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This paper brings to perspective issues related to research initiatives for the application of microwave (MW) and radiofrequency (RF) applications in foods. Both MW (300 MHz and 300 GHz) and RF waves (3 kHz – 300 MHz) are part of the electromagnetic spectrum that result in heating of dielectric materials by induced molecular vibration as a result of dipole rotation or ionic polarization. They have been credited with volumetric heat generation resulting in rapid heating of foodstuffs. Due to their lower frequency levels, RF waves have a larger penetration depth than MW and hence could find better application in larger size foods. Besides the popular domestic use of MW ovens, commercialized applications of MW/RF heating include blanching, tempering, pasteurization, sterilization, drying, rapid extraction, enhanced reaction kinetics, selective heating, disinfestations, etc. This paper reviews the current status and research needs for in-packaged sterilization technologies for commercial applications. Technological challenges include process equipment design, microbial destruction and enzyme inactivation kinetics, temperature and process monitoring, and achieving of temperature uniformity. Other issues also relate to the use of packaging material in in-package sterilization applications, package/container concerns in domestic MW ovens, receptor technology for creating dry-oven conditions, modeling and time-temperature process integrators. There is also the issue of non-thermal and enhanced thermal effects of microwave heating on destruction kinetics.

Key Words: microwave, radio frequency, sterilization, food package, thermal processes

INTRODUCTION

Microwave (MW) (300–300,000 MHz) and radio frequency (RF) waves (0.003–300 MHz) are a part of the electromagnetic (EM) spectrum. MW and RF energy generate heat in dielectric materials such as foods through dipole rotation and/or ionic polarization (Metaxas and Meredith, 1993). The MW oven, one use of this technology, is now a common household appliance. Whereas in the food industry, popular industrial applications of MW heating in food processing operations include tempering meat or fish blocks and precooking bacon or meat patties, while RF heating is commonly used in the drying of freshly baked products. Such applications shorten processing times, reduce floor space, and improve product quality, compared to conventional methods (Ramaswamy and van de Voort, 1990; Schiffmann, 1992). Extensive research has been carried out over the past 50 years on the use of MW and RF energy in pasteurization, sterilization, drying, rapid extraction, enhanced reaction kinetics, selective heating, disinfestations, etc., but results have shown there are only limited applications. However, technological challenges remain, so further research is needed on MW and RF applications for those processes.

This manuscript will focus specifically on MW and RF applications for in-package sterilization processes, for three reasons: (1) the food industry needs novel technologies, due to public demand for high-quality convenient foods; (2) the US military and NASA space program have a strong need for highly palatable, nutritious, shelf-stable, ready-to-eat meals (MRE), for military rations and for use during extended manned space missions; and (3) sterilization processes are needed that produce low-acid ($pH > 4.5$) and shelf-stable foods, but those processes require FDA acceptance for commercial applications. Since MW/RF sterilization applications require more thorough, systematic studies, as compared to other applications, these studies will have a far-reaching impact on the food industry and research community.

Retorting is the most common commercial sterilization method used to produce shelf-stable low acid foods in the food industry. In conventional thermal processes, packaged foods are heated with pressurized hot water or steam. Thermal energy is propagated throughout the

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food product to raise the temperature and inactivate pathogenic and spoilage bacterial spores within. Over the past two hundred years, since the first introduction of shelf-stable foods by French entrepreneur Nicholas Appert in 1804, this technology has evolved perhaps to its fullest potential. However, the nature of the retort process, applying slow heat to foods, results in longer processing times and often causes severe thermal degradation. Improvements in thermal processes have been made possible with the application of high temperature short time concepts, using packages in thin profile forms and agitating the containers during processing or aseptic processing. Nevertheless, novel techniques such as MW/RF, induction, and ohmic heating are continually being explored as alternatives to conventional thermal processing. MW and RF sterilization, in particular, can sharply shorten processing times and thus provide opportunities to improve the quality of ready-to-eat meals.

STATE-OF-THE-ART OF THE TECHNOLOGY

Significant progress has been made in recent years in the development of MW and RF sterilization technologies for packaged foods. This section provides an update on the development and application of those technologies.

MW Sterilization

After extensive review of the literature and consultation with experts in the field, Datta and Davison concluded in a 2000 IFT special report (IFT, 2000) that 'microbial inactivation kinetics for MWs are essentially the same as the inactivation kinetics of conventional thermal processing.' This indeed has been the basis for development of MW sterilization technologies. Any nonthermal or enhanced thermal effects can be used as added safety with respect to lethality considerations. Details on a variety of topics related to MW processing including nonthermal and enhanced thermal effects are highlighted in Datta and Anantheswaran (2004) and and Ramaswamy et al. (2002).

The FCC designates two MW frequencies (2450 and 915 MHz) for heating applications in North America. Domestic ovens and some industrial applications use 2450 MHz, while more energy-efficient 915 MHz MWs are exclusively used in the food industry. Information on commercial scale 2450 MHz MW sterilization systems, i.e., OMAC (Harlfinger, 1992) and Berstorff (Schlegel, 1992), can be found in the literature. Several 2450 MHz systems are used in commercial production of shelf-stable packaged foods in Europe (e.g., Tops Foods, Olen, Belgium) and Japan (Otsuka Chemical Co., Tokushima, Japan). Those systems were designed with multi-mode MW cavities (no published data; information obtained from Juming Tang, who visited Tops plant and talked with Ruddy Tops, owner of Tops Foods; and visited Otsuka plant and talked with Takumi Soejima, Development Leader of Tokushima Food Research Institute of Otsuka Chemica Co.). This technology has not been adopted in the USA for the commercial production of low-acid shelf-stable foods, because lack of predictable heating patterns in food packages during sterilization processes complicates FDA approval of the process. No commercial MW sterilization operation exists in North America, and over the past 10 years no research on MW sterilization of packaged foods has been reported other than from Washington State University (Pullman, WA).

The Advanced Thermal Processing research team at WSU started developing the 915 MHz single-mode MW sterilization technology in 1996, with assistance from the US Army Natick Soldier Center in using thermally produced chemical markers (M-1 and M-2) to study heating patterns and identify cold spots. Washington State University chose the 915 MHz frequency over 2450 MHz because of three advantages: (1) deeper penetration depth; the technology can produce a package depth of up to 3 cm; (2) ability to stabilize and predict heating patterns in single meal packages; and (3) higher energy efficiency. In 2001, a MW sterilization consortium was formed under a US Department of Defense Dual-Use Science and Technology (DUST) contract to facilitate scale-up and commercial application of MW sterilization. Current consortium members are WSU (WA), Ferrite Component Inc. (NH), Kraft Foods (IL), Masterfoods (CA), Rexam Containers (MO), Graphic Packaging (CO), Ocean Beauty Seafoods (WA), and the US Army Natick Soldier Center. The Food Products Association has also been involved in the consortium activities as a technical advisor for regulatory approval efforts.

With the guidance of a computer simulation model for EM field distribution, a scalable 10 kW 915 MHz pilot sterilization system was developed by the research team, with the following results (Guan et al., 2002, 2003, 2004; Pathak et al., 2003):

1. Single-mode 915 MHz applicators can provide predictable and reproducible heating patterns in foods.
2. The pilot system can sharply shorten processing time, allowing products to reach the desired sterilization temperature of >120 °C, thus providing opportunities to reduce thermal degradation in heat-sensitive foods.
3. The safety of MW-processed mashed potato was validated with inoculated pack studies using *Clostridium sporogenes* PA 3679 spores.
4. An accelerated shelf-life study (6 months at 100°F), conducted at the US Army Natick Soldier Center on

MW-sterilized chicken breasts, showed significantly higher acceptance of the MW-processed product compared to the counterpart processed with a conventional retort.
5. Computer simulation models for predicting EM field distribution can assist in the design of single-mode cavities.

The WSU MW Sterilization Consortium gave a presentation on the progress of the 915 MHz single-mode MW sterilization technology development, to the FDA Acidified and Low Acid Food Team in Washington DC, in September 2004. FDA officers highlighted the following issues that should be addressed to ensure successful filing of the technology for FDA approval: (a) process control to ensure that each food tray or pouch receives the same treatment, (b) more modeling work to establish a solid foundation for predicting heating patterns, and (c) microbial challenge studies for each filing.

Commercial 915 MHz MW power sources and MW heating components in modules between 30 and 300 kW are readily available and suited for industrial MW sterilization applications (Decareau, 1985). Key elements to the hardware development of 915 MHz sterilization technology include the design of pressurized vessels and appropriate MW applicators, integration of pressurized sections with MW power supply systems, and development of instrumentation and monitoring systems.

Process development and control are highly dependent upon products and food packages. As a result, research and development efforts will likely intensify after FDA approval of the first MW sterilization process, to capitalize on the advantages of MW sterilization technology in delivering new products to consumers.

RF Sterilization

The literature contains no reports on the commercial application of industrial RF sterilization. Again, research activity on RF sterilization of packaged foods has been limited; WSU in partnership with Strayfield, UK, and with support from the US Army Natick Soldier Center and US Army Combat Ration Network (CORANET), has developed a 27 MHz 6 kW pilot-scale RF sterilization system capable of processing foods in either one 6 lb polymeric tray or four 10 oz trays at a time. WSU, under the support of the US Army Soldier Center, is developing a multi-tray system to simulate a large-scale industrial system. The following observations and conclusions highlight the research results obtained from WSU (Wang et al., 2003a, b; Chan et al., 2004; Luechapattanaporn et al., 2004, 2005; Tang et al., 2004).

1. RF energy inactivates heat-resistant spores in packaged foods.
2. RF heating shortens process times by about 1/3 compared to the conventional retort method used to produce shelf-stable prepackaged foods.
3. RF sterilization produces selected foods (i.e., eggs, pasta, meats) with higher quality compared to conventional processes.
4. RF energy can be applied to foods packaged with polymeric trays sealed with aluminum laminated lid stock.
5. RF energy can heat products volumetrically in polymeric trays with a depth of more than 5 cm (this is impossible for moist foods heated by MW).
6. Computer models based on commercial finite element method packages have been developed to predict RF energy in packaged foods with some success, but more improvement and validation work is needed.
7. The dielectric loss factor of most foods increases with temperature, which may cause thermal runway and reduce heating uniformity during processing. It is critical to design RF sterilization systems with uniform electric energy in packaged foods to prevent thermal runway.

Upscaling of RF systems, to provide uniform EM field patterns in commercial-scale processes, remains a major challenge in RF research.

RESEARCH NEEDS

The following priorities have been identified by Academia, Industry, and Government researchers on MW/RF heating.

Research to Seek FDA Acceptance

There is a need to speed up research and development efforts in seeking FDA approval of MW and RF sterilization processes. The following aspects need to be considered to meet this need:

Computer Simulation

Commercial finite difference and finite element-based software packages incorporating EM fields are available for use in desktop computers. The dielectric properties of most foods are dependent on temperature, thus there is a need to develop and evaluate truly coupled EM and heat transfer models for MW/RF sterilization. Models need to be validated through temperature and/or marker data. Effective computer simulation models validated by experiments in pilot testing are needed to guide design of industrial scale systems and development of new thermal processes based on MW and RF energy (Pathak et al., 2003; Chan et al., 2004).

Chemical Markers

Chemical markers (M-1 and M-2) developed by the US Army Natick Soldier Center are effective in evaluating heating patterns in selected model foods (e.g., mashed potato and whey protein gels). M-2 can be used for short MW processes, and M-1 for relatively long RF processes to identify cold spots. Further research on correlations between marker yields and thermal lethality to *Clostridium botulinum* spores (F_o values) needs to be established. Research is also needed to evaluate the feasibility of using model foods to study heating patterns in real food systems such as meat, fish, pasta, etc. (Ramaswamy et al., 1996; Lau et al., 2003; Wang et al., 2004).

Dielectric Properties

Because dielectric properties of foods and food components determine their interaction with EM energy, accurate dielectric property data within the sterilization temperature range at MW and RF frequencies are needed to support computer simulations. Since the dielectric loss factor generally increases with temperature at RF frequencies, gathering information at these frequencies is particularly important to avoid possible thermal runaway in RF systems (Piyasena et al., 2003a, b; Guan et al., 2004).

Temperature Measurement and Other Instrumentation

Researchers need to evaluate the best method for temperature-time data gathering (e.g., fiber-optic vs. others such as remote sensors/data tracers). Fiber-optic sensors that do not interfere with EM energy can provide accurate data comparable to sensors in standard thermocouples, but they are generally very fragile. Remote data tracers are needed for monitoring product temperature in continuous MW sterilization processes.

Directional couplers are useful in monitoring MW powers launched into MW applicators, but EM field strength sensors need to be evaluated and developed to monitor the processes and to detect deviations before being used for industrial applications.

Process Development

There is a need to collect temperature distribution data for specific system designs to improve heating uniformity and to develop process protocols.

Microbial Considerations

Since microbial destruction in MW and RF heating is considered the result of only thermal effects, the nonthermal effect can provide a safety margin. PA 3679 spores can be used as a surrogate to validate MW/RF sterilization processes (Guan et al., 2003; Luechapattanaporn et al., 2004).

Food Quality

Research on thermal degradation kinetics for heat sensitive foods with short-time processing, compatible with MW and RF sterilization processes (e.g., 4–30 min at or more than 121 °C), is needed to guide the design of appropriate process parameters in producing high-quality food products. There is also a need to define the best operation parameters (heating rate, power/intensity, final temperature, etc.) for optimizing food quality.

Packaging

There is an acute need to evaluate and select food-packaging materials for extended shelf life products (i.e., 1 year for retail, 3 years for the Army, and 5 years for NASA). It is very important that food packages are compatible with MW heating and can provide desired post-process barrier mechanical properties. Considerations in future studies should, therefore, include compatibility and interaction between MW and foods, barrier and mechanical performances, migration of packaging components into foods and costs.

System Design

Efforts are needed on equipment design to improve energy efficiency (industry) and to reduce cost. For RF processes, there is a need to address system stability arcing problems and scaling up.

Criteria to Establish Priorities for Research

The following issues were identified as priorities for support with public research money:

1. Safety/FDA acceptance
2. Food quality (sensory and nutrition)
3. Packaging
4. Industrial standard
5. Cost efficiency

Support with Public Research Funds

The group suggested that public research funds be allocated and prioritized as follows to support fundamental and applied research (100% of total grants available for MW/RF research):

1. Safety/FDA approval (50%)
2. Food quality (30%)
3. Packaging issues (20%)

Researchers recommend a multidisciplinary approach involving university-industry-government collaborations to address FDA approval concerns and food packaging issues.

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