also using temperature-sensitive indicator strips embedded in the seeds. The RF treated seeds were cooled down to room temperature. The untreated and RF treated seeds were dehulled and milled to produce pea flour. Wet extraction processing using alkaline extraction and acid precipitation yielded high-protein pea isolates (Figure 1). An Agilent 6890 GC/5973 MSD equipped with a PAL RSI 85 autosampler (Agilent Technologies, Santa Clara, CA, USA) was used to analyse the volatile profiles. A 2g powder of each sample was weighed into clear glass vials (20mL; Chromatographic Specialties, Brockville, ON, Canada). A blank was prepared with 2g of NaCl. The vials were stored at 4°C and were brought to room temperature (21-23°C) for 1 h before volatile analysis. Volatile compounds in the free head space above the samples were extracted by placing them in an agitator set at 50°C for 45min and were absorbed on a SPME fibre [4]. A carboxen/Polydimethylsiloxane (CAR/PDMS) (Supelco, Bellefonte, PA, USA) fibre was conditioned at 285°C for 3min before the volatile compound adsorption. GC front inlet was set as pulsed splitless mode. The SPME fibre desorption was performed at 285°C for 0.3min, followed by elution at 35°C using pure helium (1.5mL/min) on a DB-5MS capillary column (30m × 0.25mm × 0.25µm film thickness, Agilent Technologies). The gradient was held at 35°C for 3min, increased to 80°C at a rate of 6°C/min, then up to 280°C at a rate of 20°C/min and held at 280°C for 2min. The MS was acquired by scan from 35 to 200m/z with the source set at 230°C, quad set at 150°C and 70.3eV of fixed electron energy. Compound identification was done using library search (NIST 20.L database) using the Agilent Mass Hunter software.

RESULTS

HS-SPME-GC-MS was used to characterize the volatolomes of samples, which is a study of the volatile compounds present in a food matrix. The untreated whole seeds mainly contained toluene. Upon both RF pre-treatments, the quantity of aldehydes, such as hexanal and isovaleraldehyde, increased compared to the untreated seeds. Interestingly, several new

alkyl pyrazines were present abundantly in the RF High treatment. While hexanal was one of the most dominant compounds present in the RF Low samples, 2, 5-dimethyl-pyrazine was more abundant than hexanal in the RF High samples. In all three dehulled and milled flours, toluene became the dominant volatile compound. Hexanal was still identified in all three flour samples. The pyrazine compounds were reduced in the RF High flour when compared to the RF High seeds. In all three protein isolate samples, the hexanal content was increased compared to whole seeds and flours. In the RF Low and RF High pea isolates, the ketone compound 4-hydroxy-4-methyl-2-Pentanone, was identified as a significant peak. The pyrazines that were found in RF High seed and flour were absent in the RF High isolate.

DISCUSSION

Hexanal is an off-flavour compound present in pea and other plant-based ingredients. It has a green or grassy aroma that is perceived as a negative sensory factor. It is a product of oxidative break down of fatty acids and its production is promoted by both enzymatic and thermal degradation. Although both the RF treatments had triggered an increase in hexanal in seeds and flours, with time and favourable conditions, the untreated pea isolate had hexanal content that was almost comparable to the RF treated isolates. Interestingly, in the RF High pre-treated whole seeds and flour samples, several pyrazine compounds were present abundantly and some of them were present at higher amounts relative to hexanal. Pyrazines are associated with favourable aroma characteristics, such as roasted and nutty. However, these pyrazine compounds were diminished or absent from the volatiles of the RF High pea isolate, either because they are transient in nature or because they were washed away during the wet fractionation process.

CONCLUSION

RF pre-treatment of peas induced significant changes in the volatile organic compounds of the whole seeds, as well as the downstream ingredients obtained from them. RF High treatment at an average temperature of 115°C led to the production of several abundant pyrazine compounds in situ, leading to the development of a favourable roasted aroma profile and masking of the original grassy odour. Thus, RF pre-treatment of peas could be used as a strategy to enhance its flavour profile and increase consumer acceptance.

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Identification of Turntable Function in Solid-state Microwave Heating Processes with Shifting Frequencies

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Keywords: solid-state microwave, turntable function, elevation, rotation, heating performance

INTRODUCTION

The rotating turntable has been used in the conventional magnetron-based microwave ovens to improve the heating uniformity. Meanwhile, with the solid-state technique, the well-designed frequency-shifting strategies have shown promises in yielding better microwave heating outcomes. Experiments indicate that without using a rotating turntable, solid-state microwave heating with fluctuating frequencies can achieve comparable or even enhanced heating performance compared to traditional ovens equipped with a rotating turntable [1]. The rotating turntable could be made redundant in a solid-state microwave system, whose concept has not been thoroughly explored yet. Hence, the study aimed to undertake a comprehensive assessment of the turntable's elevation and rotation functions in influencing the microwave heating results with varying frequencies within a solid-state microwave oven. Multiphysics models were used to comprehensively assess the heating performance, with various affecting factors accounted, including horizontal and vertical positions of the sample, rotation status of the turntable, and different frequency strategies (constant-frequency, orderly-sweeping frequency, and complementary-shifting frequency).

METHODOLOGY

A previously validated 3D-scanned oven cavity (Panasonic Model NN-SN936W) was used for model setup (Fig. 1A). For evaluating heating performance with samples (380 mL mashed potato) at different vertical positions, a plane floor (Fig. 1B) was created for scenarios with samples placed on the oven bottom directly, with no turntable included.

To evaluate the elevation function of the turntable, mashed potato samples were placed at three vertical positions (floor, turntable, lifted 20 mm over turntable) and three horizontal positions (center, edge, and back) (Fig. 2). Only constant-frequency strategy (2.40 to 2.50 GHz at an interval of 0.01 GHz) was used.

To evaluate the rotation function of the turntable, the mashed potato samples were placed on the turntable (only one vertical position) at three horizontal positions (center, edge, and

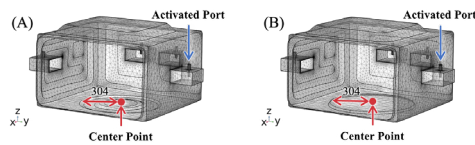


Figure 1. Diagram of (A) the 3D-scanned oven cavity [2], and (B) modified oven cavity with a self-created plane floor. The plane floor was to evaluate the heating scenario with the sample placed on the oven bottom directly. (mm).



Figure 2. Model settings for samples. (A) Mashed potato samples with homogeneous properties placed on (A) turntable at different vertical positions (turntable and lifted 20 mm over the turntable), and (B) self-created floor, at different positions (center, edge, and back). (mm).

back), two turntable conditions (stationary and rotatory), and three frequency strategies (constant-frequency at only 2.45 GHz, orderly-sweeping and complementary-shifting). A total of 18 models were simulated.

The simulated heating scenarios only included one activated port (one right-side wall of the oven), operated at 200W. The rotational speed of the turntable is 10 s/circle under rotatory condition, and the frequency shifting rate is 10 s/frequency, if applicable. Volumetric average temperature and Heating Uniformity Index (HUI) were calculated as criteria for comparing the heating results obtained under various conditions.

RESULTS

Quantitative results (Fig. 3) showed that elevation could affect the microwave heating outcomes (Fig. 3A) regardless of the horizontal position of the sample. Putting the samples on floor directly, with no distance between the oven bottom and sample, would reduce the volumetric temperature and raise the HUI value, indicating a lowered power efficiency and heating uniformity. The most significant function of rotation (Fig. 3B) can be seen in the reduced HUI values (p -value = 0.0004), but only in the scenarios using constant-2.45 GHz; if with frequency-shifting strategies (either orderly or complementary), the contribution by rotation was diminished.

Correlation evaluation on the turntable functions and heating results (Fig. 4) shows that, elevation of food is more critical than rotation to a better heating uniformity (shown in HUI), while rotation is more related to the temperature difference between hot and cold spots. Scenarios with samples placed on the oven floor directly had the lowest power efficiency and worst heating uniformity, which highlighted the importance of the space between food and oven floor, and pointed out the critical role of elevation rather than rotation in a solid-state microwave oven.

DISCUSSION

With the novel solid-state technique, the major function of the turntable shifted from rotating to elevating the food. The rotating effect of turntable could be diminished by using

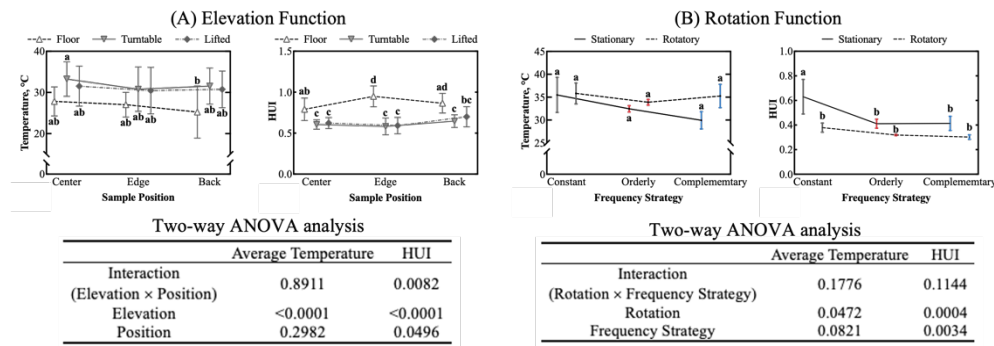


Figure 3. Evaluation results on the (A) elevation function, where the error bars were calculated based on heating scenarios using constant-frequency strategy using frequencies between 2.40 and 2.50 GHz, (B) rotation function of the turntable, the error bars were calculated based on heating scenarios with samples placed at different horizontal positions (center, edge, and back of the turntable). Letters denoted post-test results for two-way ANOVA analysis, and different letter within the sample plots implied significant difference (p-value < 0.05).

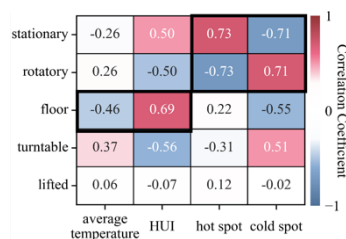


Figure 4. Correlation evaluation of the turntable functions (rotation and elevation) and the corresponding heating results (volumetric average temperature, heating uniformity index, hot spot temperature, and cold spot temperature).

the frequency-shifting strategies under stationary conditions. This will simplify the solid-state microwave oven design with more flexibilities. For example, different heights of racks can be included in the oven cavity for food placement during heating.

CONCLUSION

Comprehensive evaluation of the turntable functions showed that elevating the food is more important in raising the heating uniformity with frequency-shifting enabled by the solid-state microwave generator. This conclusion can provide useful information for design of the next-generation solid-state embedded microwave ovens.

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Comparing Solid-state Microwave and Conventional Baking Methods: A Study on Madeira Cake

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Keywords: microwave baking, heating uniformity, magnetron-based systems, solid-state microwave generator.

INTRODUCTION

Microwave baking offers advantages in terms of both time and energy efficiency compared to conventional baking. Additionally, in many cases, the final product exhibits enhanced nutritional value due to the lower temperatures achieved during the cooking process. Therefore, there are also drawbacks which include a reduced volume that leads to a firm and tough texture where hot spots are present, along with the absence of browning and flavor development, resulting in an undercooked and moist aspect in areas with cold spots.

The main contribution of this article to the great literature on microwave baking consists in testing a promising and quite recent technology in the field of microwave generators with an experimental approach. Notably, one of the key advantages of utilizing the solid-state technology over the classical magnetron-based generators is the possibility to precisely control and adjust parameters such as frequency, the power and, in cases involving multiple channels, phase shifts [1]. Each of these parameters influence the distribution of the electromagnetic field within the cavity, thereby determining the location of hot and cold spots. The possibility to change these parameters, which are uncontrollable in a magnetron-based system, has been demonstrate to improve the uniformity of heating [2]. What is missed is the testing of these advantages in a real, practical cooking case and not only in reheating ready-made food. Therefore, in this study, the cooking performance of a solid-state and a magnetron-based microwave systems are compared with that of traditional baking, focusing specifically on leavened cake.

Madeira cake serves as a representative case study in this research. The investigation involves temperature profiles, moisture loss rates and surface coloration. A comprehensive instrumental analysis is conducted to examine the evolving parameters that affect the final product quality. This includes continuous monitoring of surface and minimum cake temperatures throughout the cooking process, alongside specific tests to quantify moisture loss over time.

For each cooking method, a comprehensive overview of product evolution during the process is provided. This approach serves the dual purpose of evaluating the efficacy of the

solid-state technology and establishing a foundation for future studies on optimization the cooking process combining various cooking methods with the aim of reducing duration while upholding high-quality standards.

METHODS AND MATERIALS

The first device utilized in this study is the combined Electrolux oven model KME768080M; the capacity of the oven is 43 L. This oven serves as the platform for conducting both traditional baking tests and those involving a commercial microwave generator. The oven lacks a turntable but includes a stirrer for improved heating uniformity. The second microwave oven employed is a prototype equipped with a solid-state generator. Detailed specifications of this prototype are classified and provided exclusively by the company responsible for its design and development. Microwaves are directed into the cavity through four coaxial cables inserted into four waveguides shown in Figure 1a, which are in communication with the cavity.

Madeira cake is chosen for this study due to its frequent use in the scientific literature as a benchmark for comparing microwave and conventional baking methods. A standardized procedure is implemented to minimize variability in results stemming from the dough preparation process.

In this study, data is collected both during and at the end of the process, shedding light on the transformations occurring in food subjected to various baking techniques and the ultimate outcomes. Throughout the tests, a TS3 fiber optic sensor is strategically positioned both at the cake's center and in its coldest region. This arrangement allows for temperature monitoring during the experiments and facilitates the determination of the cooking endpoint. The FOTEMP OEM thermometer, along with its FOTEMP Assistant software, is employed for this purpose. At the end of each test, the minimum and maximum height and the surface color are evaluated. Height measurements are taken using calipers by slicing the cake and selecting slices with the highest and lowest heights. Surface color analysis, conducted prior to cake slicing, employs the WR10QC BELEY colorimeter. Additionally, total moisture loss post-cooking is assessed by weighing the cake before and after the test using the precision balance WTB 2000. Specialized tests are also conducted to evaluate changes in surface temperature and moisture loss over time. The evolution of the surface temperature during the cooking process is tracked using a Teledyne Flir A5 thermal imaging camera.

For a fair comparison of different cooking methods, process parameters are chosen to achieve the optimal cooking outcome for each cooking method. Preliminary tests are conductive to set microwave power in the two microwave systems used, in order to have the same power absorbed in food.

RESULTS

An example of the result is depicted in Figure 1b, illustrating the surface and lateral aspects of the cake cooked using the three different analyzed methods. Note the absence of hot spots using solid-state microwaves, as confirmed by thermographs acquired during the cooking process.

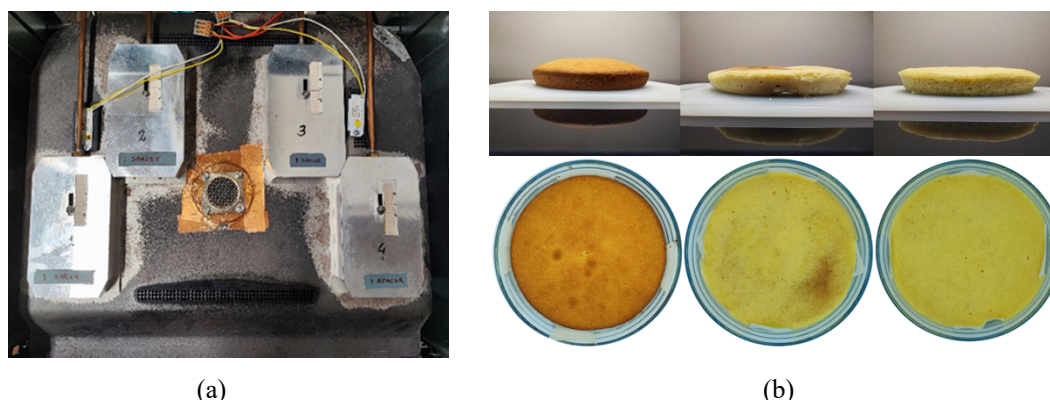


Figure 1. (a) Four channels on the top of the cavity, and (b) surface and lateral aspect of the cake cooked with different methods. Starting from the left static oven, magnetron-based microwave oven and solid-state system.

DISCUSSION

The cakes produced via three different baking methods are evaluated with a comprehensive instrumental analysis that encompasses the evaluation of surface color, height and total moisture loss.

Traditional oven baking is the sole method that permits to obtain a surface caramelization and to produce cakes with a uniform shape characterized by lower height near the container walls and maximum height in the cake's center. During conventional microwave baking, the uneven distribution of hot and cold spots makes the hotter parts to become dry and overcooked waiting for the colder ones to reach the minimum wanted temperature. Solid-state microwave baking is the method that permits lower cooking time, higher uniformity of surface color and lower moisture loss during the cooking process.

CONCLUSION

The flexibility provided by the solid-state microwave generator, permitting adjustments in frequency, power, and phase shift, leads to reduced cooking times when compared to magnetron-based microwaves while effectively mitigating the issues associated with the creation of hot and cold spots.

A clear understanding of the phenomena that unfold during the processes of microwave and traditional baking creates the basis to explore how to combine these different cooking methods to achieve a high-quality baked product in less time.

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Development of a Real-time Dynamic Complementary Relative Phase Shifting Strategy for Dual-port Solid-state Microwave Heating Process

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Keywords: relative phase, complementary, solid-state microwave, sinusoidal shape, heating uniformity

INTRODUCTION

Solid-state microwave processing is under development to deliver better heating results than magnetron-based heating. Dual-port microwave system with relative phase between two sources can be precisely controlled to deliver a higher total microwave power output and potential more uniform heating than single-port heating. Previous study showed that the overall heating uniformity can be improved by orderly sweeping the relative phase of two ports [1]. Inspired by the complementary frequency shifting strategy [2], similar complementary relative phase shifting strategy can be developed to improve dual-port solid-state microwave heating performance further.

A Multiphysics modeling of dual-port microwave heating process showed that the microwave power dissipation densities at any given location within the food products varied in a sinusoidal shape along with the change of the relative phases between two ports in the dual-port microwave heating process [3]. This implies that the temperature change at any given location within the food product also follows a sinusoidal shape as a function of the relative phase, if ignoring the influence of heat transfer within the food products. Mathematically, one sinusoidal shape function $[f(\theta) = a \cdot \sin(\theta + \theta_0) + b]$ is described by four parameters of amplitude (a), initial phase angle (θ_0), sinusoidal period (or frequency), and vertical displacement (b). For the relative phase-dependent heating results (local microwave power density and temperature change), the period is one loop of phase angles (360°); the three other parameters of amplitude, initial phase angle, and vertical displacement of the sinusoidal function can be determined from the sinusoidal values at three relative phase angles. In this study, we propose to develop a real-time dynamic complementary relative phase shifting strategy upon this mathematical principle to achieve better dual-port solid-state microwave heating performance.

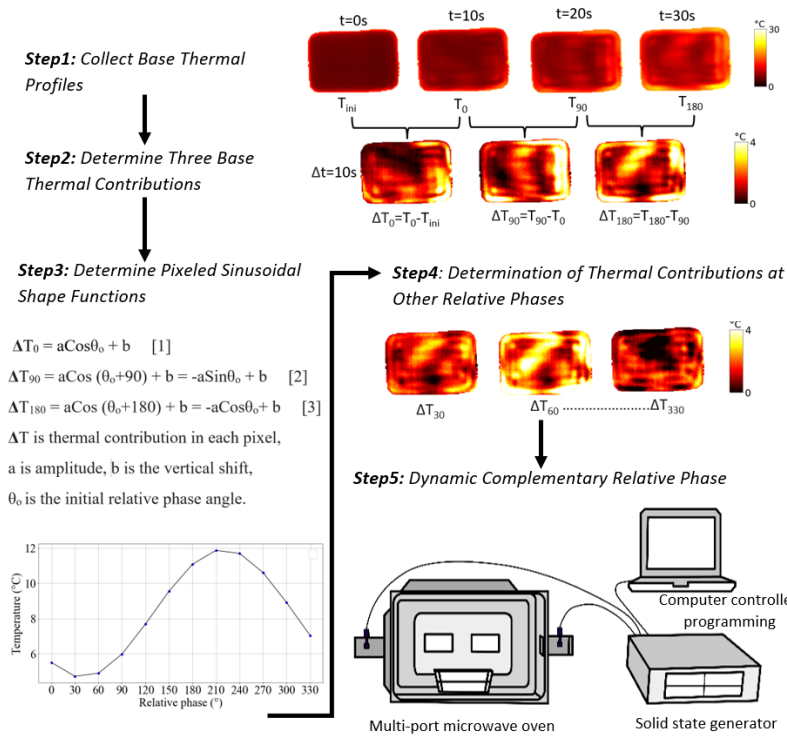


Figure 1. Concept of the real-time dynamic complementary relative phase strategy

METHODOLOGY

A dual-port (200 W each) solid-state microwave system with a top mounted thermal image camera was used to heat a tray of gellan gel sample (300 g) for a total of 180 s. Both ports of the microwave system were operated at a constant frequency (2.45 GHz) and the following described real-time dynamic complementary relative phase shifting strategy. The concept of the relative phase shifting strategy has 5 major steps, as shown in Figure 1.

Step 1 (Collect Base Thermal Profiles): the sample was heated using three relative phases of 0°, 90°, and 180° for 10 s each and four thermal images at the top surface of the food products were collected with top mounted thermal camera at time = 0, 10, 20, and 30 s. **Step 2 (Determine Three Base Thermal Contributions):** three base thermal contributions (also known as temperature change) of relative phases of 0°, 90°, and 180° were calculated by subtracting the previous thermal profiles. **Step 3 (Determine Pixeled Sinusoidal Shape Functions):** the pixeled values of three thermal contributions were used to calculate the pixeled sinusoidal shape functions (pixeled amplitude, initial wave angle, and vertical displacement) for all the pixels of the thermal images. **Step 4 (Determination of Thermal Contributions at Other Relative Phases):** the pixeled sinusoidal shape functions were used to calculate the thermal contributions at any arbitrary relative phases (every 30° in this study) as potential thermal contribution candidates. **Step 5 (Dynamic Complementary Relative Phase):** Complementary relative phases were determined with the predicted thermal contributions and implemented for dynamic control of microwave systems in real-

Table 1. Comparison of microwave heating performance among various relative phase strategies

Relative phase strategies	HUI	PAE (%)	Minimum Temperature (°C)	Maximum Temperature (°C)
Fixed	0.39± 0.02 ^a	48.81 ± 0.85 ^a	7.94 ± 0.57 ^a	68.04 ± 1.12 ^a
Orderly sweeping	0.31 ± 0.02 ^b	50.76 ± 0.85 ^a	16.22 ± 1.21 ^b	64.76 ± 0.98 ^b
Complementary	0.26 ± 0.01 ^c	54.52 ± 0.76 ^b	17.75 ± 0.41 ^b	69.00 ± 0.71 ^a

time experiments following similar procedures as described in the complementary-frequency work [2]. In general, the complementary relative phase could generate a heating pattern that is complementary with previous heating results for better heating uniformity and power absorption than other relative phases.

At the end of the heating process, the thermal images of the top and middle layers were collected to determine the heating performance of heating uniformity index (HUI), Power Absorption Efficiency (PAE), and minimum and maximum temperatures following reported procedures [2]. The microwave heating performance of this real-time dynamic complementary relative phase shifting strategy was compared with strategies of fixed relative phase and orderly sweeping relative phase.

RESULTS AND DISCUSSIONS

The microwave heating results showed that the complementary relative phase strategy significantly ($P < 0.05$) improved the heating uniformity and increased the microwave power absorption than the fixed relative phase and orderly sweeping relative phase strategy, as shown in Table 1. The complementary relative phase strategy could use limited (3) thermal contribution results to predict relative phase-dependent heating pattern and then dynamic select complementary relative phases to achieve better microwave heating performance. The minimum temperature and the maximum temperature were also found to be relatively higher in the complementary approach.

CONCLUSIONS

The real-time dynamic complementary relative phase strategy is useful for the future development of intelligent solid-state microwave systems to achieve higher uniformity and power efficiency.

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Microwave-assisted Combustion of Biological Material

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Keywords: microwave-assisted combustion, microwave-assisted drying, microwave-assisted incineration, cremation

INTRODUCTION

Biological material contains a large amount of water which makes it difficult to reach the ignition temperature for combustion processes. Consequently, it is essential to remove or lower the amount of retained water and moisture from biological materials before combustion can be efficient. In a novel concept using microwave heating, the content of retained water and moisture of biological material is significantly reduced before increasing process temperature for efficient combustion.

EXPERIMENTAL SETUP FOR MICROWAVE COMBUSTION TESTS ON BIOLOGICAL MATERIAL

The new microwave assisted combusting of biological material is performed in two steps. In the first step, the biological material is heated by microwaves to 100°C - 200°C. At this temperature, only minor degradation of the biological material occurs and retained water easily vaporizes. As a result, the moisture content of the biological material is reduced fast and efficiently. After the biological material is sufficiently dried, step 2 begins, and the microwave power is raised to reach temperatures significantly above 200°C where the biological material starts to incinerate (combustion step) [1].

Combustion tests of biological material using microwaves were performed in a large cylindrical barrel made of stainless steel. The front cover of the cylindrical barrel can be unlocked for loading and unloading. 915 MHz microwaves are injected into the cylindrical barrel by four ports. The ports allow optimization of microwave coupling into the cylindrical barrel, where the microwaves are directed on the biological material placed on a tray at the bottom of the cylinder. This configuration avoids cross coupling of microwaves from different ports as well as reflection of microwaves via adjacent ports or ports on opposite site. The design of the cylindrical barrel was developed by Neo Joule, in cooperation with MUEGGE for the electromagnetic considerations for that design.

PROCEDURE AND RESULTS OF MICROWAVE COMBUSTION TESTS ON BIOLOGICAL MATERIAL

For the experiments, 14 kg of meat (size of a small pig) was used. 915 MHz microwaves from a single 100 kW microwave generator were distributed via power splitters to the four ports of the cylindrical barrel. The power splitters allow selection of the microwave power level at each port according to the shape of the biological material and its position inside the cylindrical barrel. The dielectric loss due to high water content of at least 50% - 70% accounts for microwaves not completely penetrating the biological material at the beginning of the drying phase. However, continuous evaporation of water will decrease the dielectric constant of the biological material, hence reducing its ability for microwave absorption. In order to maintain microwave absorption for heating and evaporation of water, microwave susceptor materials (e.g. tiles of silicon carbide) can be placed underneath the biological material at the bottom of the cylindrical barrel [1]. From the moment microwaves begin being absorbed by the susceptor material, microwave energy is transformed into thermal radiation, which applies additional heat to the biological material.

Continuous air flow through the cylindrical barrel guarantees the continuous removal of water vapor. The use of air or another oxygen-containing gas mixture is critical, as sufficient oxygen is the prerequisite for complete incineration of the dried biological material after reaching ignition temperature in the subsequent combustion step. In principle, microwave power can be significantly reduced during combustion, especially when the dried biological material is surrounded by combustible material (e.g. wooden container). Moreover, microwaves positively interact with emerging flames during incineration, which allows the reduction of microwave power as soon as the incineration of the biological material has started. In a microwave-assisted combustion test it was demonstrated that this novel concept is applicable for cremation to replace gas-powered cremators. The test object (14 kg of meat) was efficiently combusted using microwave power of 30 kW (20 minutes of drying), which was reduced to 15 kW in the subsequent combustion phase of 105 minutes, followed by 45 minutes of combustion without microwave energy [1].

CONCLUSION

The microwave-assisted combustion tests performed using a 100 kW microwave generator successfully showed shorter process time and improved energy efficiency compared to gas-powered systems. Having demonstrated its applicability in industrial processes, microwave-assisted combustion is currently qualified for processing hazardous biological waste and cremation of human or animal bodies.

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Industrial Development of Microwave Applicators Dedicated to the Treatment of Powders and Granular Media

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Keywords: dielectric properties, microwave heating, food powder, modeling

INTRODUCTION

The main objective of this study was to optimize the microwave heat treatment of granular materials, particularly powders and divided solids, by improving the understanding of the interactions between the microwaves and the materials. To achieve this, a microwave heating system was assembled and used to heat paprika. This work, abbreviated as Diamond project, is part of the successful collaboration between researchers from the joint research unit GEPEA-ONIRIS and the company SAIREM. GEPEA's added value lies primarily in its expertise in multiphysics simulation of microwave processes, while SAIREM's R&D activities are focused on targeted applications in the food and chemical sectors. The collaboration was financed by the French National Research Agency under the DIAMOND project within the framework of “préservation emploi R&D France Relance”.

METHODOLOGY

Paprika was chosen as the subject of the experiments, and its dielectric properties were characterized using two measurement techniques: the open-ended coaxial probe (OECF), conducted at GEPEA-ONIRIS lab, and the cavity perturbation, measured at SAIREM company using equipment built especially for this purpose.

Experimental measurements were performed to determine the thermophysical properties of paprika, including specific heat (C_p , $\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$) using a differential scanning microcalorimeter ($\mu\text{DSC VII Evo}$, Setaram Instrumentations, France), thermal conductivity using a Thermal analyzer TEMPOS with a KS-3 conductivity meter (Meter, München, Germany) and apparent density was determined by a graduated glass cylinder.

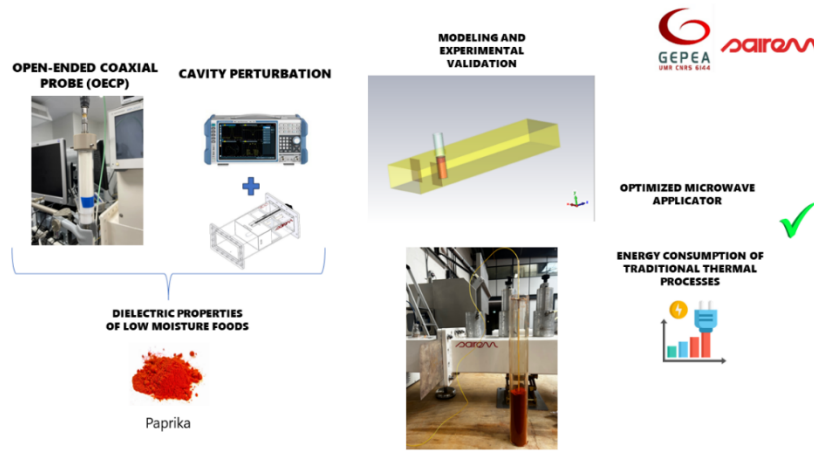


Figure. 1. Summary of the activities carried out during the Diamond project.

Electric field distribution within the microwave applicator containing the food powder was modelled and compared using CST Studio Suite[®] and COMSOL Multiphysics[®], with an experimental validation through measurements using a Vector Network Analyzer (VNA) for the reflected signal S11.

RESULTS

The dielectric constants determined for paprika using the open-ended coaxial probe (OECF) and cavity perturbation at 915 MHz were 1.53 ± 0.09 and 1.96 ± 0.00 , respectively. The corresponding loss factors were 0.20 ± 0.04 with the OECF technique and 0.24 ± 0.00 with cavity perturbation. The specific heat of the paprika powder was measured at $2.45 \pm 0.27 \text{ kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$, thermal conductivity of $0.044 \pm 0.001 \text{ W m}^{-1} \text{ K}^{-1}$ and apparent density of $0.619 \pm 0.001 \text{ g cm}^{-3}$. The optimal configuration for the microwave cavity containing paprika (at room temperature) was achieved with an iris opening of 88 mm and a total cavity size of 826 mm (measured from the iris position to the end of the manual sliding short-circuit). This configuration resulted in the lowest reflected power S11 (expressed as a percentage).

The numerical models developed using CST Studio Suite[®] and COMSOL Multiphysics[®] were successfully validated, demonstrating similar reflected signal results: -12.47 with COMSOL Multiphysics[®], -12.57 with CST Studio Suite[®], and -15.92 experimentally measured with the VNA. The dielectric properties considered for paprika were of 1.96 for the dielectric constant and 0.24 for the loss factor.

DISCUSSION

The OECF is an efficient technique for analyzing a broad range of frequencies but may lack in accuracy especially for materials with low loss factors. In contrast, resonance

techniques provide exceptional accuracy, particularly for measuring the dielectric loss factor, but are limited to analyzing individual frequencies at a time. Therefore, the choice

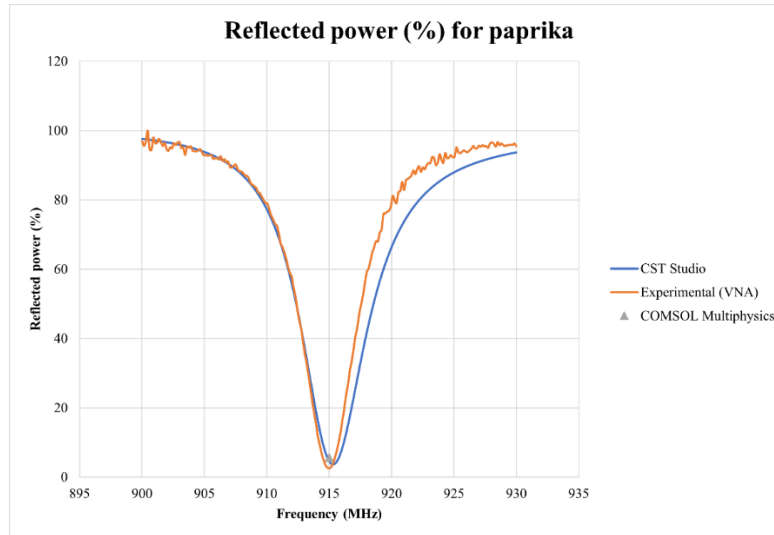


Figure 2. Reflected power in the microwave cavity with paprika for dielectric constant of 1.96 and loss factor of 0.24.

between these techniques depends on the specific needs of the application, the desired frequency, and the required level of accuracy. The insights into the dielectric properties of food powders and grains obtained through the OECP and cavity perturbation methods enhance the modeling of microwave heating processes dedicated to granular materials. These data serve as valuable input parameters for predicting electromagnetic field distribution within a microwave cavity. Additionally, the novelty of the study lies in the comparison between two dielectric measurement techniques, a rarity in existing literature focusing on granular materials. The examination of simulation and modeling software for predicting electromagnetic behavior adds originality to the research, as such comparisons are not commonly addressed in scientific studies.

CONCLUSION

Paprika's dielectric constant was 1.96 ± 0.00 using cavity perturbation at 915 MHz, while the loss factor was 0.24 ± 0.00 . The optimal microwave cavity configuration for paprika achieved a reflected power (S11) as low as -15.92, and numerical models successfully predicted this value with high accuracy. These quantified results provide valuable data for future research and applications involving microwave for treating low moisture products. The outcomes of the project form the foundation for precise modelling of microwave processing, contributing to the design and optimization of microwave applicators.

Advanced Dual-level Pulse Generators in Nanosecond Range at 2.45 GHz

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Keywords: ns pulsing, dual level, SSPG, plasma

ABSTRACT

Dual-level pulsing in microwave plasma systems, coupled with the capability of nanopulsing, introduces a groundbreaking dimension to plasma technology. Nanopulsing involves extremely short and intense bursts of energy, allowing for the generation of non-thermal plasma. This form of plasma, characterized by low electron temperatures and high concentrations of reactive species, holds immense potential for applications where thermal effects need to be minimized. The combination of dual-level pulsing and nanopulsing provides an unprecedented level of control over plasma parameters, enabling the creation of tailored non-thermal plasmas with enhanced efficiency and precision. This breakthrough not only opens new avenues for material processing but also facilitates advancements in fields such as surface modification, nanomaterial synthesis, and environmentally friendly plasma-assisted technologies. The synergistic effects of dual-level pulsing and nanopulsing contribute to the evolution of plasma applications with increased versatility and adaptability to diverse industrial needs.

With the TRUMPF Hüttinger's 'TruPlasma MW series' of solid-state microwave power generators at 2.45 GHz, it is now feasible to intentionally produce nanopulses with on/off times ≥ 30 ns at two individual power levels. This functionality is made possible by an inventive control circuit integrated into the platform, enabling the effective utilization of the mentioned advantages in an industrial setting. The presentation will delve into the introduction and comprehensive analysis of the block diagram illustrating the control mechanism of TRUMPF Hüttinger's microwave solid-state generators.

Breakthroughs in Solid-State RF Power Generation for Industrial, Scientific, and Medical Frontiers

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Ampleon, Nijmegen, Netherlands

Keywords: GaN, LDMOS, ART, solid-state, TWT, plasma, heating, medical, industrial microwave

INTRODUCTION

Embark on a journey through the cutting-edge landscape of Solid-State RF Power Generation as we unveil the latest breakthroughs in Gallium Nitride (GaN) and Laterally Diffused Metal Oxide Semiconductor (LDMOS) technologies. In this presentation, we will delve into the realm of high-performance RF power transistors that redefine efficiency and reliability across industrial, scientific, and medical applications.

Our focus will be on the unparalleled power efficiency achieved through advancements in GaN and LDMOS technologies. Witness the transformative power cycling capabilities, pushing the boundaries of endurance and ruggedness. Explore continuous wave dedicated designs with proven reliability, substantiated by extensive aging characterization, ensuring optimal performance over time.

Dive into the realm of guaranteed longevity as we showcase a continuous track record in product durability. Discover how our innovative RF power transistors set the industry standard for reliability, with a commitment to continuous support and thought leadership in High-Power Solid-State Power Amplifiers (HP-SSPA) for Continuous Wave Industrial, Scientific, and Medical (CW ISM) applications. Join us at the forefront of RF power technology and witness the future unfold.

METHODOLOGY

During the past two decades Solid-State RF power solutions have been developed into various domains that were traditionally dominated by TWT amplifiers. This resulted in new insights and product improvement in both reliability as well as performance to meet the tough industry requirements. On top of this we developed new features to our Solid-State devices, such as internal stability networks, thermal sensing and drain voltage sensing, so that we created designer friendly, sense and control enabled smarter, controllable applications with enhanced performance and product lifetime.

The dominating technologies discussed are GaN, LDMOS and ART. ART stands for Advanced Rugged Transistor technology, which is under the hood based on LDMOS, but with many technology enhancements, to enable high drain voltage, extremely high mismatch capability and durability, due to long lifetime and many on/off cycle capabilities. All these combined in affordable industry standard packages.

RESULTS

With this paper the authors like to highlight today's Solid-State offerings to the broad and diverse Industrial, Scientific, and medical markets. We will show application examples and how they are used.

DISCUSSION

The paper will outline dedicated applications from particle accelerators to MRI equipment and industrial heating. This will show the advantages these Solid-State offerings have over a TWT based solution.

CONCLUSION

The Solid-State amplifier is gaining momentum and slowly taking over parts of the TWT dominated applications.

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Innovations in High Power GaN Solid-State Microwave Generators for Heating and Plasma Generation Applications

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Keywords: waste pyrolysis, nanomaterial, microwave-assisted heating, microwave-assisted plasma, hydrogen production, carbon-nano tubes

ABSTRACT

The rapid advancement of Gallium Nitride (GaN) solid-state technology represents a significant paradigm shift in the fields of microwave heating and plasma generation applications. Historically, conventional magnetron tube-based systems have dominated these areas. However, the time is now ripe for the adoption of GaN solid-state technology, offering unprecedented advantages in terms of digital control, precise frequency modulation, and superior power stability. This transition towards GaN solid-state microwave generator systems is not only imminent but also essential, given the increasing demand for power outputs exceeding 100 kW, a threshold unattainable with magnetron-based systems. Furthermore, the necessity for precise control over both frequency and power output makes GaN solid-state technology the logical choice. GaN solid-state technology unlocks transformative capabilities, such as phased array technology, which enables the integration of multiple lower-powered units into arrays capable of delivering up to 1 MW of power. This paper will showcase the innovative research projects undertaken by RFHIC utilizing GaN solid-state microwave generators and their immense potential in various applications. Examples include waste pyrolysis on cruise ships and the cost-effective, energy-efficient production of carbon nanotube powder. These developments herald a new era in microwave-based heating and plasma generation technologies, promising greater efficiency and versatility in a wide range of applications.

Innovative RF Transistors: Pioneering Next-Gen Solid-State Microwave Ovens

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Keywords: RF power transistors, microwave oven, LDMOS, solid-state oven, smart cooking control, thermal sensing, mismatch protection, intelligent cooking

INTRODUCTION

The evolving trend in kitchen appliances emphasizes the integration of smarter, connected devices that facilitate remote control and enable precise execution of recipes provided by food suppliers and chefs. Traditional microwave ovens face challenges with accuracy and power degradation over time, complicating the development of smart microwave appliances.

In contrast, RF ovens, utilizing solid-state transistors, offer superior control over power and frequency, ensuring more uniform cooking through multiple channels. However, these advanced ovens are costlier and more complex due to the cost of RF laminates, RF transistors and features such as an internal power measurement system and circulators protecting RF power amplifiers.

A new generation of LDMOS RF power transistors with smart sensors for internal temperature, power dissipation, mitigates overpower risks and enables the transistors withstand mismatch conditions. These sensors also allow tracking power consumption and delivery to the oven, simplifying power management without requiring an enhanced measurement system. Moreover, these transistors come in low-cost plastic overmold packages, providing an economically attractive alternative to traditional ceramic RF power transistors.

This technological advancement paves the way for a novel smart RF oven, featuring simpler electronics and at the cost of reduced accuracy compared to existing RF ovens. Despite being more affordable, these ovens can be effectively paired with a smart meal system, utilizing predefined cooking algorithms supplied by food or meal providers.

METHODOLOGY

The current generation of solid-state RF ovens relies on a measurement and control system, utilizing RF couplers and power detectors behind RF power transistors. This setup, which requires an RF circulator, ensures accurate readings of injected and reflected power. The

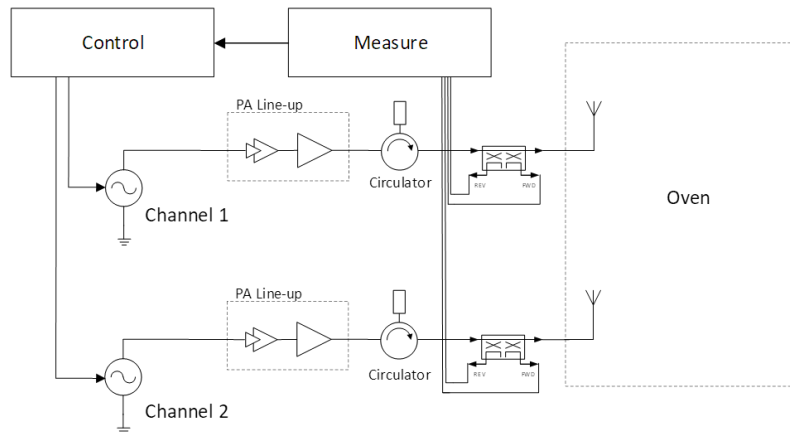


Figure 1. Electrical architecture of a Current generation 2 channel solid state RF oven

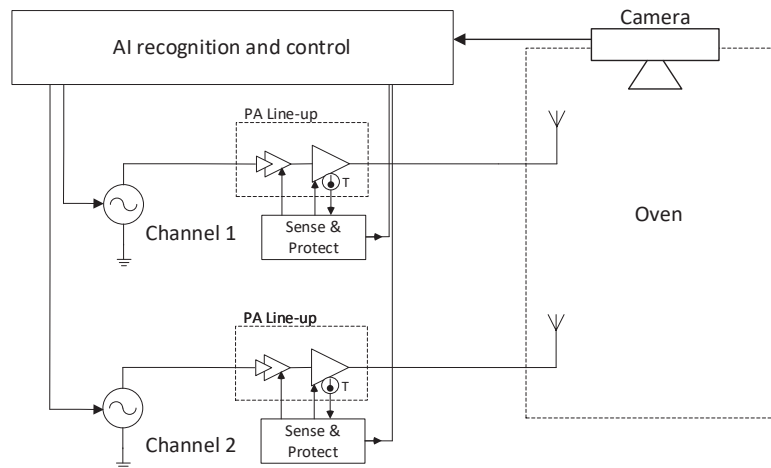


Figure 2. Electrical architecture of a proposed new generation 2 channel solid state RF oven

RF circulator is also protecting the transistor from potential damage due to reflected signals.

In contrast, the new generation of Ampleon LDMOS RF power transistors are designed to operate without the need for a circulator. These transistors are designed to work in harsh environments, where the transistor may be exposed to reflected power.

Without circulators, variations in the voltage and current waveshape of reflected power impact power readings obtained via couplers. To tackle this challenge, an alternative approach is to measure the active die temperature within the transistor, which directly correlates with dissipated power. When combined with DC supply power, this enables the calculation of the RF power delivered and absorbed by the load in the oven cavity.

In cases of severe mismatch, measuring high levels of dissipated power triggers the protection circuit to intervene by reducing power. However, it's important to note that the reaction time of the sensing and protection circuit requires careful consideration,

necessitating a gradual ramp-up of power inside the oven to allow the circuit to respond effectively.

Transistor overheating can be the result of mismatch, wherein a portion of the generated power reflects back from the RF antenna to the transistor. However, not all mismatch scenarios result in high power dissipation. The shape and phase of the reflected voltage wave can also cause the drain voltage inside the transistor to exceed the breakdown voltage. To mitigate this, the supply voltage is adjusted to ensure that the peaks in voltage, even at full power and under maximum mismatch conditions, remain below the breakdown voltage of the transistor.

RESULTS

Currently, the innovative oven is in the conceptual stage, but efforts are underway to make the required transistors with internal sensors, as discussed in this concept, accessible to the market. The technology is already in existence, and examples of it can be demonstrated.

DISCUSSION

Introducing a simplified and more affordable version of the solid-state RF oven poses a new challenge. With less accurate power measurement, alternative methods for cooking in such an oven must be explored. An evident control approach is the utilization of AI to generate cooking recipes, potentially based on images captured before and during the cooking process.

CONCLUSION

Microwave ovens, although they will persist long into the future, are commonly associated with imprecise cooking outcomes and are primarily utilized for meal reheating. Advanced solid-state ovens, on the other hand, provide enhanced cooking capabilities and accuracy but come with a substantial price tag. The incorporation of new solid-state technology, featuring rugged transistors with a robust sense and protect system, has the potential to introduce a novel category of solid-state ovens. These ovens could effectively bridge the performance and cost gap between conventional microwave ovens and high-end solid-state RF ovens.

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Practical, Real-World Efficiency Comparison Between L-Band Magnetron and SSPA Microwave Sources

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Keywords: magnetron, solid state amplifier, efficiency

INTRODUCTION

The emergence of SSPAs in the Industrial, Scientific, and Medical (ISM) sector has ignited a conversation about their efficiency compared to traditional magnetrons. This paper delves into the key factors impacting the total cost of converting AC power into usable microwave energy delivered to the product. We'll explore the influence of transmission lines, applicator designs, cooling systems, and operating conditions on overall efficiency. A survey of publicly available data has been conducted to determine baseline data to compare available technologies.

METHODOLOGY

This paper, the overall microwave system efficiency is defined as the percentage of energy delivered from the AC power line to the load, impacting operating costs. These factors apply to all industrial microwave systems (heating, drying, etc.) regardless of power source (magnetron tubes or solid-state) and frequency band. The focus here is 902-928 MHz, but principles apply to other industrial frequency bands. I will review the major system elements and quantify their contribution to total energy consumption.

For review, magnetron-based generators are fixed frequency sources. The nominal frequency is set by the physical dimensions of the magnetron tube. It has been shown the nominal frequency will shift up or down based on the power level and load conditions the tube may be subjected to. This effect is not controllable. Maximize energy transfer using magnetron systems is typically achieved through mechanical tuners or modifications to the applicator. While these approaches work using solid state systems, other tools such as frequency shifting may be used with solid state systems to further improve the load match. This is because some applications perform best at frequencies unavailable at standard magnetron frequencies of: 896, 915, 922 and 929 MHz. In either case, the better the load match, the better the efficiency of the system. Solid state sources offer unique capabilities to further improve match.

All microwave or coax components attenuate the power due to resistive losses due to material conductivity losses or based on the design of the component. The normal attenuation of a transmission line is the ratio of the output power to the input power when the load is matched to the characteristic impedance of the transmission line. This is typically defined as the attenuation or insertion losses and is expressed in decibels (dB).

These losses result in the heating of the transmission line and are permanently lost as heat.

Return loss is another factor that will impact the overall system efficiency. Like insertion loss, all components exhibit some amount of return loss. Like insertion loss, return loss is defined in dB or as a Voltage Standing Wave Ratio (VSWR). Return loss is the amount of power that is reflected back to the source. This reflected power is absorbed in either low or high-power isolator loads and like attenuation, would be permanently lost as heat.

The power factor of the entire system is an additional consideration. Power Factor (PF) is the ratio of the actual electrical power dissipated by an AC circuit to the apparent power where apparent power is the vector sum of real and reactive power and is defined as: $PF = kW/kVA$. The difference between the two is caused by reactance in the circuit and represents power that does no useful work. A circuit with a Power Factor less than unity will use higher currents to transfer a given quantity of real power than a circuit with a higher Power Factor. Current (I) will be returned to the utility which increases the total demand on the distribution network. If this is not managed, the user will realize a higher cost for delivered power.

All high-power microwave systems require chilled water cooling. The cost of running chilled water systems should be considered as part of the overall efficiency of the microwave system. The Energy Efficiency Ratio (EER) is a common term used to define cooling efficiencies for industrial chiller systems. EER is typically provided at specific operating conditions and varies over the operating parameters of any chiller such as cooling water set point and ambient operating temperatures. The efficiency of the generator plus the reflected power, due to poor match conditions, contribute to the overall size and energy required in the chilled water system.

RESULTS

Based on the market survey, overall efficiency has been evaluated based on the total power output / power input. This was determined based on the generator's Voltage and Full Load Amperes (FLA) or current draw in Amperes (A). The formula to calculate the total power required in kilo-Volt Amperes (kVA) to run the generator at full power is $P_{\text{apparent}} = V \cdot A \cdot \sqrt{3}$

Magnetron generator manufacturers do not typically advertise efficiency. However, tube manufacturers advertise typical efficiencies of 83-88%. However, these advertised values do not reflect the actual system level efficiencies that will be realized. It is also important to note, these are efficiencies of new tubes. Magnetron efficiencies will drop as the tube ages. To determine generator level efficiency, actual power use must be calculated. To do this, we must know the Full Load Ampere (FLA) draw and the operating voltage.

If overall efficiency is not given for the generator, efficiency is calculated based on the Apparent Power values provided by the manufacturer. A summary of this analysis is provided below:

Manufacturer	Solid State, 12.5 kW SS	Solid State, 50 kW SS	Brand A, 75 kW	Brand A, 100 kW	Brand B, 75 kW	Brand C, 5 kW	Brand C, 18 kW	Brand C, 35 kW	Brand C, 54 kW	Brand C, 75 kW	Brand C, 100 kW	Brand D, 50 kW	Brand D, 75 kW	Brand E, 75 kW
Power Supply Type	SM	SM	Linear	Linear	Linear	SM	SM	SM	SM	Linear	SM	SM	SM	Linear
Output Power (OP)	12.5 kW	50 kW	75 kW	100 kW	75 kW	5 kW	18 kW	35 kW	54 kW	75 kW	100 kW	50 kW	75 kW	75 kW
Voltage, 3 Ph	480 VAC	480 VAC	480 VAC	480 VAC	480 VAC	415 VAC	415 VAC	415 VAC	415 VAC	420 VAC	420 VAC	480 VAC	480 VAC	480 VAC
Full Load Amp (FLA)	30 A	120 A	128 A	168 A	135 A	14 A	38 A	56 A	84 A	131 A	174 A	84 A	111 A	125 A
Apparent Power (kVA)	25 kVA	100 kVA	106 kVA	140 kVA	112 kVA	10 kVA	28 kVA	40 kVA	60 kVA	95 kVA	127 kVA	70 kVA	92 kVA	104 kVA
Efficiency (OP/AP)	50%	50%	70%	72%	67%	50%	65%	88%	89%	79%	79%	72%	81%	72%

DISCUSSION AND CONCLUSION

Based on the survey and analysis, solid-state generators do not currently meet the efficiency values of new magnetron generators. However, opportunities exist to bridge this gap, if the application is sensitive to the new features of solid-state generators. One example would be where a poor match was to improve from 10 to 20 dB return loss. This effectively translates to a 10% gain in system efficiency. Another opportunity exists where the process can operate in pulse power mode with the same product output. System efficiency increases proportionally with each percentage decrease in the duty cycle. This effect is predominantly seen in single mode or high Q applicators such as plasma chambers or single mode applicators. Frequency tuning improvements are typically not seen in multimode cavities such as continuous drying or tempering ovens.

Based on interviews with major chip manufacturers, major customers in the telecommunications and defense markets are driving increased efficiency and lower cost using GaN transistors. Currently, the volumes in these markets are supporting continued R&D and improvements in package characteristics, including efficiency. Efficiency improvements are being seen as manufacturers move from 0.5 to 0.1 micron and smaller line widths. Additional development in higher voltage transistors (50 to 65V for example) will result in lower cost systems as power supplies and conductors will decrease in size. These innovations will transfer to industrial microwave focused products as manufacturers seek to consolidate around common manufacturing methods.

Given these improvements, generator level efficiencies > 65% look to be within reach.

Design and Realization of a “Flameless Burner” for Microchemistry Applications

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Keywords: microwave heating, solid-state RF energy, chemical reactions, cavity design
electromagnetic modeling

INTRODUCTION

In the realm of laboratory heating devices, flame-based burners have long been a staple due to their simplicity and versatility [1]. However, concerns associated with open flames, such as safety hazards and the generation of unwanted by-products, have prompted the exploration of alternative heating technologies. This paper introduces a novel approach to laboratory heating through the design and realization of a “flameless burner”. Our proposed system harnesses the power of a TM_{110} microwave cavity operating at 2.45GHz with a 50W power source. The proposed system not only addresses safety concerns but also aims to enhance precision and efficiency in heating applications. The incorporation of a flameless solid-state microwave-based heating system represents a significant step forward in laboratory practices, offering distinct advantages over traditional burners and existing microwave methodologies.

METHODOLOGY

The paper presents the design process of the state-of-the-art waveguide-based applicators with optimized overall size, components, and laboratory needs. We used the finite elements method implemented in the electromagnetic modeling tool HFSS from Ansys [2]. Through a detailed parametric analysis of the different design parameters of the cavities, including tuning elements, the final geometry was developed to accommodate a wide variety of possible vials and reagents.

To achieve a high-density electromagnetic field distribution the applicator is made in the form of an elliptical microwave cavity designed to resonate within the 2.45GHz frequency band. The cavity (with internal dimensions 130 x 117 x 95 mm) is excited with a monopole antenna at one focal point of the ellipse and creates a eTM_{110} mode [3] carrying and presenting the energy in the second focus (see Figure 1).

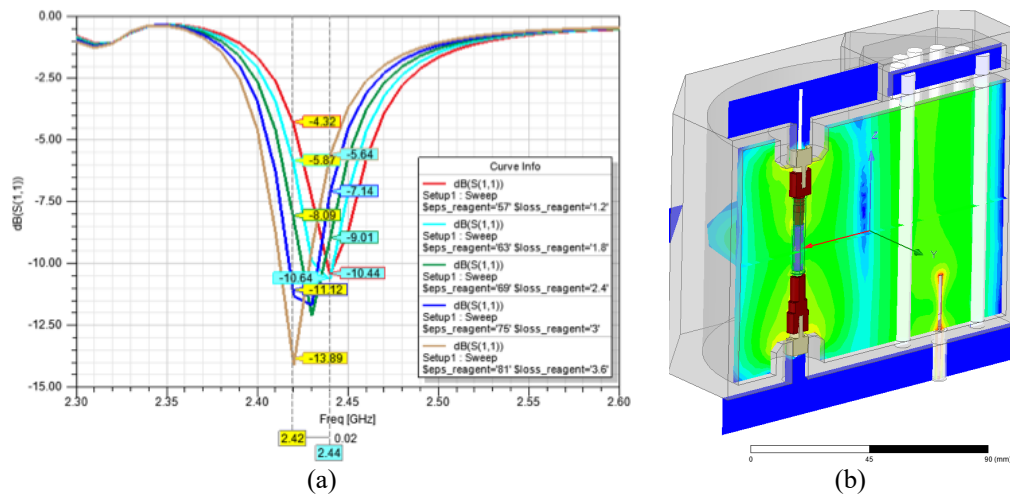


Figure 1. $|S_{11}|$ graphs for different liquid properties (a) and an electric field distribution (2.42 GHz; vertical cross-section) from EM modeling of the cavity (b).

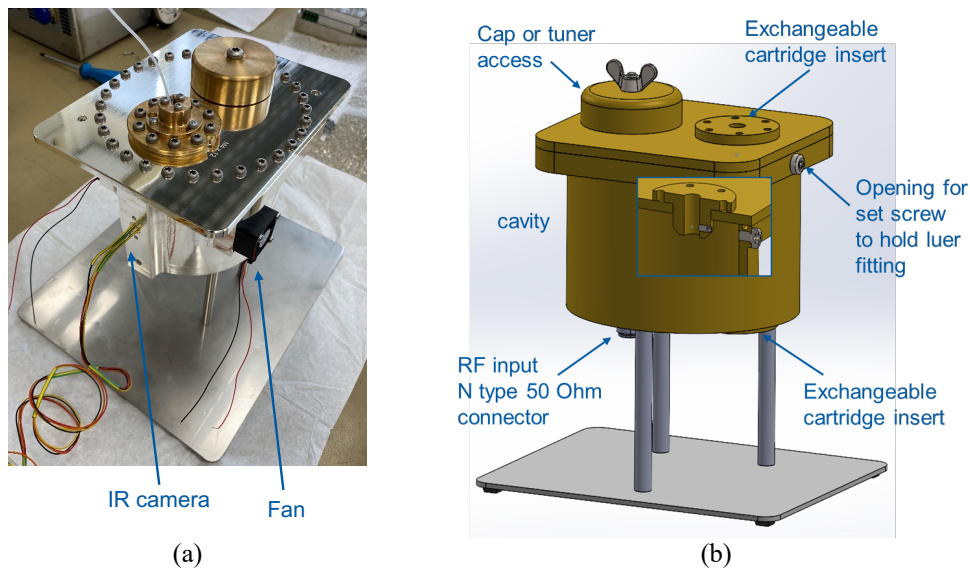


Figure 2. High-density microwave applicator implementation (a) and descriptive schematic (b).

RESULTS

The goal of the design process is to achieve good matching ($|S_{11}| < -10\text{dB}$), i.e., power delivery efficiency, for a range of plastics (PE, PP, etc.), and liquids (different saline solutions), also at higher temperatures.

Once the design goal was achieved, the applicator was manufactured (see Figure 2) and tested alongside a 50W solid-state microwave generator with smart heating control capabilities.

DISCUSSION

The system has been used in different applications, showing very accurate and reproducible heating capabilities, typically in small quantities. The 50W of power is smartly managed (by using thermal data from an IR sensor) to deliver the exact amount needed according to the required thermal profile and, hence, providing precise control in, e.g., synthesis processes, leading to optimized processing times and energy consumption. Moreover, non-renewable energy sources are not needed and no subproducts from a burning process are created.

CONCLUSION

The presented “flameless burner”, employing a TM₁₁₀ microwave cavity at 2.45GHz powered with up to 50W solid-state generator, not only addresses safety concerns associated with traditional burners but also heralds a new era of precise, green, and efficient laboratory heating.

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An Integrated Single Mode Microwave Applicator Cavity Combiner

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Keywords: microwave applicator, single mode, power combiner, solid state

ABSTRACT

Multiple microwave power generators are often used in processes that require higher power delivery than available from single commercially available generators, thus necessitating a means to combine the generator power outputs for delivery to the process load. Combining the outputs of non-coherent magnetron-based generators within a multi-mode applicator cavity is common for many industrial processes [1]. For processes utilizing a single-mode applicator cavity, transmission line (including coax and waveguide) combining of coherent solid-state microwave power generators is common for delivering power through a single power feed port [2]. An alternate and potentially more economical approach to external combining is a single-mode applicator cavity combiner utilizing multiple coaxial couplers in an arrangement similar to that of resonant cavity (i.e., non-applicator) combiners. Axisymmetric cylindrical (TM_{0x0}) mode cavity applicators are commonly used for heating materials passing through the cavity axis [3]. Computer simulations are presented for a proposed design of a quasi- TM_{020} mode cylindrical applicator cavity with integrated power combiner for microwave heating.

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Comparison between Microwave and Hot-air Drying Methods for Herbs

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Keywords: herbs, microwave, drying, food processing

INTRODUCTION

Herbs are defined as 'any plant with leaves, seeds, or flowers used for flavoring, food, medicine, or perfume' [1]. The herb industry employs drying technology to extend shelf-life and maintain quality due to herbs' high moisture content (M.C.) and temperature sensitivity is expected to continually increase in the future [2]. Microwave drying methods offer faster heating compared to conventional methods like hot-air or sun drying, utilizing electromagnetic energy for volumetric heating and relying solely on electricity, minimizing carbon emissions. With applications extending to medical, toiletry, and perfume industries, investing in microwave drying equipment holds promise for meeting rising market demands for dried herbs.

The objective of this test is to determine drying efficiency of microwave drying (MWD) compared to hot-air drying (HAD) using Sairem's equipment. The information could provide useful information to optimize microwave drying condition for the herbs.

METHODOLOGY

For the test, a multi-purpose microwave oven was used (Figure 1a). The system consists of two 6 kW generators (total 12 kW), hot air pump, and air extraction pump. The system recorded incident power and reflected power during all processes. IR sensors were used to check the reached maximum temperature during the drying process. Basil was purchased from the local market (Norcross, GA), and stored at refrigerated temperature. The samples were used for the drying experiment within 4 days (Figure 1b). Experiments were conducted with basil of varying weights: 150g, 300g, and 450g.

The total microwave power was configured at 1.2 kW and 1.6 kW, with each generator set at 0.6 kW and 0.8 kW, respectively. In HAD test, the temperature of the hot air pump was established at 80 °C. The air ventilation pump was activated for each experiment. To determine drying rate, the sample weight was recorded at intervals of 2-10 minutes. The M.C. (wet basis) of the samples was determined based on the solid content obtained by a moisture.



Figure 1. Schematics of the chamber in FL12000 (a) and basil in FL12000 (b).

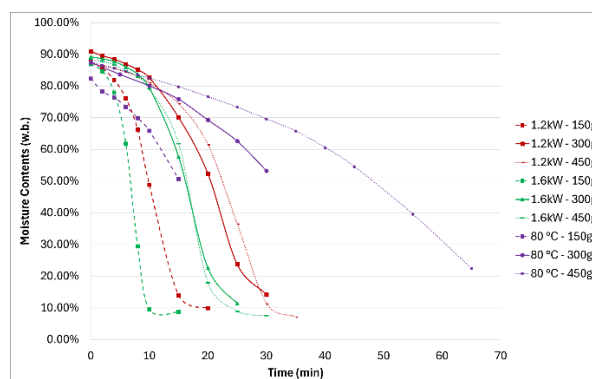


Figure 2. Moisture content changes of basil during microwave and hot air drying.

RESULTS

The initial M.C. of basil were 90.95 to 80.75%. The drying rates and trends of MWD were examined in comparison to hot air drying (Figure 2). It was observed that, for equivalent drying durations, MWD exhibited a phase of decreasing drying rate, whereas HAD generally maintained a consistent drying rate. In the case of HAD, a noticeable decrease in drying speed was observed as the sample volume increased. However, in the context of MWD, there was little discernible difference in the trend between 150g and 300g samples. For the 450g sample, the drying speed remained faster than HAD; nevertheless, it was significantly slower compared to samples of the same weight. During MWD, it was observed that the temperature rose to a maximum of 80 to 105°C.

Figure 3 shows the visual appearance of dried basil subjected to both HAD and MWD. MWD basil exhibits a greener hue compared to its HAD basil. ΔE of HAD and MWD were 23.5 and 16.3, respectively. Analysis of LAB color values reveal a significantly lower a^* value for MWD basil (-4.9) in comparison to HAD basil (-0.2), suggesting that MWD may yield superior quality basil compared to HAD.



Figure 3. Color comparison between (L) hot air dried and (R) microwave dried basil.

DISCUSSION

In contrast, MWD, with its ability to transmit thermal energy more deeply, demonstrated the capability to heat larger volumes of samples without significant speed loss. These findings demonstrate a significant capacity to preserve the product's color, suggesting that rapid heating effectively mitigates the enzymatic browning phenomenon. For MWD, it was observed that the reflected power gradually increased as the M.C. began to decrease. This is believed to be a result of changes in dielectric properties due to the reduction in moisture, preventing proper penetration of microwaves. Therefore, it is deemed necessary to find more optimized conditions for MWD to prevent overheating.

CONCLUSION

HAD and MWD in herbs based on drying speed were investigated. In terms of drying rate, it was evident that HAD exhibited more distinct limitations associated with sample volume compared to MWD. To achieve more optimized drying conditions, further testing under various conditions is required.

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Electromagnetic Monitoring of the Drying of In-shell Macadamia Nuts

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Keywords: macadamia nuts, dielectric constant, coaxial resonator

INTRODUCTION

Macadamia nuts are highly valued for their taste and texture. The Macadamia tree originated in Australia and is grown commercially in diverse locations including Africa, , Australia, Chian, Hawaii and Central America, as well as in domestic gardens. The nut kernel is surrounded by a very hard shell and a soft husk. As harvested, the shell is particularly hard to crack, and it is difficult to remove the kernel because it clings to the inside of the shell. The kernel at this stage has a coconut-like taste. It is generally advised to dry Macadamia nuts before shelling, slowly, at temperatures in the range of 38-60 °C [1]. Furthermore, drying brings out the full flavor of the nut, and helps preserve it.

While the dryness can be tested by cracking a few nuts and tasting, it would be useful to have a convenient method to objectively determine completion of the drying process. Y. Wang *et al.* [2] and MMC Tang and JK Fuji [3] developed methods to determine dielectric properties of ground samples. It would be useful to have a technique for determining nut dryness of a sample of whole nuts (i.e. kernel in shell), i.e. without shelling or grinding, that could eventually be incorporated into the drying apparatus. The method should sample over a population of nuts, as properties, including size, differ from nut to nut. The objective of the present research was to develop such a method.

METHODS AND MATERIALS

Macadamia nut samples were gathered in 2022 and 2023 from the ground under author's tree in his garden in Herzliya, Israel (32.16° N, 34.86° E). Nuts begin to fall in late August, and continue through December. Normally the nuts are dried by placing them in a disposable Al baking pan, covering them with a glass pane, and leaving them outside exposed to the sun. Early in the season, the temperature in these "solar ovens" reaches ~50 °C, and ~two weeks treatment is sufficient. Late in the season much more time is required, and additional treatment in an oven, typically at 50 °C for overnight, is required.

Nut Collection 1, harvested in the mid-late 2022 season and comprised of about 31 husked nuts, was geometrically characterized. Each nut had approximately a slightly flattened spherical shape, as did the kernel. 28 nuts were randomly selected from the above collection, and the mass m , height h , maximum diameter d_l , and minimum diameter of the

Table 1. Nut and kernel volume and density from Nut Collection 1.

	V_{nut} (ml)	ρ_{nut} (g/ml)	V_{kernel} (ml)	ρ_{kernel} (g/ml)
average	3.3	1.0	1.0	0.8
stdev	0.7	0.1	0.7	0.3
stdev/av	0.2	0.1	0.6	0.3

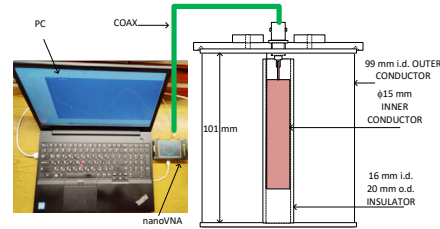


Figure 1. Measurement system based on a personal computer, nanoVNA and coaxial resonator.

shell, and of the kernel if it could be extracted either whole after cracking the shell, or in two pieces that could be reconstructed, were measured. From these measurements, the approximate volume $V = (4\pi/3) [(d_1 + d_2 + h)/6]^3$ and the approximate density $\rho = m/V$ of the whole nut and the kernel were calculated. Each was averaged over the sample, and the results are presented in Table I. The shell thickness was approximately $\tau=2$ mm. The average shell volume was then calculated as $V_{shell} = 4\pi[(d_1 + d_2 + h)/6]^2\tau \approx 2.1$ ml. The air volume in the shell was estimated from $V_{air}=V_{nut} - V_{shell} - V_{kernel} = 0.2$ ml. Nut Collection 2 was gathered on 23 October 2023. It comprised 1.6 kg of hulled nuts that fell and accumulated from 1 October.

Husked nuts were placed in a coaxial resonator shown, schematically in Fig. 1, which was attached to a miniature vector network analyzer, nanoVNA-V2. The real and imaginary parts of the back-scattering parameter spectrum $S_{11}(f)$ were recorded. The frequency of the first zero of the real part, $f_o[\text{Re}(S_{11})=0]$ and $f_n[\text{Re}(S_{11})=0]$ for the empty resonator and the nut-filled resonator, respectively, were obtained. An effective relative dielectric constant was defined as $\epsilon_r = (f_o/f_n)^2$.

RESULTS

Nut collection 1 was treated for 6 weeks in the solar oven, and then two nights in an electric oven set at 50 C. Samples at room temperature with a volume of 670 ml were placed in the resonator at various stages and f_n was measured. The results are shown in Fig. 2. It may be seen that f_n increased during the course of the treatment.

Nut collection 2 was treated in a convection oven in a disposable Al tray as follows: (1) 10 hr at 45°C, (2) 10 hr at 50°C, (3) 5 hr at 55°C. Three samples were extracted from different parts of the tray before each heat treatment, placed in the resonator up to its top (808 ml net volume). The nut sample was weighed, f_n was measured, and ϵ_r was calculated. The results are shown in Fig. 3 as a function of heating time. It may be seen that the mass of the nut sample, as well as the relative dielectric constant, generally decreased with heating time. As soon as the nut collection was removed from the oven, the resonator was filled with a sample; during the cool-down, f_n was measured and ϵ_r was calculated, and the results are shown in Fig. 4. Each $\epsilon_r(T)$ curve showed that generally ϵ_r decreased with temperature, but not monotonically. Rather each curve seemed to have a peak at some point during the cooling, and the location of the peak moved to lower temperatures in successive curves,

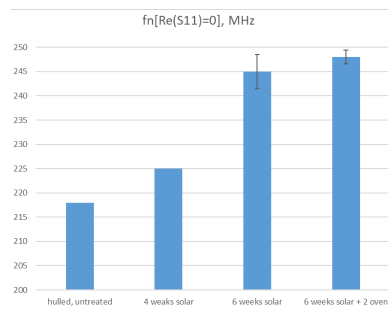


Figure 2. $f_n[\text{Re}(S_{11})=0]$ for Nut Collection 1 during a mixed solar and oven drying process.

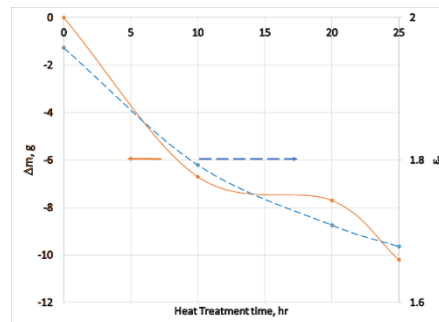


Figure 3. Mass change and effective relative dielectric constant of Nut Collection 2 during oven drying.

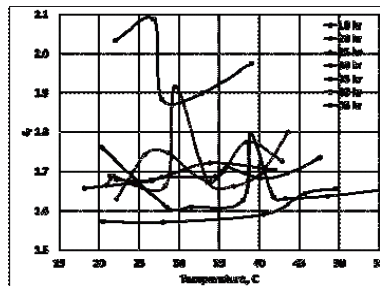


Figure 4. Effective relative permittivity during cool-down of Nut Collection 2 after oven heating.

i.e. with increased accumulative heating time. Successive curves, i.e. at increasing total heating time, had lower values of ϵ_r , as expected from the previous results.

DISCUSSION

Generally the mass decreased, f_n increased and hence ϵ_r decreased during drying. Presumably, this was caused by the loss of water and possibly volatile oils. The general decrease in ϵ_r during cooling, and the presence of a peak, is surprising and invites further investigation. The peak might signify some chemical change or phase change during cooling. In-situ measurements during drying should provide interesting results.

CONCLUSION

The effective dielectric constant of whole Macadamia nuts provides an effective indication of their dryness.

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Microwave Dielectric Properties of Sugarcane Juice

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Keywords: sugarcane juice, dielectric properties, coaxial-line probe, quality indexes

INTRODUCTION

Sugarcane is the main material for sugar production because of its high sugar content. Current methods for the characterization of sugarcane juice are labor intensive and time consuming. They involve the use of near infrared polarimetry to measure sucrose content, refractometry to measure soluble solid content (Brix), and measurements of fiber content. In the food and agricultural industries, dielectric properties were successfully used to determine instantaneously and nondestructively important quality attributes including, moisture content, water activity, and bulk density [1]. Dielectric properties of sugarcane solutions were measured at microwave frequencies and different temperatures [2], [3]. In this paper, dielectric properties of sugarcane juice of different quality indexes were measured with an open-ended coaxial-line probe and a vector network analyzer over a broad radiofrequency range (200 MHz to 20 GHz) and at a room temperature of 25 °C. The main objective of this paper is to analyze the obtained dielectric spectra and identify correlations between the dielectric properties and sugarcane indexes.

METHODOLOGY

Samples of sugarcane juice were obtained from mixing the juice extracted from two varieties of sugarcane stalks (Ho 02-113 and L 01-299) [4]. Table 1 shows the characteristics of each sample, where TRS is the Theoretical Recoverable Sucrose. TRS is the most critical measurement as it is used to estimate field sucrose yields. Brix was determined with a refractometer and the percent sucrose by using a polarimeter. The % fiber was determined by oven drying the fibrous material remaining after juice extraction (65 °C for 3 hours). The dielectric properties, ϵ' and ϵ'' , of each sample were measured with a Keysight N1501A high-temperature open-ended coaxial-line probe and a PNA-L N5235B network analyzer as shown in Figure 1. Settings were made to provide measurements at 101 frequencies on a logarithmic scale from 200 MHz to 20 GHz. Before the measurements, calibration was performed at the tip of the probe by using air, short-circuit block, and distilled water at 25 °C.

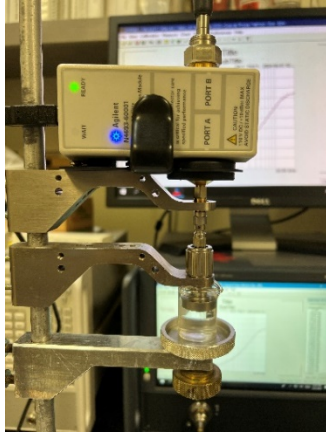
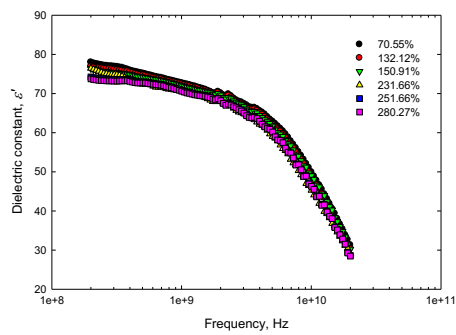


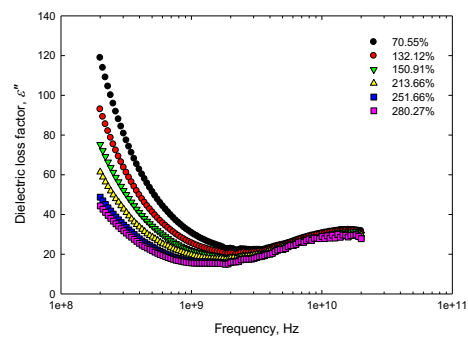
Figure 1. Measurement setup

Table 1. Sugarcane juice indexes

Sample	Brix, %	Sucrose, %	Fiber, %	TRS
1	10.49	6.73	36.48	70.55
2	12.55	9.85	30.31	132.12
3	13.36	10.77	28.39	150.91
4	16.38	14.64	23	231.66
5	16.96	15.41	20.87	251.66
6	17.61	16.50	18.38	280.27

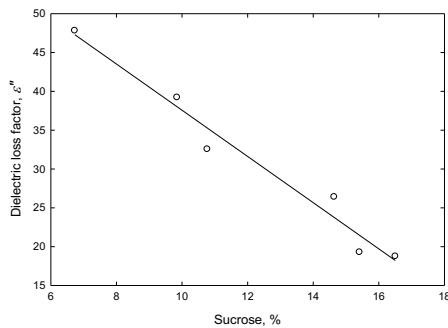


(a)

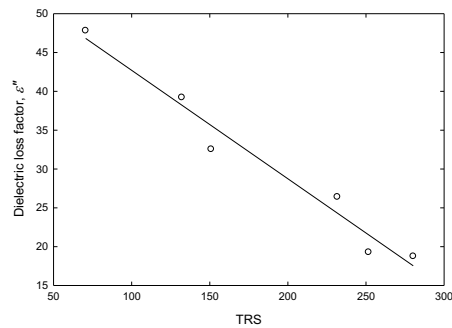


(b)

Figure 2. Variations of dielectric constant (a) and dielectric loss factor (b) with frequency at 25 °C and indicated TRS values.



(a)



(b)

Figure 3. Variations of dielectric loss factor as a function of % sucrose (a) and TRS (b) at 500 MHz and 25 °C.

RESULTS AND DISCUSSION

Figure 2 shows variations of ϵ' and ϵ'' with frequency. The dielectric constant, ϵ' , decreases with frequency with a slope change at 3 GHz. The dielectric loss factor, ϵ'' , first decreases with frequency and then increases with frequency starting at 2 GHz. At the lower region of the spectrum, ϵ'' decreased with TRS and a distinct curve was obtained for each sugarcane juice sample. However, for frequencies higher than 3 GHz, the curves are nearly superimposed, and a relaxation can be observed for each sample at frequencies between 15 and 20 GHz. The dielectric loss factor behavior in the lower frequency range can be used to identify correlations between ϵ'' and the sugarcane indexes. Figure 3 (a) shows that ϵ'' decreased linearly with sucrose content. A linear regression provided the following correlation between ϵ'' and sucrose content:

$$\epsilon'' = -2.976 \text{ Sucrose}(\%) + 67.323 \quad r^2 = 0.968$$

From this equation, sucrose can be calculated as:

$$\text{Sucrose}(\%) = \frac{67.323 - \epsilon''}{2.976}$$

Similarly, figure 3 (b) shows that ϵ'' decreased linearly with TRS. A linear regression provided the following correlation between ϵ'' and TRS:

$$\epsilon'' = -0.139 \text{ TRS} + 56.66 \quad r^2 = 0.966$$

From this equation, TRS can be calculated as:

$$\text{TRS} = \frac{56.66 - \epsilon''}{0.139}$$

CONCLUSION

Measurement of dielectric properties of sugarcane juice at microwave frequencies revealed that the dielectric loss factor was sensitive to changes of the sugarcane juice indexes. This behavior was used to identify linear correlations between ϵ'' and each sugarcane juice index at a single frequency (here 500 MHz). From these correlations, each index can be calculated in terms of ϵ'' . Resulting equations can be used for nondestructive and instantaneous determination of sugarcane indexes from a single measurement of the dielectric loss factor.

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Predicting Hotspot Generation from Local Electric-field Enhancement During Microwave Sintering

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Keywords: support vector machines, microwave sintering, ceramics, hotspots, electric-field

INTRODUCTION

Microwave sintering is a growing field-assisted sintering technique that has the potential to consolidate ceramic dielectrics. Being a non-contact sintering method, microwaves of certain frequencies and powers can be irradiated on non-conducting ceramics that heats up due to dielectric loss through polarization and dipole rotation. Furthermore, a hybrid approach is incorporated to sinter poor dielectrics such as alumina ceramics, wherein susceptors surround alumina to indirectly heat the green samples at lower temperatures (<1000 °C). Susceptors, made of semi-conducting ceramics such as silicon carbide, undergo additional ohmic loss after absorbing microwave power, thereby ramping up the temperature of alumina through infrared heating. However, the efficiency of power absorption by the lossy susceptors depends on multiple factors including the surrounding electric-field distribution, shape and proximity of lossy materials relative to each other. Sharp edges and corners specifically, result in localized field enhancement at the given frequency due to the dense electron distribution over sharply curved surfaces. This local field enhancement is intensified when the distance between the particles is reduced [1]. The resulting high intensity electric-fields are responsible for hotspot generation in the susceptors that can melt the ceramics to be sintered and/or the insulation package holding the ceramic-susceptor assembly. These hotspots can arise as an effect of the non-linear combinations of various input parameters, the most common and easily controllable being, microwave power ramping rate and target sintering temperature. Due to a varied non-linear input space defined by these two parameters, prediction of hotspots using machine learning is needed. This novel work uses support vector machines (SVMs), a supervised machine learning classification algorithm, to classify detrimental high energy hotspots arising during microwave sintering of alumina. The results from this study are particularly useful to sinter complex-shaped ceramics with a higher density (>95%) which is only achievable at higher sintering temperatures (>1500 °C) where thermal hotspots are prominent.

METHODOLOGY

PROCEDURE

Cylindrical alumina pellets, having diameter of 12.7 mm and height~6 mm, were fabricated as green samples to sinter inside a 2.45 GHz microwave reactor. Silicon carbide susceptor blocks, having 25.4 mm sides each and 10 mm height, were used for indirect heating (Figure 1a). The preliminary experimental studies helped in understanding the effects of microwave process controls, such as sintering temperature, holding duration and susceptor configuration during faster ramping, on the final densities of sintered alumina samples [2]. Higher sintering temperatures and heating rates led to higher part densification, but hotspots were prominent at higher temperatures (>1400 °C). To better understand hotspot generation, a multi-physics numerical model was developed using COMSOL multi-physics software to simulate the experimental conditions and predict the electric-field and temperature distribution during microwave sintering. The best configuration of susceptors was selected based on the temperature uniformity inside the insulation package. Power ramping rate and target sintering temperature were the input process controls influencing hotspot generation during microwave sintering. Different combinations of these two input spaces were simulated to collect training and testing data for hotspot prediction due to highly intensified electric-fields inside the insulation package. SVMs, with soft decision boundaries for outliers, were trained to classify the input space for hotspot generation as it fits well on small datasets, thereby making it particularly useful for tailored engineering applications. F1 score determination using confusion matrix was used as a metric to evaluate SVM model for this binary classification problem. Finally, random test cases were selected from the simulation dataset for experimental validation.

METHODS AND MATERIALS

Ball-milled prismatic-shaped alumina powder with a theoretical density of 3.95 g/cm^3 , nominal tap density of 1.81 g/cm^3 (about 46% of theoretical density), melting point of 2072 °C, average particle diameter of $28 \text{ }\mu\text{m}$ and $>99\%$ purity with no sintering aids, was supplied by ExOne®. Silicon carbide square blocks, with a nominal density of 1.99 g/cm^3 , were used as susceptors surrounding the green samples. High temperature (<1600 °C) Fiberfrax® fiber, made of alumina-silicate, was used to form the cylindrical insulation package of 140 mm diameter and 102 mm height. Alumina crucible chips, supplied by AdValue Technology®, were used as base plates for the green samples inside the insulation package during microwave sintering. Sintering temperatures, ranging from necking temperature of alumina to 0.96 times melting point of alumina (~ 1300 °C to ~ 2000 °C) and power ramping rates, based on the preliminary experimental studies ensuring lesser hotspots, ranging from 50 to 100 W/min were chosen as the input space for SVM [2].

RESULTS AND DISCUSSION

Preliminary studies about the influence of different configurations of silicon carbide lossy susceptors on electric-field intensification and thermal hotspot generation, indicated hexagonal configuration having the highest intensified electric-fields locally over the sharp

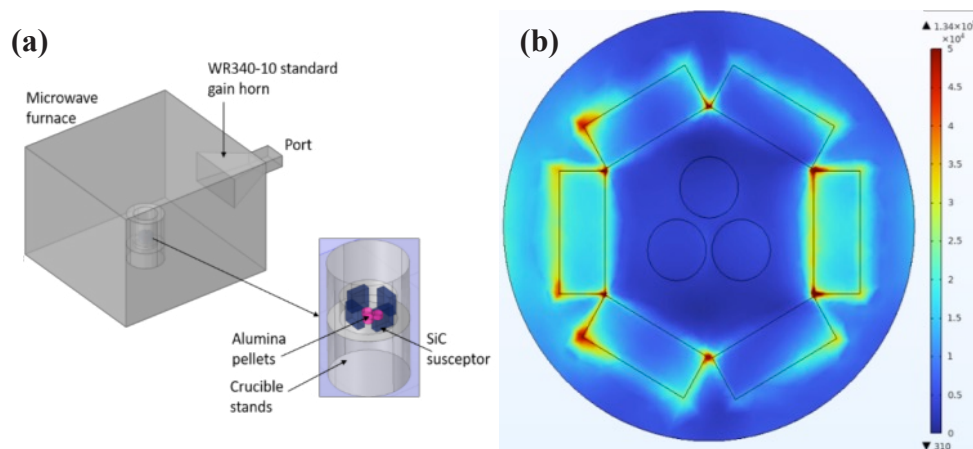


Figure 1. Schematic diagram of the 2.45 GHz microwave reactor used in the simulation model to generate SVM model training and testing data (a), and top view of the insulation package showing electric-field distribution (V/m) inside the hexagonal susceptor configuration (b).

edges of susceptors as shown in Figure 1b. Different configurations of susceptors such as square, triangular, pentagonal and hexagonal were explored for the best susceptor arrangement selection. The minimum distance between the silicon carbide susceptor blocks in the case of hexagonal arrangement resulted in the highest local electric-field intensification. These high intensity electric-fields were responsible for hotspot generation in the silicon carbide susceptors. However, owing to high thermal conductivity of the susceptors, the hotspots were quickly conducted to the alumina crucible chip stands at the bottom. In addition, surface-to-surface radiation and convection also helped in heating the alumina pellets. As a result, the most uniform temperature distribution was observed in the hexagonal configuration where the lowest temperature gradients of 60 °C and 20 °C were computed for susceptors and green samples respectively, thereby making this configuration suitable to sinter complex-shaped ceramics. Currently, different combinations of sintering temperatures and power ramping rates are being simulated using the hexagonal configuration to collect dataset for SVM model training and hotspot predictions.

CONCLUSION

This novel work optimized the susceptor configuration for complex-shaped ceramic sintering using 2.45 GHz microwaves. It laid out the foundation for ongoing studies on machine learning-based thermal hotspot predictions during microwave sintering alumina at high temperatures.

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Multiphysics Modeling of Microwave Heating Behavior in Particulate Beds

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Keywords: multiphysics modeling, particle-resolved model, local temperature profiles, particle bed

INTRODUCTION

Microwave-based heating is gaining much attention as an enabling technology for chemical process electrification; however, the technology is not widely adopted by the chemical industry due to existing knowledge gaps and scale-up challenges. Improving temperature homogeneity when processing large material volumes, energy efficiency, and developing scalable reactor designs are needed to bridge the gap from bench-scale demonstrations to industrial implementation. Chemical processes involving particulate solids are common in applications such as heterogeneous catalysis, thermochemical conversion processes, and material synthesis. Microwave heating characteristics of particulate solids differ from those of homogeneous liquids and it is well known that microwaves may induce localized field effects between individual solid particles leading to hot spot formation. Local particle-scale temperatures are difficult to measure experimentally due to inherent temperature measurement challenges in microwave systems; therefore, numerical modeling is a useful tool for investigating microwave heating behavior in porous beds and is able to resolve local temperatures.

Existing numerical modeling studies on microwave heating of solid particle beds have mainly employed a porous media model where average porosity and effective material properties are used to define the particle bed domain. While this modeling approach is convenient and provides information about microwave heating in the bulk material, it is unable to resolve inter- and intra- particle electromagnetic field effects, which are important in certain chemical reactions. This work aims to simulate local microwave heating phenomena in a particle bed, by employing a particle-resolved model. Further, as one of the main objectives for improving energy efficiency during microwave processing is by maximizing the microwave power utilization, i.e., by increasing power absorption efficiency, power absorption efficiency will also be evaluated.

METHODOLOGY

COMSOL Multiphysics was used to simulate microwave heating of mono-sized spherical particles in a cylindrical reactor based on finite element methodology. Electromagnetic and heat transfer physics were coupled to simulate microwave heating within the different

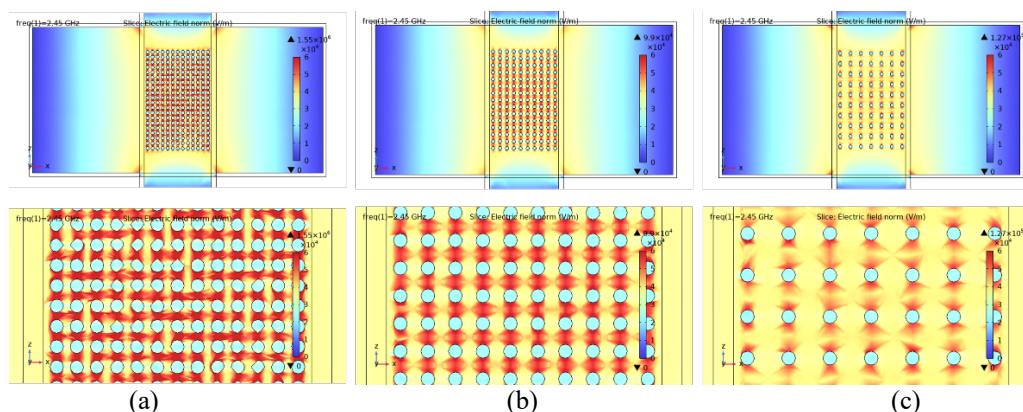


Figure 1. Electric field profiles of the simulated particle beds consisting of 1 mm spherical particles and particle spacing of (a) 0.5 mm, (b) 1 mm, and (c) 2 mm. The color scale bar ranges from 0 to 6×10^4 V/m.

bed geometries irradiated by 1 kW, 2.45 GHz microwave energy in a single mode (TE₁₀) applicator. Different particle packing densities were modeled to represent closely packed and loosely packed beds to compare the resulting power absorption efficiencies and thermal profiles during microwave heating. For the baseline model, material properties are assigned equally to all particles. The model is also extended to a mixture of two materials: a low loss material (poor microwave absorber) and a high loss material (good microwave absorber), as is often done to enable processing of poor absorbers such as biomass. To define this case scenario, the respective material properties are randomly assigned to individual particles to achieve the desired volume mixtures.

RESULTS

E field and thermal profiles were simulated for cylindrical particle beds consisting of 1 mm spheres with different particle spacings (0.5, 1.0, and 2.0 mm). As shown in Fig. 1, electric field intensification is observed between particles aligned parallel with the direction of the electric field (vertical z-direction), with greater field intensities between more closely spaced particles. This effect leads to greater power absorption at the poles of the particles.

Total dissipated power was estimated by performing a volume integration of the electromagnetic power loss solution. Dissipated power increases linearly with increasing particle bed density (Fig. 2). As expected, more power is absorbed at higher packing densities due to the greater number of particles present in the volume. Therefore, greater power absorption efficiencies may be attained in particle beds with particle arrangement.

DISCUSSION

The data presented in this work provides a better understanding of microwave heating behavior in tubular reactors under different particle packing densities commonly encountered in industrial chemical processes. For simplification, the particle bed geometries represented in the model are regular particle packing arrangements, i.e. mono-sized spherical particles arranged in a hexagonal lattice. As this regular arrangement may

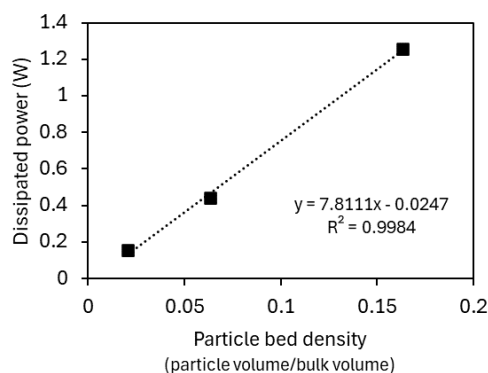


Figure 2. Electromagnetic power dissipation in the particle bed as a function of particle density.

not accurately represent particle packing structures encountered in industrial practice, future work will investigate more realistic particle packing arrangements and non-spherical particle geometries to model their microwave heating behavior more accurately.

CONCLUSION

This work provides fundamental insights about microwave heating in porous beds, while investigating local inter- and intra-particle heating phenomenon. The results from this study are relevant to developing microwave-based chemical processes involving particulate solid materials, which may play a significant role in decarbonizing the chemical industry.

Optimal Defect-Layer Positions in Thin Electromagnetic Energy Absorbers

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Keywords: electromagnetic heating, thermal runaway, power delivery

INTRODUCTION

High-power wireless transmission requires an effective means of converting incoming electromagnetic radiation into energy that produces useful work. One requirement of the system is the conversion of electromagnetic energy into internal energy for an absorbing material. Recent theoretical approaches to analyze composite structures have centered on layered geometries that enhance the Fabry-Bragg resonance [1]-[3]. Lossless layers surround a lossy “defect” layer, whose loss factor increases exponentially with temperature, with the permittivities of the lossless layers larger than those in the defect layer. Here, we investigate asymmetric configurations of the general N -layer geometry with a single defect layer, allowing for this layer to reside in different positions. Our goal is to see how the position of the defect layer affects the efficiency of EM energy absorption.

METHODOLOGY

Consider the N -layer configuration shown in Fig. 1. A laminate system of N layers are irradiated symmetrically by a monochromatic plane wave. One layer is a lossy ceramic whose loss factor is temperature dependent, while the real part of the dielectric constant of all the layers are independent of temperature. We assume that the thickness of the entire system is sufficiently thin that the temperature in all the layers is the same constant, but unknown, value. Conservation of energy requires a balance between the energy absorbed in the laminate system and energy losses to the surrounding environment. At steady-state temperatures, this energy balance is represented by

$$P\varepsilon_d''(\theta)\|E_d\|_2^2 - B\theta = 0 \quad (1)$$

where P is the ratio of the applied electromagnetic power applied to the system balanced by characteristic thermal conduction through the system, $\varepsilon_d''(\theta)$ is the loss factor in the defect layer, $\theta = (T - T_0)/T_0$, where T is the system temperature and T_0 is the ambient temperature is the relative temperature difference of the system temperature and ambient with respect to the ambient temperature, and B is the Biot number representing energy losses to the

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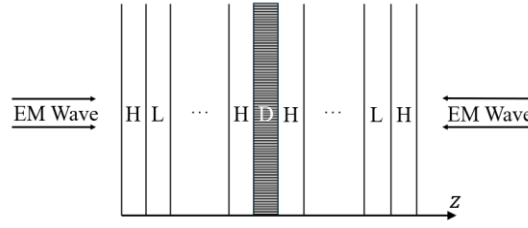


Figure 1. Diagram of a sample N -layer laminate system. Lossless layers with high permittivity are marked with an H, low permittivity marked with an L, and the defect layer is marked with a D.

environment compared to the thermal conduction in the system. $\|E_d\|_2^2$ is the L_2 -norm of the electric field in the defect layer, E_d . Equation (1) is coupled with to the solution of the electric field amplitude E_d , which needs to be determined through the solution of Helmholtz's equation in each of the layers $j = 1, 2, \dots, N$

$$E_j''(z) + \gamma^2 \varepsilon_j' E_j(z) = 0, z_{j-1} < z < z_j, j \neq d, \quad (2)$$

$$E_d''(z) + \gamma^2 [\varepsilon_d' + i\varepsilon_d''(\theta)] = 0, z_{d-1} < z < z_d, \quad (3)$$

where E_j is the electric field amplitude in layer j , γ is the free space wavenumber of the electromagnetic wave, scaled on the system thickness, ε_j' is the real part of the dielectric constant in layer j , and the domain for each layer is given by $z_{j-1} < z < z_j$. Continuity of the electric and magnetic fields are applied at each of the interfaces $z_1 < z < z_{N-1}$, and Sommerfeld radiation conditions are applied at $z = z_0$ and $z = z_N$.

To solve (1)-(3), we represent the solution of (2) in the lossless layers using the transfer matrix method to represent the left- and right- travelling-wave amplitudes to find effective boundary conditions on the defect layer. With these effective boundary conditions, we then use finite difference methods in the defect layer solve for E_d using θ as a parameter. With E_d , we find the applied power P through (1) corresponding to the prescribed temperature θ .

RESULTS

Plotting equilibrium temperature against incident power yields a bifurcation diagram known as a power response curve. Power response curves and reflection coefficients for two different wave frequencies are presented in Fig. 2. The sample considered is a 7-layer system in an asymmetric H-X-HLHLH configuration, with lossless layer permittivities $\varepsilon_H' = (7\pi/2)^2$ and $\varepsilon_L' = (\pi/2)^2$, and a defect layer with $\varepsilon_d' = \pi^2$ and $\varepsilon_d'' = 10^{-3}e^{3T}$. Fig. 2(a) is a power response curve for $\gamma = 1$, featuring an additional stable branch compared to what has been observed in previous work. The reflection coefficient's plot in Fig. 2(b) shows that low reflection coefficients occur at points corresponding to the first two unstable nodes of the power response curve.

DISCUSSION

In asymmetrical geometries, like those used to generate Fig. 2, there is a subsystem on each side of the defect layer where separate resonance can take place. The objective of this work

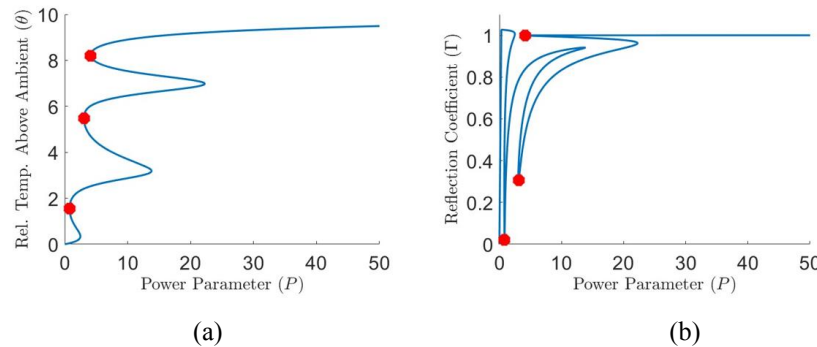


Figure 2. Power response curve (a) and reflection coefficients (b) for $\gamma = 1$. Reflection coefficient values at unstable nodes are highlighted on both graphs.

is to categorize how these pairs of resonant systems interact with the defect layer in terms of thermal response. The power response curve presented in Fig. 2 demonstrates a higher level of resonance than exhibited by previously studied systems [1], [3], possessing four branches, all of which occur at relatively low powers.

Low reflection coefficients occur at and around both the first and second unstable nodes. Hence, absorption efficiency is locally optimized near the left lower two limit points shown in Fig. 2(a).

CONCLUSION

We have shown that it is possible to achieve higher levels of resonance in a thin electromagnetic energy absorber by using asymmetric layer configurations. Placing the defect layer in an asymmetric configuration allows for the absorbing system to be operated more efficiently compared to the symmetric case. By changing the position of the defect layer, engineers can use this as a design parameter for better electromagnetic energy absorbers.

ACKNOWLEDGMENT

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A Panoramic View of Temperature and Field Distributions of the Structured Catalyst Under Microwave Irradiation Using Experimental and Modeling Approaches

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Keywords: microwave catalysis, microwave-material interaction, numerical modeling

INTRODUCTION

The demand for intensified catalytic reaction processes using renewable energy sources has led to increased popularity of applying energy-saving microwave irradiation to chemical reactors. It has been shown that microwave irradiation provides several advantages to heterogeneous catalytic systems, such as improved heating efficiency and enhanced product yields. Despite microwave irradiation showing its potential in chemical reaction engineering and heterogeneous catalysis, the intrinsic physics of microwave-material interaction is, in general, difficult to illustrate solely through experiments. The control and measurement of temperature under microwaves is key to driving chemical reactions but is complicated by many dynamic and interrelated factors including penetration depth, temperature dependence of complex permittivity, and changing sample properties under reaction (e.g., reduction) that affect absorption. Therefore, this work combines a state-of-the-art temperature measurement method with numerical modeling to provide a panoramic view of microwave-material interaction and the resulting microwave heating effect, which allows researchers to better understand the role of microwave irradiation in the chemical reaction processes.

METHODOLOGY

COMSOL Multiphysics (version 5.6) with heat transfer and radiofrequency modules was used as the modeling tool. As a reference, a unit cell model with 27 particles was employed to represent one of the periodic cells inside the catalyst bed (Figure 1a) and to represent the assumption of the perfect mixture of microwave absorber (SiC) and catalyst, SiC was assigned to be at the corners of the cell and the center of each face of the cell (highlighted

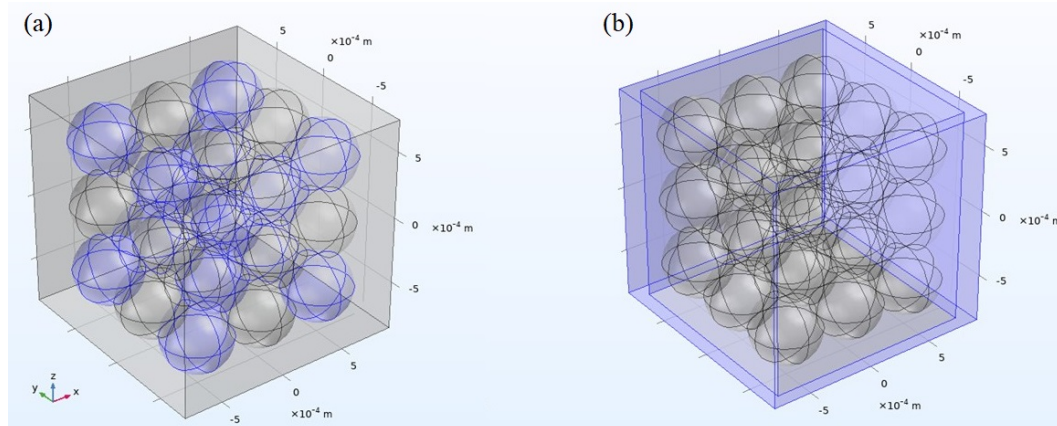


Figure 1. The geometry of a) the Particles model; b) the Monolith-particles model; Highlighted material is SiC.

in Figure 1a). For the monolith scenario, a particle model with SiC monolith surrounding (the “Monolith-particles model”, Figure 1b) was established. The outer particles are in contact with the monolith. The void volume is filled with air. For all models, the assumptions are listed below:

- The particle of the material is spherical with a diameter of 0.5 mm.
- The power density is assumed to be 7.5 W/cm^2 , which is equivalent to 280 W of microwave energy that was evenly distributed throughout the cross-section of the catalyst bed. This value is determined by the average of the experimental record.
- The fluid flow rate (u) was set as 0.0239 m/s in the negative-z direction, which is equivalent to 450 SCCM of the gas feed.
- The packing of the spherical particles is parallel.
- Mass transfer (chemical reactions) is not considered.
- The microwave propagates in the negative x-direction. For the E-field Cavity case, the electric field is in the z-direction; for the H-field Cavity case, the electric field is in the y-direction.
- Only convective heat loss, including the heat loss by flowing air, is considered.

A LUNA[®] system was employed to measure the temperature of the catalyst bed by inserting a fiber optic probe axially through the different parts of the catalyst bed, and the temperature was measured at every 2 mm. A reactor-scale model was built to better understand the microwave-material interaction and as well as for the reference purposes.

RESULTS

The temperature measurement results show that the catalyst-loaded monolith structure provides a lower temperature gradient between hot and cold regions within the catalyst

bed. However, the existence of the monolith wall creates more than 30% of electric field decay per monolith channel in the reactor, while negligible decay was observed in the particle mixture reference. By flipping the direction of the electric and magnetic fields, even though no difference was observed in the periodic models other than the direction of the electric field, the simulation result from reactor-scale model shows a more homogeneous heating pattern. The temperature gradient between hot and cold regions is narrowed and it was observed experimentally that the system was more stable.

DISCUSSION

The field decay observed in the modeling study not only can affect the heating of the far side of the bed but may also affect the potential activation of the intermediates triggered by the moderate electric field intensity. It was observed previously that in microwave-assisted dehydroaromatization, the mixture of catalyst and microwave absorber produced more ethylene and ethane, which are important intermediates from methane dimerization, while less benzene was observed because of the higher electric field intensity, which triggered benzene hydrogenolysis [1]. It has been observed that more benzene was produced in monolith case, which indicates the difference in electric field distribution can affect the product selectivity of the process. Therefore, by numerical modeling approach, the field distribution and temperature gradient of the reactor can be visualized and analyzed; and such properties can be optimized for different chemical reactions by altering the form of catalyst and the reactor setup.

CONCLUSION

The intrinsic microwave-material interaction was demonstrated in this study through experimental measurement and numerical modeling approaches. Different material combinations and reactor setups were investigated and compared. By combining numerical modeling with advanced measurement techniques, the microwave-material interaction and the relationship between electromagnetic field and heating can be better understood, which further benefits the development of microwave-assisted reactors and their application in process intensification.

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Performance Enhancement of a 915 MHz 100 kW Atmospheric Microwave Plasma Torch for Gas Treatment through CFD Modeling and Optimization

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Keywords: H₂ production, downstream plasma source, plasma torch, microwave induced plasma, plasma diagnostics, CFD modeling, gas treatment

INTRODUCTION

In response to the growing demand for gas treatment technologies, Sairem has developed a groundbreaking 915 MHz 100 kW atmospheric plasma torch (Figure-1) designed for emerging industrial applications. This innovative device features a meticulously designed structure encompassing critical components like the plasma ignition system, water- and air-cooling mechanisms, and gas injection technology.

METHODOLOGY

To maximize operational efficiency and enhance performance, a comprehensive computational fluid dynamics (CFD) model was developed (Figure 2 and 3). Utilizing CFD, we meticulously investigated the influence of vortex parameters on gas dynamics within the plasma chamber also for plasma confinement. Parameters including number of inlets, inlet diameter, and incident angle were rigorously analyzed.

RESULTS

Leveraging insights from the CFD simulations, we optimized the vortex design (Figure 4). This optimization process led to a significant increase in the gas flow rate within the plasma chamber, from 1700 l/min to 5000 l/min (Figure 5). This enhancement, along with an increase of the thickness of the protective layer surrounding the plasma (Vortex Thickness), contributes to improved plasma confinement, lower body temperature (cavity) (Figure 6), and extended overall longevity (operation time).



Figure 1. View of the 915 MHz 100 kW microwave plasma torch.

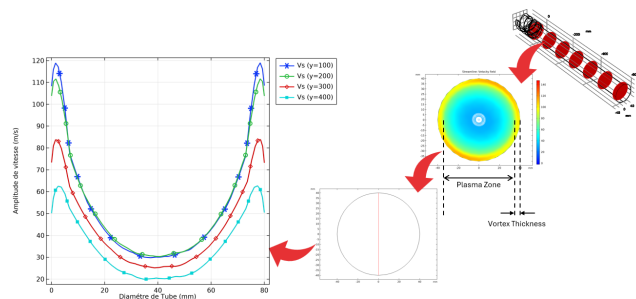


Figure 2. computational fluid dynamics (CFD) model of the 915 MHz 100 kW microwave plasma torch. (Tube: R40 mm radius, Height: 630 mm. Vortex Piece: 2 Inputs, Flow rate 5000 l/min)

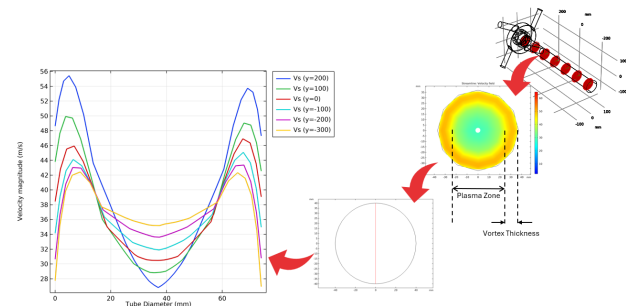


Figure 3. computational fluid dynamics (CFD) model of the 915 MHz 100 kW microwave plasma torch. (Tube: R37 mm radius, Height: 630 mm. Vortex Piece: 4 Inputs, Flow rate 5000 l/min)

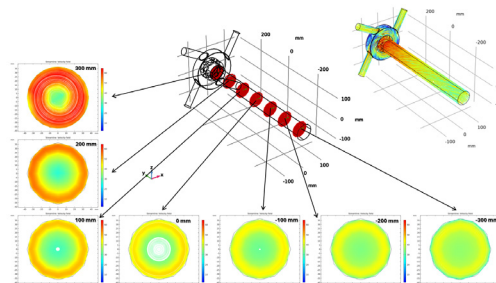


Figure 4. computational fluid dynamics (CFD) model of the 915 MHz 100 kW microwave plasma torch. (Tube: R37 mm radius, Height: 630 mm. Vortex Piece: 4 Inputs, Flow rate 5000 l/min)

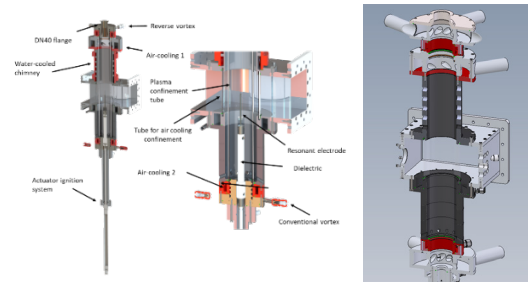


Figure 5. Mechanical design of the Plasma downstream 915MHz 100kW source left: Vortex piece (R5 mm, input Angle: 30°, RVR), right: Vortex Piece (R10mm, input angle 45°, CVR).

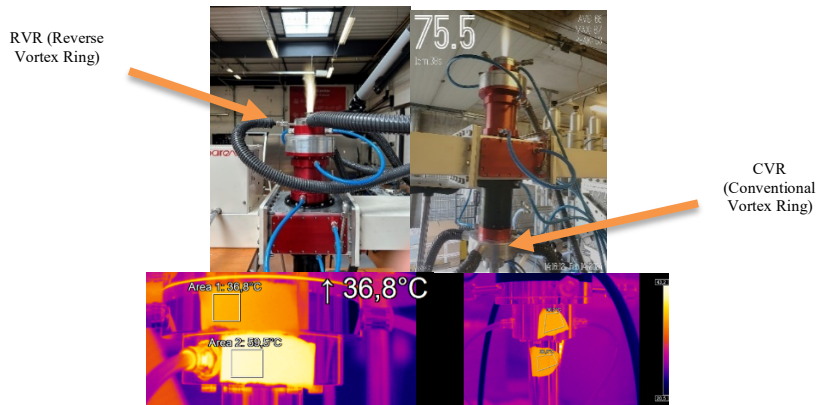


Figure 6. The Plasma downstream 915MHz 100kW source left: RVR, Flow rate 1700 l/m, Power 100kW. Right CVR, Flow rate 5000 l/min, Power 100kW.

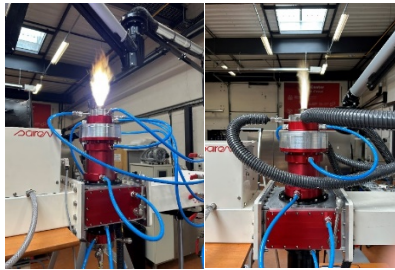


Figure 7. The Plasma downstream 915MHz 100kW source left: RVR, without Axial injection, Right RVR, with axial injection 400 l/min

CONCLUSION

The axial injection was investigated to examine how it impacts the system's performance. Two scenarios are compared: with and without axial injection (Figure 7). Axial injection is expected to improve flow stability, plasma confinement, and tube protection by boosting gas velocity along the walls. We'll then analyze injection velocity and positioning to optimize these benefits. Ultimately, we aim to find the ideal axial injection setup for a more stable flow (narrower exit flame), better plasma confinement, and enhanced tube protection, leading to an overall improvement in system efficiency and lifespan.

915 MHz Industrial Magnetron: 60 Years Later

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Keywords: magnetron, 915 MHz, high efficiency, vane and strap

INTRODUCTION

In 1964 Twistleton reported on a 20 kW Continuous Wave (CW) vane and strap magnetron that operated at efficiencies higher than 80% [1]. Since then, 10s of thousands of this magnetron design has been sold for industrial applications that range from bacon cooking, ceramic drying to diamond growth, with CW powers up to 100 kW and pulsed powers near 300 kW. Although the overall design has not changed much, the processing of these magnetrons has changed in order to meet the ever-increasing desire for higher powers. This paper will discuss some of the improved processes required for high power operation as well as the reason for the high efficiencies of this particular magnetron when compared to others similar devices.

EFFICIENCY

The efficiency of a magnetron (not including the cathode) is given by $\eta = \eta_e \eta_c$. Where η_e is the electronic efficiency, efficiency converting DC energy to RF in the anode and η_c , the circuit efficiency, which is the efficiency to the load², where the energy is delivered. So, in order to maximize the overall efficiency, both η_e and η_c have to be maximized.

The electronic efficiency, η_e , is improved by increasing the ratio of (V/V_o) , the operating voltage divided by the characteristic voltage of the device V_o , which is determined by the geometry of the anode and the frequency of operation. See Figure 1 below. V/V_o will be calculated and an upper limit of η_e will be estimated.

The circuit efficiency is related to the coupling to the load and can be calculated from S11 return loss curve. See Figure 2. From this curve, knowing the depth and frequency of the resonance, the value of η_c can be calculated and thus a value for η total.

OPERATION

The low Q value of the S11 curve in Figure 2 indicates that the electromagnetic energy that is generated in the anode is heavily coupled to the waveguide and load, which is necessary for high efficiency operation.

Unfortunately, this also means that anything that happens in the waveguide is easily transmitted back to the magnetron. Circulators are put in the waveguide setup to minimize

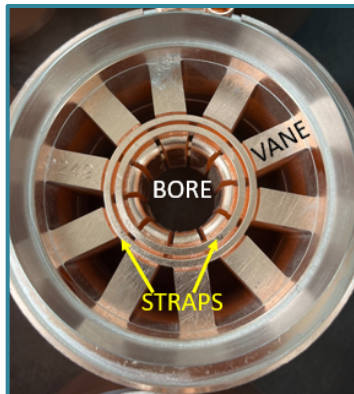


Figure 1. 100L anode top view

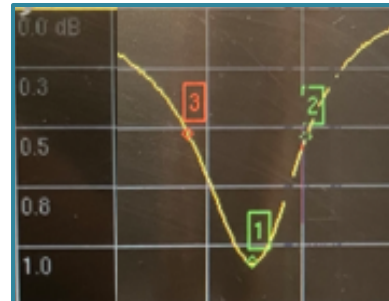


Figure 2. Typical S11 curve for an 100L Industrial Magnetron

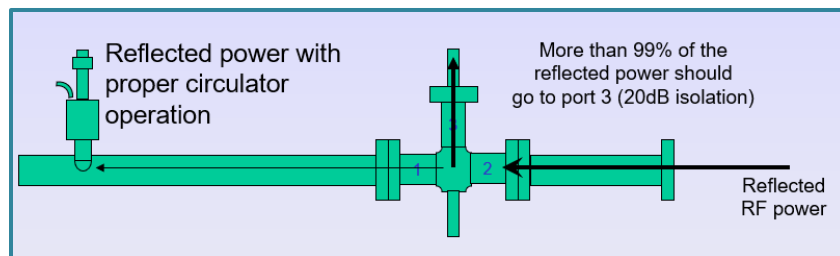


Figure 3. Illustration of Proper Magnetron Operation with a directional circulator

this effect (see Figure 3 below). With proper circulator operation, less than 1 percent of the power makes it back to the magnetron. There are two complications to this setup: 1. Circulator effectivity is often determined by cold test measurements in the milliwatt range, which may or may not be accurate: 2. High power electronic components, like circulators, wear out and do not function properly. Both of these cause power to be reflected back to the magnetron, causing damage to the anode and the cathode of the magnetron.

FAILURES

Figure 4 displays a magnetron anode that has been subjected to high levels of reflected power, either from a poorly operating circulator or arcing in the waveguide. The power is transferred to the straps and ohmic losses heat the copper to the point of melting. This almost always occurs on the Antenna/Launcher side of the magnetron further indicating it is due to reflected power.

The cathode/filament can also suffer damage due to reverse power. Figure 5 below displays: a. A Solidworks model of the filament and b. a biased used filament near failure. The sweet spot, in temperature, for the filament is hot enough to produce electrons of sufficient quantity, but cool enough to minimize evaporation of the tungsten filament. Reverse directed power can overheat the filament which can cause arcing and eventual failure of the magnetron. There are several ways to monitor the filament temperature which in turn would allow for adjustment of the filament bias to minimize overheating.

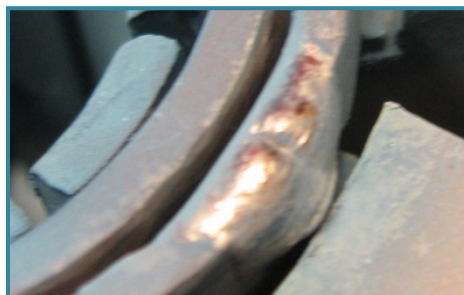


Figure 4. Anode straps melted by high reflected power

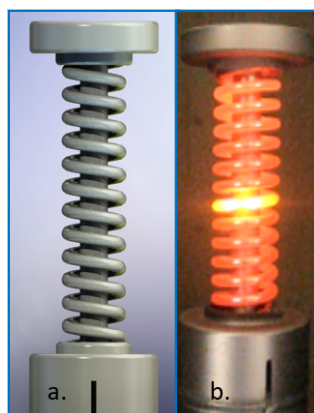


Figure 5. (a) Solidworks model and (b) biased used filament, near failure

CONCLUSIONS

Invented 60 years ago, the 915 MHz industrial magnetron is an amazing device, converting DC potential into RF energy at ~85% efficiency. The reasons for this high efficiency will be presented. This high efficiency also brings the aforementioned problems, and others not mentioned in this abstract, due to the heavy coupling to the launching waveguide. Several methods of monitoring and regulating operational parameters can be facilitated to minimize these operational problems which will also be covered.

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Tuning Considerations for Microwave Heating Systems

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Keywords: efficiency, microwave heating, tuners

INTRODUCTION

Maximum power transfer from a power source occurs when the impedances of both the source and load are equal. Designing a terminating load that perfectly matches the power source impedance isn't always practical or feasible. To optimize system efficiency, tuners are used to match the system load impedance to the power source. In microwaves, impedance is a complex value having a real and imaginary component, resistance and reactance respectively. To assist in calculations of complex impedances, the Smith Chart is a common tool that is used. A Smith Chart transforms the Cartesian complex impedance plane into a normalized polar plot. If the impedance of the terminating load is not ideal, tuners may be used to create a generator impedance that maximizes power transfer. The generator needs to be the conjugate of the load impedance with an equal real component and a negated imaginary component as shown in Figure 1.

Physically there are several methods to introduce the required conjugate impedance matching. For waveguide systems, probe tuners, stub tuners and hybrid-based tuners are the most common [1]. Examples of these tuners are shown in Figure 2. Each approach has advantages and disadvantages, the one critical aspect is that it must be able to achieve the expected magnitude of the terminating load impedance at any possible phase angle. Probe tuners can be supplied with a varying number of probes and probe spacing depending upon the required frequency bandwidth and the magnitude of the mismatch that needs to be achieved. With the probes fully retracted, the tuner will be in a neutral position. Insertion of a probe will introduce a mismatch approximately along a radial line on a Smith Chart. Stub tuners will typically be designed with two or three stubs again dependent on the necessary bandwidth and mismatch magnitude. They have the added benefit of introducing mismatches in opposing arcs as they are moved in or out from their neutral position. Hybrid-based tuners may utilize quadrature hybrids or magic tee hybrids and are capable of operating under the highest power and mismatch conditions.

The concept of using tuners for power transfer optimization is straight forward but there are challenges in the implementation. These challenges include measurement of the load impedance, definition and calibration of a measurement phase plane, accounting for generator frequency variations and understanding and correcting for changes in the material being heated. A discussion of the methodology used to design a high-power automated tuner capable of reliably correcting for large mismatches in a microwave heating

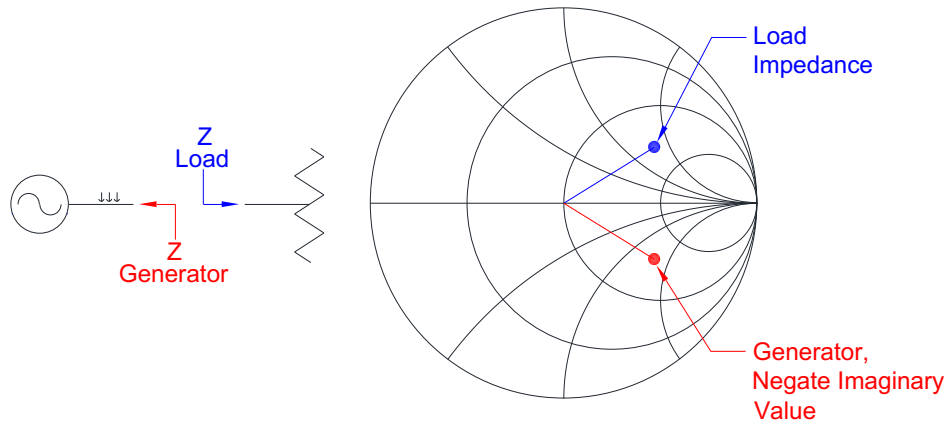


Figure 1. Smith Chart representation of impedances.

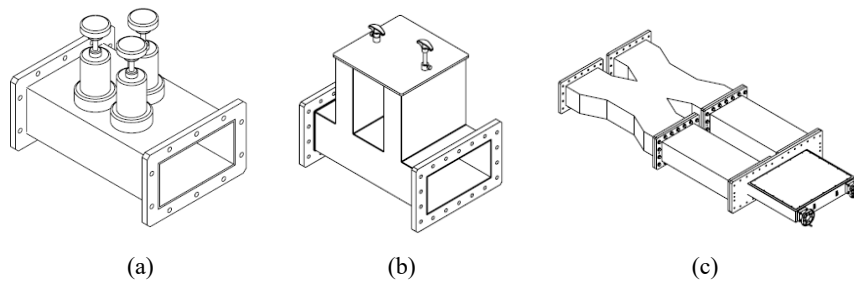


Figure 2. Typical waveguide tuner options: probe (a), stub (b), and hybrid (c).

system will follow. The design goals were to maintain less than 1% reflected power in a 100+ kW system under varying mismatch conditions up to a 20:1 VSWR (voltage standing wave ratio). It needed to be simple to operate with a preference to not require liquid cooling.

METHODOLOGY

The power level, tuning range, and desire to avoid liquid cooling dictated that a hybrid-based tuner should be used. An in-line package with the smallest possible overall envelope was also desired. A “folded” magic tee with contactless, motorized sliding short circuits was selected for the tuner topology. To automate the system, continuous monitoring of the load impedance is required. The magnitude of the mismatch is easily calculated from the reflected power, determining the phase angle of the mismatch is more difficult [2]. There are integrated circuit (IC) detectors that will provide differential amplitude and phase measurements from a pair of inputs. To implement these to measure the terminating load over the full impedance plane, a pair of these detectors are required in addition to directional couplers and low-level splitters. A commercial programmable logic controller (PLC) was selected that interfaced to the motors used on the tuner in addition to having a versatile graphic user interface (GUI) and the ability to easily capture measurement data.

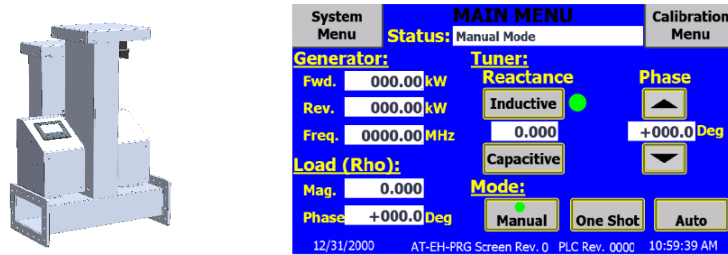


Figure 3. E-H tuner mechanical design and the control system's main operating screen.

RESULTS

Prototypes have been manufactured to allow low-level and high-power factory and field testing. Software has been developed to control and monitor the tuner from a built-in touch screen. Tuning may be done manually, as a one-shot optimization to the calculated impedance or automatically with the tuner continuously performing optimizations when user settable thresholds are encountered. A data-logging feature allows all the monitored data to be easily exported from the built-in web server in a convenient comma separated value (CSV) format for further analysis.

DISCUSSION

The device has been tested to 110kW under a variety of mismatches. Extended field testing has been in process for several months for a plasma application with the unit performing well. The data logging feature has proven to be extremely helpful for both code development and for the end user to understand the impact process or material changes have on the microwave system. Excel spreadsheets have been developed to help display and interpret the data using both rectangular and polar plots. The hardware design is being finalized and a formal product launch is expected very soon. Software development will continue with new algorithms currently under test. The device was primarily designed for efficiency improvements of microwave processes. The accurate generation of a predictable mismatch has also attracted attention to the device for evaluation and production testing of devices under high VSWR conditions.

CONCLUSION

New applications for industrial microwave equipment will often require higher power, larger variations in power and the ability to operate efficiently into varying load impedances. A fresh look at the fundamental theory and the latest available technology can lead to new unique designs with significant advantages.

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A Complementary Relative-phase Strategy to Improve Heating Performance in a Dual-port Solid-state Microwave System

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Keywords: solid-state microwave systems, relative phase heating, heating uniformity, complementary phase shifting, dual-port microwave heating

INTRODUCTION

Solid-state microwave heating is superior to magnetron-based microwave heating with consistent heating results and potentially more uniform heating due to the precise and flexible control of microwave parameters of frequency, power, and relative phase (of multiple sources) [1]. Previous studies have developed different frequency-shifting strategies to improve microwave heating performance using a single microwave port. Several studies used dual-port microwave systems and reported that arbitrarily sweeping the relative phase of two microwave sources could deliver more uniform heating than the fixed relative phase heating strategy [2]. However, the constructive and destructive microwave interactions at some relative phases may deter the microwave heating performance during the arbitrary sweeping process [3]. This study aimed to develop and evaluate a complementary-relative-phase heating strategy and compare it with the reported fixed and sweeping relative phase strategies on their microwave heating performance of heating uniformity and microwave power absorption efficiency.

METHODOLOGY

The study utilized a dual-port solid-state microwave operated at a frequency of 2.45 GHz and a power level of 200 W each. A tray of 300 g gellan gel sample was heated in the solid-state microwave system for 180 s using three distinct relative heating strategies, namely fixed relative phase, orderly sweeping relative phase, and complementary relative phase shifting, as shown in Figure 1. The fixed relative phase strategy used a 0° relative phase during the whole heating; the orderly sweeping relative phase strategy orderly swept the relative phase from 0° to 315° in a loop with an interval of 45° and each relative phase was used for 10 s; the complementary relative phase shifting strategy first collected phase-dependent heating patterns at the top surface using an orderly sweeping loop from 0° to 315° at an interval of 45° with a thermal image camera mounted at the top of the oven cavity and then specifically selected relative phases with complementary phase-dependent

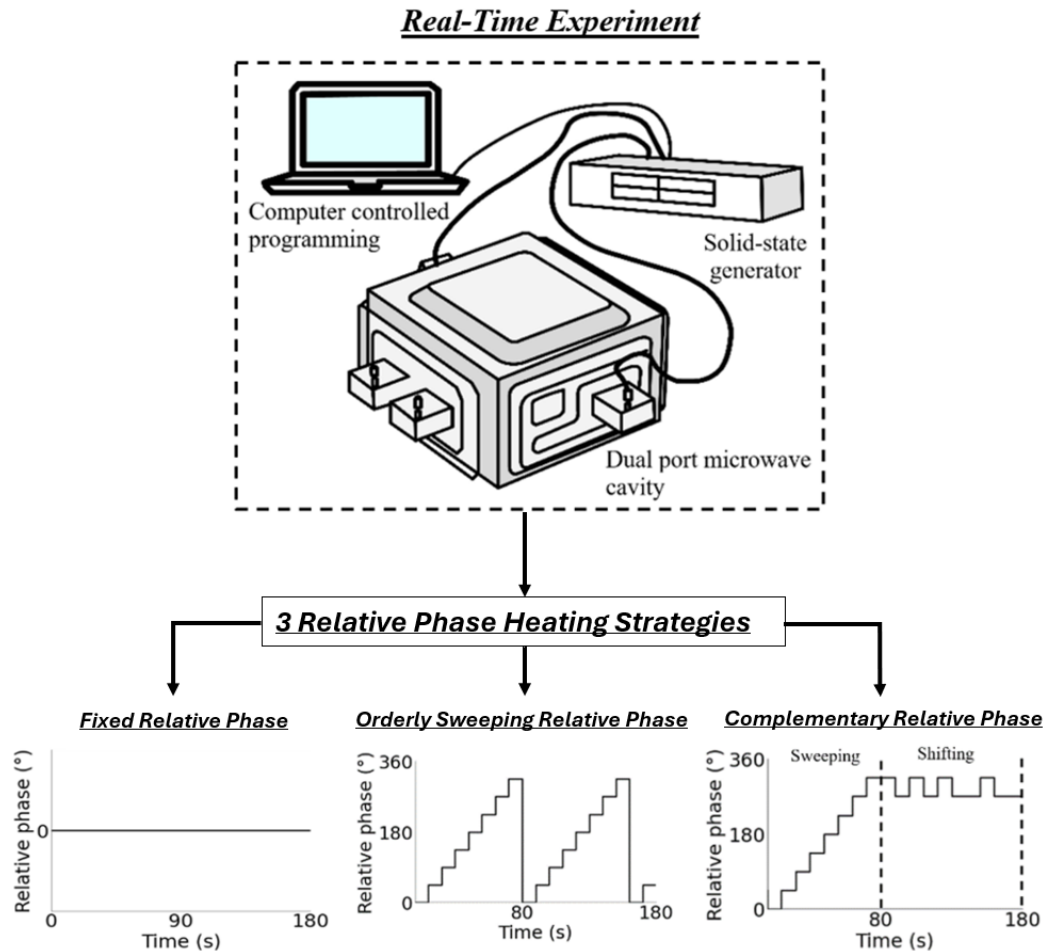


Figure 1. Dual-port microwave heating with three relative phase heating strategies

heating patterns that could deliver minimum Heating Uniformity Index (HUI) for every 10 s during the rest of the heating process.

After the microwave heating process, the thermal images at the top and middle layers of the heated gellan gel samples were captured. The HUI and the total microwave Power Absorption Efficiency (PAE) were estimated based on the combined two layers of temperature profiles. The microwave heating experiments were conducted for three replications and statistical analysis was performed to compare the significant difference ($P < 0.05$) among the three heating strategies.

RESULTS AND DISCUSSIONS

The experimental results revealed notable differences in heating uniformity, microwave power absorption, minimum temperature, and maximum temperature across different relative phase heating strategies as shown in Table 1.

Table 1. Comparison of microwave heating performance among various relative phase strategies

Heating Strategies	HUI	Power Efficiency (%)	Maximum Temperature, °C	Minimum Temperature, °C
Fixed Relative Phase	0.39 ± 0.02^a	48.81 ± 0.85^a	68.04 ± 1.12^{ab}	7.94 ± 0.57^a
Orderly Sweeping Relative Phase	0.31 ± 0.02^b	50.76 ± 0.85^a	64.76 ± 0.98^a	16.22 ± 1.21^b
Complementary Relative Phase	0.27 ± 0.01^c	51.60 ± 1.2^a	64.04 ± 2.25^a	16.79 ± 1.00^b

The complementary relative phase heating strategy showed the best heating uniformity, which was significantly smaller ($P < 0.05$) than the other two relative phase heating strategies. All three relative phase strategies showed similar microwave PAE, whereas the complementary phase shifting strategy had a slightly higher efficiency without significance. The fixed relative phase strategy showed higher maximum temperature and lower minimum temperature than the orderly sweeping relative phase and complementary relative phase heating strategies, indicating a thermal run-away effect. The orderly sweeping and complementary relative phase strategies showed similar maximum and minimum temperatures without significant differences ($P < 0.05$). Overall, the complementary phase shifting strategy showed superior heating uniformity followed by the sweeping relative phase strategy, and then the fixed phase heating.

CONCLUSIONS

The complementary phase-shifting strategy showed promise for use in future solid-state microwave ovens by addressing non-uniform heating and increasing overall heating performance in dual-port microwave applications.

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Demonstrating In-situ Tools to Study the Non-equilibrium Phenomena Underlying Microwave-assisted Nanomaterials Synthesis

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Keywords: microwave-assisted synthesis, synchrotron, in-situ total scattering

INTRODUCTION

The nature of the interactions between microwave radiation and matter that give rise to technologically appealing phenomena, such as reduced processing temperatures/times or enhanced product properties, remains unclear. Clarifying the influence of microwave radiation in materials synthesis has been hindered by a lack of instrumentation to study structural transitions in situ and structural alterations on the atomic scale. Therefore, the objective of this study is to help elucidate the role of the microwave field in materials synthesis by probing the kinetics and energy landscape of microwave-induced reactions via in-situ, atomic characterization techniques.

METHODOLOGY

A bespoke 2.45 GHz microwave reactor and modular flow-through system was developed to enable high throughput, in-situ microwave studies. Furthermore, this system is deployed at a synchrotron beamline (BNL, NSLS-II, 28-ID-2 XPD) to utilize high-energy (~68 KeV) X-rays that can resolve atomic dimensions. To leverage the synchrotron X-rays for investigating specific nonthermal microwave effects that may reside in the atomistic domain, this experimental platform is coupled with the atomic pair distribution function analysis (PDF) technique that is well suited for quantitatively characterizing local structural fluctuations in the atomic environment – from amorphous precursors to partially crystalline intermediary phases leading to the final crystalline powder product. Using total scattering PDF analysis contrasts with conventional X-ray diffraction (XRD) measurements, which are applicable for characterizing well-ordered phases and long-range crystallinity but are ill-equipped for studying mixed amorphous-crystalline samples and features on the nanoscale. In sum, a custom microwave system enabling in-situ PDF analysis is installed at a synchrotron to monitor and compare the synthesis of Tin oxide nanoparticles via microwave-assisted and hydrothermal methods.

RESULTS AND DISCUSSION

An Arrhenius plot is generated from the experiments to isolate the activation energies of the reactions. Microwave-assisted synthesis of Tin oxide nanoparticles manifest lower apparent activation energies than that of conventional hydrothermal synthesis, suggesting that microwave irradiation promotes chemical reactions by lowering the energy barrier to product conversions. This ability of microwave radiation to navigate unique reaction pathways has energy-saving implications for materials design and manufacturing. Our novel experimental platform (combining X-ray probes with microwave sources) can be expanded to other synthetic systems that would benefit from high analytical temporal and atomistic resolution.

CONCLUSIONS

A better understanding of the unique role of the microwave field in materials synthesis is a requisite step towards furthering its widespread application in accessing novel materials and disruptive processing advantages.

***In situ* XRD Analysis of Microwave-enhanced Catalytic Pyrolysis of Lignocellulose by a Perovskite Oxides**

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Keywords: catalytic pyrolysis, perovskite oxide, in situ XRD, biomass

INTRODUCTION

Microwaves can efficiently convert electricity into energy to accelerate various chemical reactions. Microwave-assisted chemical processes are now attracting attention as a key technology for establishing an electrified chemical industry driven by renewable energy. Microwaves heat catalysts highly selectively and rapidly accelerate various catalytic reactions [1,2]. In addition, focused microwave energy by using a semiconductor microwave generator and a cylindrical cavity resonator enables “ultra” rapid pyrolysis of lignocellulosic biomass [3].

METHODOLOGY

This study demonstrates the rapid catalytic pyrolysis of lignocellulosic biomass (bamboo powder) by combining focused microwaves on both biomass and solid catalysts. We exploited the excellent microwave absorption properties of perovskite-type oxides as the solid catalyst. Furthermore, we analyzed the mechanism of microwave-enhanced catalytic pyrolysis using in situ X-ray diffraction (XRD).

RESULTS AND DISCUSSION

Perovskite-type oxides such as BaTiO₃, (La_{0.80}Sr_{0.20})_{0.95}CoO_{3-x}, and La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O₃ (LSCF6428) rapidly heat up under microwave irradiation as compared to conventional heating (CH) using (TG-DTA). By using microwave heating, higher H₂ production was obtained by 2.9-8.0 times from bamboo powder (Figure 1). Furthermore, microwave heating resulted in a higher CO/CO₂ ratio and H₂ production than CH, indicating that rapid microwave heating suppressed the product's complete oxidation.

Then, we used a microwave in situ synchrotron XRD to directly observe the structural changes in LSCF6428 during microwave heating (Figure 2). Focusing on the shift in the

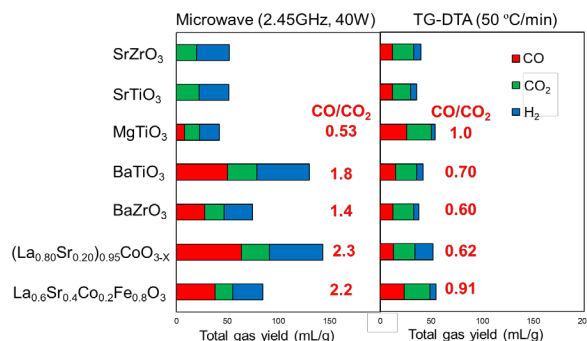


Figure 1. Catalytic pyrolysis of bamboo powder using microwave and conventional heating (TG-DTA) using perovskite catalysts.

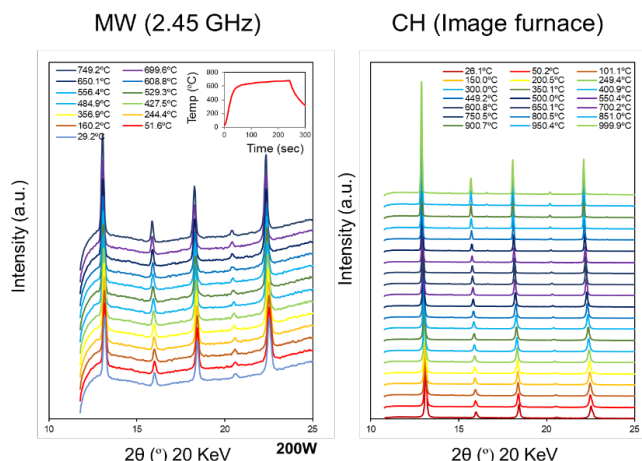


Figure 2. In situ XRD patterns of LSCF6428 under microwave and conventional heating.

diffraction peaks, CH exhibited a peak shift of -0.35° while it was only -0.2° by microwaves. Microwave heating suppressed the thermal expansion of the perovskite oxide and the introduction of oxygen defects. Therefore, microwaves have suppressed the complete oxidation of the products by preventing their oxidation due to the lattice oxygen of the perovskite oxides, thereby yielding higher H₂ and CO than CH.

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Detailed Insights into Microwave Assisted Ammonia Synthesis based on Thermodynamic Equilibrium

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Keywords: heterogeneous catalysis, ammonia synthesis and decomposition, hot spots

INTRODUCTION

Microwave-assisted NH_3 synthesis has recently emerged as a promising energy input method for thermo-catalytic Haber-Bosch processes. Especially, microwave heating allows selective heating of catalysts, while the feed gas is not heated. This selective process results in highly efficient heating of the catalytic system. Many demonstrations of NH_3 synthesis reaction enhancements caused by microwaves have been reported, and it has been argued that the reason for such enhancement is due to the formation of hot spots within the catalyst bed. However, more research, such as quantitative estimation of hot spots in the catalyst bed and discussion of the resulting energy-saving benefits by microwaves, still needs to be done. Furthermore, detailed empirical studies based on complex reaction kinetics, which have been described in previous reports on NH_3 synthesis are still insufficient, and only a few examples of reports that separate the reaction thermodynamics from the reaction kinetics are available.

This paper demonstrates a method to determine the hot spot temperature calculated back from achievable thermodynamic equilibrium in microwave-assisted NH_3 synthesis/decomposition over supported Ru catalysts¹. Our stance is that the gas composition of N_2 , H_2 and NH_3 at equilibrium under a given condition should reflect the thermodynamic temperature driven under microwave irradiation, which then strictly provides the energy efficiency under microwaves compared with that of conventional heating methods. We will propose the evaluation method of complex hot spots in a catalyst bed under microwave irradiation. Compared to the reported method on spectroscopic methods for hotspots evaluation such as X-ray absorption², this study allows us to estimate the energetic advantage of microwave assisted catalytic reaction, even in more practical and complex particle packing beds.

METHODOLOGY

Ru/CeO_2 catalyst (5 wt%) was prepared by impregnation method using $\text{Ru}_3(\text{CO})_{12}$ as a precursor. The obtained powder was treated at 350 °C under Ar flow prior to the catalytic reaction. Figure 1 shows the experimental setup of the microwave driven NH_3 synthesis. A

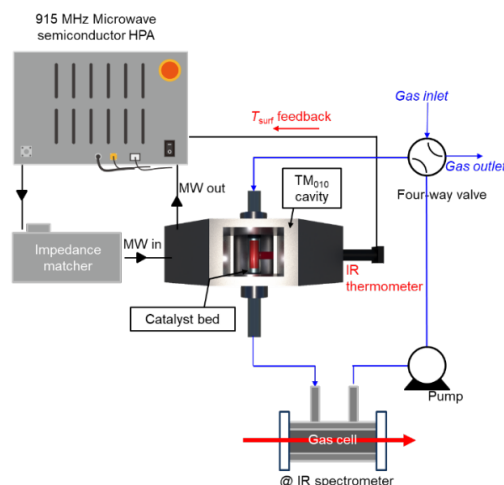


Figure 1. Schematic diagram of ammonia (NH₃) synthesis reactor for microwave-assisted heating.

high-power microwave semiconductor amplifier with an oscillation frequency of 915 ± 13 MHz was used. The microwave power was supplied to TM010 mode microwave resonance cavity via an impedance matcher. The catalyst bed was filled in the quartz tube with an internal diameter of 4 mm. The side surface temperature of the cylindrical catalyst bed temperature, which was defined as T_{surf} , was monitored using an infrared thermometer. The catalytic reaction was performed with a plug flow or a closed recirculating batch configuration. For the closed recirculation configuration, the quartz tube with catalyst bed was connected to the gas cell, pump, and four-way valve. Once the reactant gases (N₂ and H₂) were introduced into the system through the four-way valve, the gases were recirculated using the pump at 200 mL min^{-1} , and the internal volume of the closed circulation system was 145 mL. The reaction was performed under atmospheric pressure. Therefore, the internal gas composition could be assumed to be sufficiently homogeneous. The quantity of the accumulated NH₃ gas was estimated from the amount of infrared absorption passing through the gas cell.

RESULTS AND DISCUSSION

The microwave-assisted NH₃ synthesis equilibrium was performed in a closed recirculation batch system. As the T_{surf} became higher, the time to reach equilibrium became shorter, and the equilibrium N₂ conversion accordingly decreased (Figure 2(a) left). The N₂ conversion reaches plateau under each condition with time, suggesting that the actual temperature reaches different steady states. For lower temperatures ($T_{surf} < 260 \text{ }^{\circ}\text{C}$), the microkinetic rate expression³ was used to simulate the N₂ equilibrium conversion. The saturated N₂ conversions were compared with the ammonia equilibrium temperatures (Figure 2(a) right), which was denoted as T_{eq} . Figure 2(b) shows the difference between T_{eq} and T_{surf} at various T_{surf} . In each measurement, the T_{eq} value could be observed to be more than $100 \text{ }^{\circ}\text{C}$ higher than T_{surf} . Therefore, hot spots in the catalyst bed were present and were not detectable with the IR thermometer. In the presentation, the estimated hotspot temperature will be compared with the temperature estimated by in situ X-ray absorption spectroscopy.

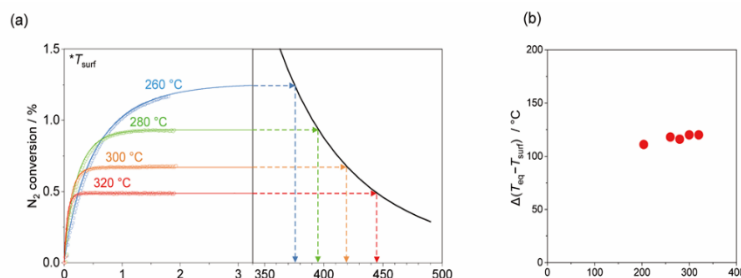


Figure 2. (a) Comparison of time course measurements of N₂ conversion using Ru/CeO₂ under microwave irradiation at various T_{surf} and equilibrium N₂ conversion at varied temperature (N₂ 25 kPa, H₂ 75 kPa). (b) Difference between T_{eq} and T_{surf} at various T_{surf} .

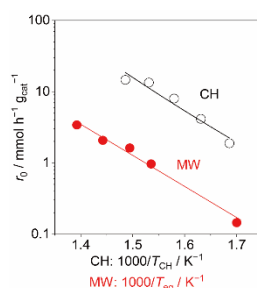


Figure 3. Arrhenius plots of NH₃ synthesis.

Arrhenius plots are shown in Figure 3 in which the zero-conversion extrapolated rate (r_0) for eliminating the contribution of NH₃ decomposition is plotted as a function of T_{eq} for microwave heating or T_{CH} for conventional heating. The slopes of the Arrhenius plots are comparable, indicating similar activation energies of approximately 85 kJ mol⁻¹ in both cases. It was found that the reaction rates under microwave irradiation were about one-tenth compared to those under conventional heating at each temperature. This result indicates that approximately 10 % of the active sites reaches the hot spot temperature under microwaves and dominates the reaction equilibrium.

CONCLUSION

An undetectable and meso-scale hot spots temperature estimation method was proposed based on thermodynamic equilibrium for microwave driven NH₃ synthesis/decomposition equilibrium. This localization of hot spots in such a particle-filled fixed bed is difficult to determine their temperature rigorously by the surface temperature measurement by e.g., an IR thermometer. The temperature determination approach using equilibrium gas compositions proposed in this paper should be direct especially when the catalytic reaction results are of interest.

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Synthesis of Entropy Stabilized Oxides using Electromagnetic Radio Frequency Technique

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Keywords: radiofrequency, DC heating, entropy stabilized oxides, CF/graphene-ESO composites

INTRODUCTION

Entropy stabilized oxide (ESO) represents a captivating category of ceramics distinguished from conventional oxides by their ability to incorporate multiple cations dispersed throughout the material, all while retaining a singular primary phase [1]. ESOs are also known as high entropy oxides with excellent energy storage, low electrical and thermal conductivity, and dielectric, magnetic, optical, catalytic, and mechanical properties. Recently, radiofrequencies (RF) with low-frequency range 1-200MHz were employed to heat rapidly the carbonaceous materials primarily sp^2 hybridization [2]. RF can also be used for the synthesis of materials and additive manufacturing with low-energy input, enabling non-contact heating, and out-of-oven synthesis. This work mainly deals with the synthesis of ESOs using a novel approach of RF heating in the presence of graphene, which absorbs the RF energy and dissipates it as heat energy to enable ESO synthesis.

METHODOLOGY

An equimolar mixture of nitrate salts Magnesium Nitrate Hexahydrate, Cobalt(II) Nitrate Hexahydrate, Nickel Nitrate Hexahydrate, Copper(II) Nitrate Hemipentahydrate, and Zinc(II) Nitrate Hexahydrate were dissolved in deionized water. Then the glycine was added with ratio 0.5:1 with respect to nitrate salts. The precursor solution was stirred for 1h using a magnetic stirrer to get a homogeneous solution. The graphene susceptors were added to the precursor solution. the whole solution was poured into a ceramic crucible and was placed on a fringing field RF applicator (Figure 1). RF heating setup consisted of a signal generator (Rigol Inc., DSG815) and a 500 W amplifier (Prana R&D, GN500D) that supplied RF power to a fringing field applicator via a 50 ohm coaxial cable. A FLIR infrared camera (FLIR Systems Inc., A700) was used to record the temperature during the reaction. A frequency of 144 MHz was used with 20 W of input RF power for the synthesis of ESO. Further, the synthesized materials were characterized using XRD, XPS, SEM, and Raman Spectroscopy.

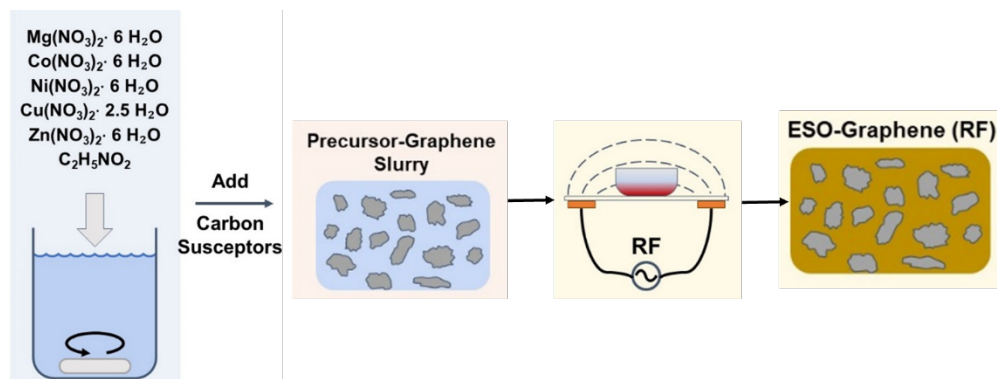


Figure 1. Synthesis of ESOs using RF fringing field in the presence of a carbon susceptor

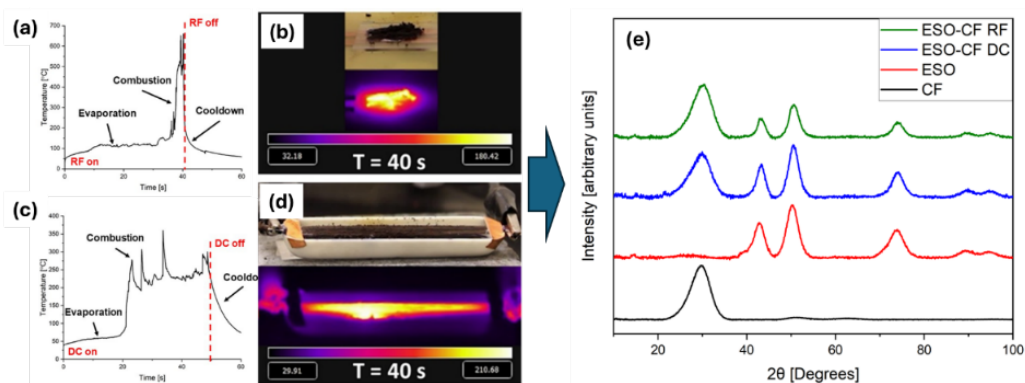


Figure 2. Entropy stabilized oxides from (a) & (b) for RF heating and (c) & (d) for DC heating responses and their FLIR camera images, respectively. (e) XRD peaks for the ESO formed from different heating.

RESULTS

The synthesis of ESO was carried out on a parallel fringing field, keeping a ceramic crucible containing precursor solution of ESOs made from respective nitrates and glycine used as fuels for the combustion of the salts. The reactions were initiated at low input powers and then ramped up to 20 W at 144MHz to achieve rapid heating rates. For comparison, we also synthesized ESOs using joule heating from DC current. We used carbon fibers as the energy susceptors for both RF heating and DC heating to initiate the reaction in nitrate slurry. Figure 2a&c show the heating response recorded using FLIR camera, and respective thermal images are shown in Figure 2 b&d. The collective XRD results are depicted in Figure 2e. Figure 3 shows the SEM morphologies and XPS results of synthesized ESOs.

DISCUSSION

The RF technique results in rapid heating in the RF susceptor and leads to the combustion of the precursors, ultimately forming ESO ceramics. The synthesized ESO using radiofrequency was well characterized using XRD analysis and it confirmed the formation

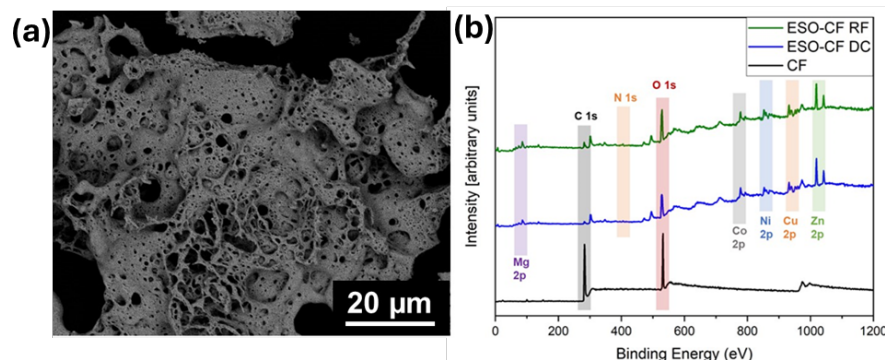


Figure 3. (a) SEM morphologies for synthesized ESOs from RF and (b) XPS results for the ESOs

of the single crystal phases in all synthesis techniques (RF and DC heating). The peaks observed at 2θ values of 36° and 42° correspond to the (111) and (200) planes, respectively, of the rock-salt crystal structure (Figure 2e). Additionally, all patterns display a notable peak at 2θ approximately between 25° and 28° , typically indicating the (200) plane diffraction of the crystalline structure of graphite. The SEM micrographs show high porosity with an average pore size of 1.8 ± 0.5 mm. XPS results indicate its electronic properties resulting in the electronic states of Mg and Ni at +2 are evident within highly stable packing structures, characterized by oxides with octahedral surroundings. This is evident from XPS analysis depicted in Figure 3b, where peaks at approximately 48 eV and 853 eV correspond to Mg and Ni, respectively. The emergence of nanocrystals indicates that ions such as Cu and Co possess oxides in a more stable ionic state, as corroborated by peaks observed at 932 eV and 778 eV.

CONCLUSION

We showed that low frequency RF (1-200 MHz) can be used to synthesize entropy stabilized oxides (ESO) through rapid RF heating at rate 200°C/s with a minimal input power of 20 W. Further, formation of crystallites and electronic structures were confirmed from XRD and XPS respectively.

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Novel W-Band Complex Permittivity Measurement Apparatus for Extreme Temperature Conditions

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Keywords: millimeter wave, hypersonic, complex permittivity, dielectric losses, extreme temperature

INTRODUCTION

Antennas and radomes constitute fundamental components in modern aircraft, playing a crucial role in enabling communication with ground stations, other airborne vehicles, and satellites. Antennas are responsible for transmitting communication signals and enable precision targeting, while radomes act as a protective shield, ensuring minimal disruption to electromagnetic transmission and safeguarding antennas from their physical environment. When these components are subjected to the extreme conditions of hypersonic speed, structural integrity becomes very important. Hypersonic flight can achieve speed greater than Mach 5 (6174 kph) which can cause the radome to experience extreme temperature ranging from approximately 1000 °C to 1500 °C, leading to thermal shock and a deterioration in dielectric performance [1]. Furthermore, the typical operating range for radar transmission and satellite communication in hypersonic radomes is within 0.3-30 GHz. However, higher frequencies within the W-band range (75-110 GHz) have attracted increased attention due to their broader bandwidth capabilities and ability to penetrate through plasmas, thereby enhancing communication systems. While there is relatively abundant dielectric properties data at room temperature for candidate materials for hypersonic flight, existing high temperature data is predominantly limited in the relevant frequency range (75-110 GHz) [2], [3] or constrained to frequencies below 35 GHz [1]. This limitation leaves temperatures exceeding 1000 °C at relevant frequency range of this work (75-110 GHz) unexplored. To address these challenges and with an aim to facilitate the advancement of W-band source technology for radomes, absorbers, and other dielectric components, this work focuses on the characterization of the complex permittivity of different dielectric materials under extreme temperature conditions using a novel W-band complex permittivity measurement apparatus developed by the Air Force Research Laboratory.

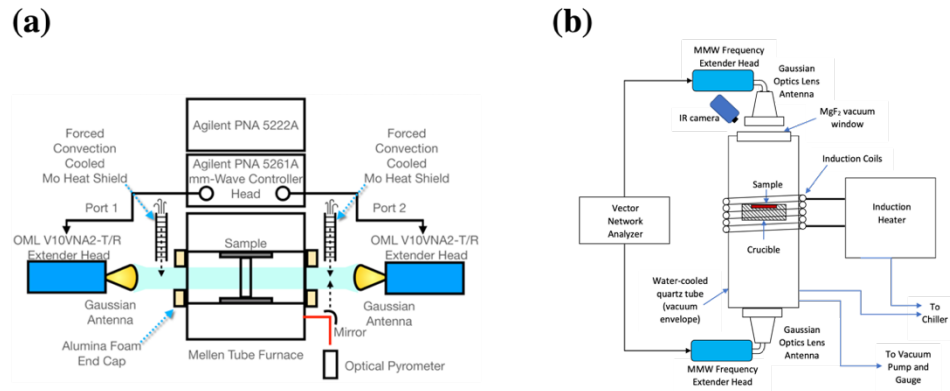


Figure 1: A schematic of the experimental setup using an (a) air furnace achieving temperatures up to 1000 °C [3] and (b) induction furnace achieving temperatures up to 2000 °C

METHODOLOGY

A diagram of the experimental setup employed for the millimeter wave measurements is shown in Figure 1. The measurements were conducted using an Agilent vector analyzer (PNA) 5222A, coupled to an Agilent N5261A millimeter head controller, and a set of V10VNA-T/R frequency extender heads (Oleson Microwave Labs, Morgan Hill, CA). These components collectively increase the PNA output to W-band frequencies. For measurements performed from room temperature up to 1000 °C, samples (typically 2" in diameter) were held in silicon carbide sample holder positioned at the center of a Mellen tube furnace (length: 31.75 cm; diameter: 15.24 cm), exposed to open air, as illustrated in Figure 1(a), and as described in previous work [2], [3]. However, for temperatures exceeding 1000 °C, a novel system using an induction furnace was implemented. This setup not only facilitated the measurements but also allowed for experimentation under vacuum, inert, or reactive condition using custom vacuum-compatible millimeter-wave lenses. Achieving temperatures close to 2000 °C involved utilizing a graphite crucible surrounded by very low thermal conductivity carbon/graphite foam, further insulated with mullite/alumina foam for the measurements, as shown in Figure 1(b). For this experiment, a water-cooled quartz vacuum chamber was integrated into the induction furnace system, providing a controlled environment over the ultra-high temperatures. The measured data from both high temperature apparatuses underwent a comparative analysis to validate the reliability and accuracy of the new system.

RESULTS & DISCUSSION

The evaluation of the new high-temperature system using an induction furnace involved comparing the complex permittivity measurements of a standard AlN:Mo sample to previously published data obtained using the air furnace system from Figure 1(a). In Figure 2, the real and imaginary part of the permittivity exhibited close alignment between the setup using the induction furnace and the air furnace within the same temperature range. The measured data displayed a marginal difference averaging 0.83% and 5.35% for the real and imaginary part of the permittivity, respectively.

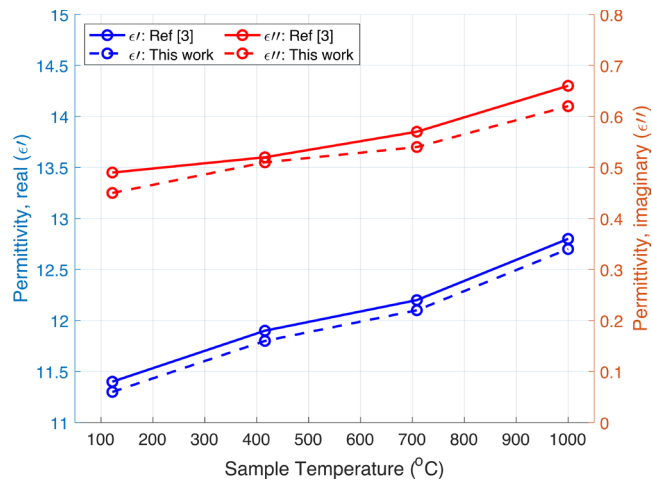


Figure 2: Data comparison between the real part of permittivity (left) and imaginary part of permittivity (right) for an AlN:Mo sample using the induction furnace and the air furnace.

CONCLUSION

The evaluation of the new high-temperature system with an induction furnace revealed generally close alignment between the real and imaginary permittivity data for a AlN:Mo sample and previously published results obtained using the air furnace system. The uncertainty of the data for the newly developed W-band complex permittivity measurement apparatus for extreme temperature conditions is currently in progress. Further efforts will focus on validating data reliability, extending measurements to higher temperatures (approaching 2000°C) and evaluating additional dielectric materials of interest for hypersonic flight.

ACKNOWLEDGMENTS

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GHz and THz Characterization of Novel Ultra-Low Temperature Co-fired Ceramic Materials for Emerging Technologies

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Keywords: dielectric properties, ULTCC materials, microwave characterization, THz characterization, THz properties.

INTRODUCTION

In this paper we discuss characterization results of a new ultra-low temperature co-fired ceramic (ULTCC) material intended for substrate material for microwave, mmWave, and THz technologies. ULTCC gains increasingly growing interest [1-3] due to lower sintering temperatures (<650°C) beyond the limit of well-established [4] low temperature co-fired ceramic (LTCC) (800-950°C) and high temperature co-fired ceramic (HTCC) (1000-1600°C) materials. Efforts target lowering energy consumption and environmental footprint by decreasing sintering temperature, while simultaneously obtaining dielectric properties competitive with classic materials and fulfilling requirements of modern communication and electronic systems. The aforementioned challenges are often competing, therefore precise characterization of dielectric properties in a wide frequency spectrum becomes crucial to support material optimization and validation. This paper presents the development and characterization of a new type of ULTCC material, with the aim of finding a promising alternative for popular LTCC materials.

METHODS AND MATERIALS

New LTCC and ULTCC composites have been developed and characterized for their dielectric properties in GHz and THz frequency ranges. Microwave characterization was conducted with the aid of a TE_{01δ} mode dielectric resonator [5-6] followed by measurements conducted with time domain spectroscopy (TDS) [7] (Fig. 1 (b)) at 0.3 - 2.3 THz. Dielectric properties of bulk composites in the GHz range were measured using a TE_{01δ} mode dielectric resonator cavity, in which sample under test serves as a dielectric resonator, cumulating the electric field inside. In this setup, the dielectric constant

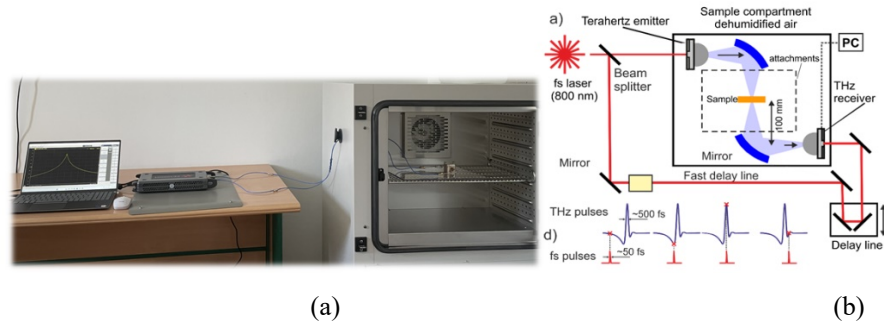


Figure 1. Measurement setup for GHz characterization of the dielectric properties and TCK (a) and the schematic of the TDS system for THz characterization.

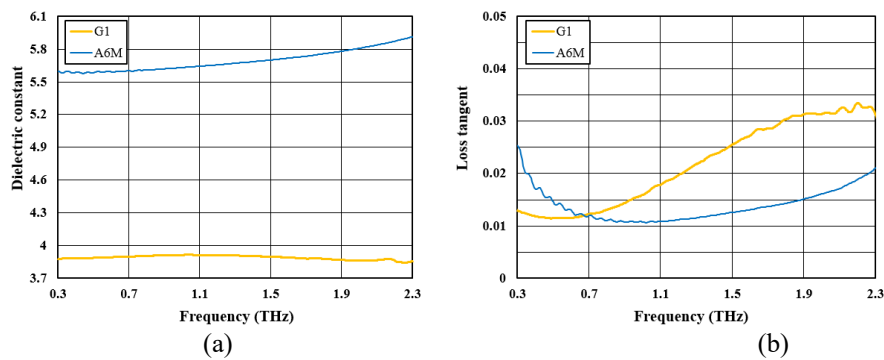


Figure 2. Dielectric constant (a) and loss tangent (b) of ULTCC composite and A6M materials measured with TDS.

and geometrical dimensions of the sample determine the measurement frequency. In the TDS, the optical beam from a femtosecond sapphire laser (800 nm) is divided into two parts, directed to an emitter and through a delay line to the receiver. The THz emitter and receiver consist of two metal electrodes on a GaS substrate, which form a photoconductive antenna. Pulses of electromagnetic radiation lasting about 1 ps are generated in the emitter and by means of the optical system reach the receiver. The advantages of the TDS method are fast measurement with a low noise to signal ratio in a broad frequency range and directly determining the complex refractive index and subsequently the complex electric permittivity of a sample using simple relationships.

Additionally, the dielectric constant and loss tangent at elevated temperatures were measured with the TE_{01δ} mode dielectric resonator (Fig. 1 (a)) and the temperature coefficient of the dielectric constant (TCK) was evaluated.

RESULTS

Measurements of the dielectric properties of newly developed LTCC and ULTCC materials were compared against the well-established commercial Ferro A6M LTCC substrate. For ULTCC composite, dielectric constant and loss tangent of 3.97 and $5.8 \cdot 10^{-3}$ were measured at ca. 14 GHz (not shown) whereas at 1 THz, 4.01 and $1.65 \cdot 10^{-2}$, were obtained respectively (Fig. 2). The measured values are very promising in comparison to the A6M substrate

parameters, having a measured dielectric constant of 5.6, and loss tangents of $1.13 \cdot 10^{-3}$ and $1.09 \cdot 10^{-2}$ at ca. 15 GHz (not shown) and 1 THz, respectively.

CONCLUSION

Measurement results obtained for the new ULTCC composite over a wide frequency range confirm its competitiveness with regards to dielectric properties against well-established commercial electronic substrates, while having an important advantage of reduced sintering temperature and energy consumption during fabrication.

ACKNOWLEDGEMENT

This work was conducted within the ULTCC6G_EPac project under the M-ERA.NET2 programme, funded from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 685451. Part of this work was funded by the Polish National Centre for Research and Development under M-ERA.NET2/2020/1/2021 contract. FHG_IKTS authors acknowledge Saxon funding agency SMWK for the financial support for the ULTCC6G_Epac project under the M-ERA.NET 2021 programme.

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Energy Efficient Processing of Carbon Fiber Composites using Radio Frequency Heating

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Keywords: radiofrequency, carbon fibers, composites, processing

INTRODUCTION

The evolution of heating technology spans millennia, significantly impacting numerous industries, including the modern aerospace and automotive sectors where carbon fiber composites are pivotal. Methods such as Joule heating, induction heating, and, more recently, electromagnetic heating have been employed for various applications requiring rapid and targeted heat treatment. Electromagnetic heating is an exciting, non-contact heating mechanism offering rapid, non-evasive, and selective heating. The interaction of RF fields with carbonaceous materials, particularly those incorporating conductive nanofillers like carbon nanotubes, carbon black, and carbon fibers is an exciting development for material processing. These interactions facilitate rapid, uniform heating, enabling various applications from material synthesis to thermal treatments. Recent advancements have extended RF heating to a broader spectrum of carbon-based materials, including curing carbon fiber-reinforced composites, exploiting the lower frequency range (1–200 MHz) to achieve deeper penetration and selective heating. This breakthrough offers substantial benefits over traditional microwave techniques, particularly in processing thicker materials and achieving uniform temperature profiles. Here we explore using carbon fibers as RF susceptors to partially cure (prepreg) or fully cure carbon fiber thermosetting composites.

METHODOLOGY

A thermosetting resin consisting of EPON 862 (a diglycidyl ether of bisphenol F epoxide) and EPIKURE W (diethyltoluenediamine) was employed; these constituents were mixed at a weight ratio of 100:26.4 to achieve an equimolar ratio of thermosetting resin. The carbon fiber materials used included unidirectional TorayT700SC-12K-50C and IM7 plain weave 6K fibers sourced from Hexcel, Stamford, CT. Carbon fiber/epoxy pre-preg samples were fabricated utilizing unidirectional and plain weave fiber alignments, ensuring a consistent fiber volume fraction of approximately 0.6. Using a doctor blade, the composite thickness was regulated to ~0.5 mm, with glass slides serving as substrates [1].

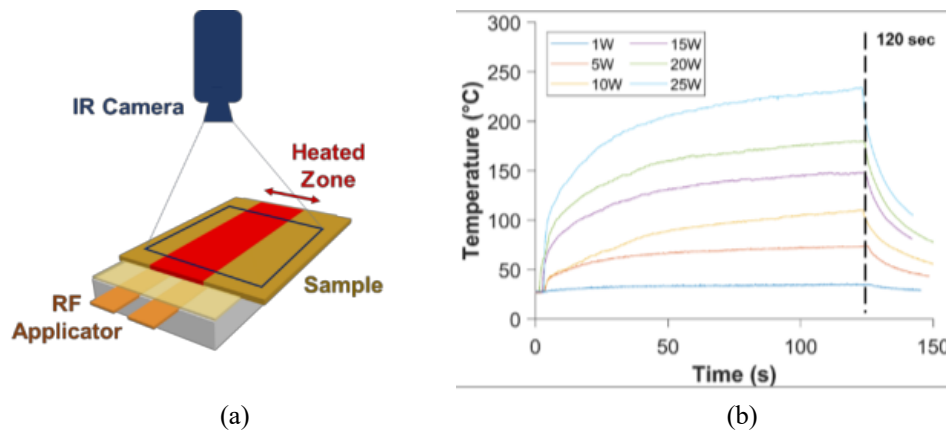


Figure 1. RF heating setup of samples using a non-contact applicator (a) and the thermal response of unidirectional CF/epoxy pre-pregs at 66 MHz at variable powers for 2 minutes (b) [1], [2].

The experimental setup consisted of a fringing field RF applicator, designed for efficient heating. This applicator comprised two parallel copper strips, each 6.35 mm in width, positioned 2 mm apart on a FR4 sheet. A signal generator (RIGOL DSG815) and a power amplifier (PRANA GN500) facilitated the delivery of RF energy via 50 Ω coaxial cables, creating an electric field that induces heating in the carbonaceous composite samples. The most effective heating rates were determined by optimizing the system's resonant frequency, which is intrinsically linked to the impedance characteristics of the setup, including the applicator and composite material [1], [2]. Temperature was monitored during the RF heating experiments using a FLIR infrared camera.

RESULTS

The thermal behavior of unidirectional carbon fiber/epoxy (CF/epoxy) pre-pregs was analyzed under RF heating at a consistent frequency of 66 MHz. It was found that input power levels dictated heating rates and maximum temperature achieved; at 1 W, the temperature increase was negligible, whereas at an elevated power level of 25 W, the pre-pregs achieved temperatures up to 230 °C within a 120-second timeframe. Similar trends were observed for plain weave [0/90] CF/epoxy pre-pregs, applying variable powers while maintaining a constant 66 MHz frequency.

The system's capability to achieve partial crosslinking within the pre-pregs was also examined, in line with traditional B-staging processes but under much shorter timescales. Specific target temperatures—50 °C, 100 °C, 150 °C, and 200 °C—were maintained using RF heating for approximately 30 minutes to assess the degree of crosslinking achieved. Post-treatment analysis using DSC revealed that the glass transition temperature (T_g) of the treated samples correlated well with the applied thermal histories, providing a quantitative measure of cure degree. Notably, the T_g values for partially cured samples were consistently below the 130-150°C range expected for fully cured bisF/DETDA epoxy, confirming controlled partial curing.

CONCLUSION

This study has elucidated the radio frequency (RF) heating behavior of unidirectional CF/epoxy and [0/90] CF/epoxy (plain weave) prepregs. Our findings highlight a significant advancement in composite material processing. RF heating can heat carbonaceous materials rapidly but in a controlled manner, achieving up to 6°C/s at 5W and up to 70°C/s at 25W. This is exciting for material processing for carbon fiber composites as it paves the way for precise control over the curing process.

From an industry perspective, the ability to rapidly heat and partially cure composites using RF energy offers a versatile, non-contact, and energy-efficient method for processing. Moreover, this technology's demonstrated scalability by using translating stages with RF applicators with closed-loop controls can find applications in continuous manufacturing processes like roll-to-roll production, aligning well with industry trends toward automation and continuous manufacturing.

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Microwave Pasteurization of Low-pH Product

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Keywords: microwave, pasteurization, organoleptic quality, energy efficient, no carbon process

INTRODUCTION

Low acid foods have been the cause of human diseases such as gastroenteritis and listeriosis. Common symptoms of foodborne illness include diarrhea, stomach cramps, fever, headache, vomiting, dehydration, and exhaustion. Proper cooking or thermal processing of foods can eliminate most of the causative agents of foodborne diseases.

The pasteurization by microwaves is a process which treats quickly and prolongs the shelf life of food while minimizing the damage of quality compared to the conventional sources of heat which transfer the energy of the outside to the interior. Microwave processing heats the product directly by absorption of electromagnetic energy by the food components (volumetric heating). This innovative process, which is still under development, is potentially more spatially uniform than conventional heating processes that rely on the thermal diffusivity of the food heated through its surface. The ability to apply energy to the interior of the food can reduce the time and total energy required to process a food product. Also, it is a process that uses as energy source only electricity, which allows to have a process with no carbon emission.

The objective of this study was to show that the microwave can be used to pasteurize bag of low acid product.

METHODOLOGY

A continuous microwave unit, was installed at CTCPA (France). The Equipment consists of 24 kW microwave power - 2450 MHz - Length 5 m. This machine is specially developed (wave distribution) for the pasteurization of ready meals.

This matrix was chosen because it is easy to manufacture and quick to set up (apple : 88.9%, sugar : 10.6%, Ascorbic acid : 0.5%). The compote was made from fresh apples. The production diagram is shown below.

1. Washing/sorting: with clean water + removal of damaged parts

2. Crushing: 15mm grid hammer mill + ascorbic acid added
3. Cooking: enzymatic inactivation 90 °c /1 min
4. Refining hot refining 1mm grid
5. Addition of sugar to reach a concentration of 24g/100g
6. Packaging

The recipe was put in rectangular bag (pp) with dimensions of 160×80×35mm for approximately 300g of product.

The monitoring and recording of temperature were done with the use of fiber optics neoptix - qualitrol corp (usa). This allows the calculation of the pasteurization value with reference microorganism: *Byssochlamys fulva* temperature (tref :93.3 °C, D value:3.44 min and z value 8.89°C) using the following formula:

$$VP_{93.3^{\circ}C} = \int_0^t 10^{\frac{T-T_{ref}}{z}} . dt$$

RESULTS

The products were treated with an initial core temperature of 50-52°C at the entrance to the microwave pasteurization tunnel. This temperature corresponds to what was done in this type of industry. The distribution of the energy was adapted to the product to have a more important treatment at the beginning of the tunnel than at the end. A total of 4.6 kW was used to carry out this treatment for an output flow of 50.4 kg/h. The treatment time was 6.7 minutes.

The final temperature of the product was 100°C at the core, allowing a pasteurization value of 33 minutes.

Concerning the shelf life of the products, the products were analyzed in accordance with standard NF V08-401.

The following incubations were carried out: 1 day at 25°C, 21 days at 32°C and 7 days at 55°C. Satisfactory results were obtained for all incubation conditions. In fact, the condition of the packaging is correct, the condition of the product is normal, the pH measurement shows no acidification, the microscopic examination shows no micro-organism growth, which is estimated to be <100 for the control (standard autoclave processing) and the treated product.

The bag does not expand during the process thanks to the system specially developed by SAIREM to limit this expansion. The thermal exchange between the projected air and the film allows to decrease the air temperature and therefore the internal pressure of the bag. The risk of breaking the film or the seal is suppressed.

DISCUSSION

The process is advantageous due to its volumetric heating principle. It can pasteurize without compromising the organoleptic properties while consuming less energy, and it is an electrical process.

CONCLUSION

Microwave technology is an effective and compatible method addressing the current concerns of both the industrial and consumer sectors for pasteurization.

Radio Frequency Combined Air Drying of Squid: Drying Kinetics and Quality Analysis

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Keywords: aquatic product, radio frequency, combined drying, drying kinetics

INTRODUCTION

Long heating time and high temperature in traditional drying usually decreases the drying efficiency and quality of aquatic products. Different from traditional drying, the main principle of radio frequency (RF) drying is that the electromagnetic energy is coupled with the water in the material, so that the water in the material is heated and lost, and the RF energy can go deep into the material to provide volume heating effect. At present, there are few studies on RF drying of aquatic products. Li et al. studied the effects of hot air (HA) drying and combined hot air-radio frequency (HA-RF) drying on the taste and volatile substances of Takifugu, and found that the total drying time of HA-RF drying (14 h) was less than HA drying (16 h) and RF drying could promote flavour. Cao et al. used HA-RF heating to dry tilapia fillets. For tilapia samples of different thicknesses, the drying rate of HA-RF was 1.1 to 1.4 times that of HA, and the HA-RF drying samples had higher rehydration rate and lower volume shrinkage rate. In these studies, HA-RF efficiently improved the drying rate of aquatic products, but the quality of aquatic products was sometimes severely damaged due to local overheating, especially at falling rate period. High drying temperature also usually negatively affected the surface color of the samples and resulted in shell-forming on the surfaces, which hinders the mass transfer process. Thus, finding appropriate combined drying methods and selecting the optimum timing based on drying kinetics may assist the development of high-efficiency high-quality food drying method. Therefore, the objectives of this study were as follows: (1) Different stages of the drying process of HA, HA-RF and CA-RF were analysed through drying rate and color changes, and the strategy of combining RF energy and traditional drying methods in the drying process was explored, so as to establish a multi-stage combined drying technology that can improve the drying efficiency and quality of squid at the same time. (2) The drying kinetics of dried squid by HA, HA-RF, CA-RF, (HA-RF)+(CA-RF) was studied. (3) The rehydration, texture, water migration and microstructure of squid dried by different methods were compared.

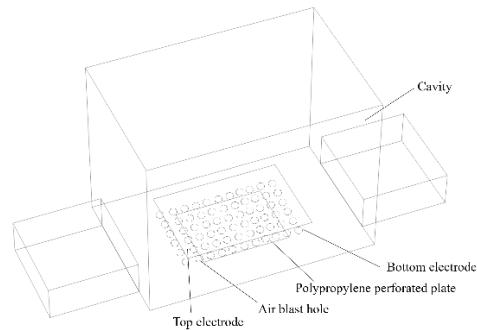


Figure 1. Schematic diagram of radio frequency combined air drying equipment

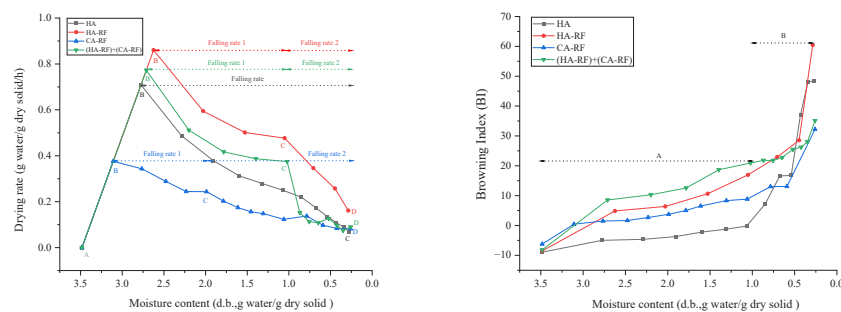


Figure 2. Curves of drying rate and Browning index of squid with moisture content under different drying methods.

METHODOLOGY

In this study, cold or hot air-assisted radio frequency (CA-RF/HA-RF) drying was performed to dry squid in a 27.12 MHz, 6 kW RF heating system. Hot air (1 m/s, 60 °C) or cold air (1 m/s, 22 °C) was input into the RF cavity through the air blower from the air blast hole of the bottom electrode, and the electrode gap was set to 120 mm. Before all the experiments, the squid was defrosted overnight at 4 °C, the head, internal organs and skin were removed, the meat slices were cut so that the two sides were symmetrical, and then rinsed. In all drying experiments, squid samples (individual size 200-300 g after pretreatment) were laid on a polypropylene perforated plate and placed on the surface of the bottom electrode of the RF heating system.

RESULTS

HA-RF (0.86 g/g·h⁻¹) drying resulted in a higher drying rate than solely RF (0.27 g/g·h⁻¹) and HA (0.70 g/g·h⁻¹) drying. However, HA-RF drying (60.45) significantly increased the Browning index (BI) compared to fresh samples (-8.18) due to the high drying temperature, and CA-RF drying caused localized overheating of squid in the falling rate period, resulting in quality damage. Therefore, (HA-RF)+(CA-RF) drying was further explored for achieving optimum product quality. This multi-stage combined drying technique ensured the drying rate (0.77 g/g·h⁻¹) while the sample had good color (BI=35.13), hardness (318.08 ± 3.85 g) and springiness (0.56 ± 0.08).

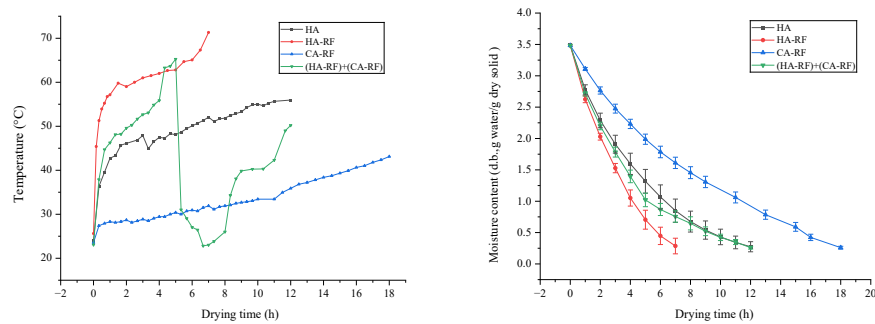


Figure 3. Temperature-time histories and drying curves of squid with different drying methods.

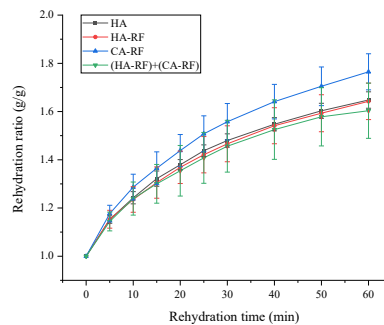


Figure 4. Rehydration ratio curves of dried squid with different drying methods.

DISCUSSION

In (HA-RF)+(CA-RF) drying, the use of HA-RF in the first stage accelerated the water transfer rate and achieved a higher drying rate; in the second stage, the use of CA-RF reduced the drying temperature, and finally obtained a lower Browning index, namely, a better sample color compared with HA and HA-RF drying.

CONCLUSION

The results provide potential methods to improve the efficiency and quality of aquatic products using combined RF heating technologies.

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