vances in Agricultural Science and Technology

Volume 1

Advances in Bioprocessing Engineering

Editors

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Vol. 2 Advances in Bio-Environmental Engineering
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FOREWORD

Application of engineering, chemical and biological technologies in production agriculture has been one of the most outstanding human achievements in the 20th century. After World War II, grain production in the world has outpaced the population growth but with less arable land. In late 1990s, agricultural production in the United States, with less than 2% of the population as farmers, contributed more than 16% of the total GDP and provided more than 18% of employment in agriculture-related industries and businesses. Each farmer met the food needs for more than 120 people.

Yet, food security remains one of the greatest challenges in today's world. The human population has increased almost four-fold during the past century, up to over six billion in 1999. A century from now, the world population probably will reach 10 to 15 billion, with most of this increase in less developed countries. Meanwhile, the cost for feeding the world has been enormous. These costs include resources depletion, species extinction, and environmental deterioration, just to name a few. Among the many constraints for further development, water may be number one for ensuring a future food supply. Global climate change, abnormalities in monsoon cycles, and over-utilization of water all contribute to the severity of the problem. On the other hand, people's lifestyles have changed so much resulting in an increasing demand for more and better agricultural products without sacrificing our living environment. Population increase, environmental degradation, and the demand for a better quality of life are the three major driving forces for further development of agriculture in the next century.

The future development of agriculture will surely not be the same as in the past century. Biological science and technology will be a major column to support the future economy, featuring a great deal of industrialization, commercialization and globalization. Agriculture is being evolved into a much broader field of, as proposed by Dr. T.C. Tso, life science industry. Indeed, as the world is moving toward the next century, agriculture is under fast and great transition. In some developed countries such as the US, production agriculture is becoming less and less significant in the national economy, yet food processing and distribution,

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human nutrition and health, resources conservation and restoration, environmental protection and beautification, are all emerging under the umbrella of agriculture and natural resources. In past decades, most of the traditional agricultural universities and colleges have changed their names and, more profoundly, their research directions and curricula. The service that agricultural science and technology provides is no longer to the grain and animal producers only, but shifting to the whole human population. It has also been recognized that many non-traditional agricultural institutions are also becoming stakeholders of agricultural science and technology.

To reflect this great transition, we proposed to edit a series of books entitled *Advances in Agricultural Science and Technology*, which aims to provide a comprehensive background in each of the major branches with the most advanced developments. We believe that such a series is beneficial to scientists, business developers, administrators, and students (seniors and graduates) in agriculture-related fields, whether emerging in or developing, in the US or elsewhere.

This idea was initially supported by the Chinese-American agricultural scientists. Since the late 1970s, hundreds of thousands of scholars have come from China to study and work in Western countries. Many of them have emerged as world-renowned scientific leaders in almost every field. After two years of communications and discussions with members of the Association of Chinese-American Agricultural Scientists, we decided to take the lead in publishing this series. To ensure quality, each volume is proposed and edited by a group of outstanding professors in that field. Contributors are identified and invited following an academic assessment by an academic advisory committee. Standard peer review procedures were applied to all the manuscripts.

We thank all the contributors for their enthusiasm and effort, the reviewers for their insight and time, the advisory board members for their care and support, and World Scientific Publishing Co. for their cooperation in this academic project. Last but not least, we are immensely grateful to our families for their continuous support.

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&
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PREFACE

At the dawn of the new millennium, our eyes must dare to vision far beyond the new horizon; our minds must dare to dream of something new and seemingly impossible. Although we are limited by what we have been able to see, we need to place ourselves above the trees of tradition, to vision, to dream.

In a way, the volumes of *Advances in Agricultural Science and Technology* are to provide new sights, hopefully above the tree of tradition. We are experiencing nanotechnology, witnessing vertical revolution, and this is only the beginning.

There are four pillars for science and technology development: science, mathematics, engineering and technology. The key technology involves nanotechnology and synthetic biology. Nanotechnology focuses on electronics, biology, advance materials, optoelectronics and nanocomputer simulation to create high performance devices. Synthetic biology is to use the synthetic capacity of organic and biological chemistry to design artificial, synthetic molecules that nevertheless function in biological systems. For example, using organic chemistry to modify the RNA.

In recent years, the frontiers of science have advanced tremendously. What lies beyond genome 2000? Yes, DNA sequence has been completed. However, proteomics is far more complex than genomics. Proteomics will produce human medicine and improve human care. One cannot help but wonder what life would be like if DNA contained more than four nucleotide bases, and proteins more than 20 amino acids? What would happen to molecular biology or industrial chemistry if synthetic amino acids other than the common 20 were incorporated for construction of proteins for plants, food, or even for life itself?

Those visions, as "dreamed" above, are far above the trees of tradition. This is the challenge, and also the opportunity for scientists to project the impossible. For example, in agricultural production, we should emphasize proper input in accordance with ecological balance instead of output, to rely on information technology, to emphasize on total utilization. Above all, to achieve a better quality of life through agricultural science and technology.

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CHAPTER I

MICROWAVE HEATING IN FOOD PROCESSING

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INTRODUCTION

Microwave heating takes place due to the polarization effect of electromagnetic radiation at frequencies between 300 MHz and 300 GHz (Decareau, 1985). Started as a by-product of the radar technology developed during World War II, microwave heating is now used in about 92% of homes in the US (Giese, 1992). Microwave heating has also found applications in the food industry, including tempering of frozen foods for further processing, pre-cooking of bacon for institutional use, and final drying of pasta products. In those applications, microwave heating demonstrates significant advantages over conventional methods in reducing process time and improving food quality. But in general, applications of microwave heating in industrial food processing are much less common than home applications. Reasons for this difference include a lack of basic information on the dielectric properties of foods and their relationship to microwave heating characteristics and the historically high cost of equipment and electricity. The food processing industry has been reluctant to make expensive investments in a technology that has not been proven thoroughly reliable in large-scale or long-term use (Mudgett, 1989). Now, with the development of more reliable magnetrons and the invention of ferrite circulators to protect generating tubes, microwave equipment has a longer operating life. The cost for microwave equipment has been steadily reduced over the years

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and is now comparable to that for conventional heating methods. The future of microwave heating in food processing applications is promising, but successful exploration of microwave heating applications relies on a thorough understanding of the interaction between microwaves and foods, and on the ability to predict and provide a desired heating pattern in foods for specific applications. Microwave heating in foods is a complicated physical process which depends upon the propagation of microwaves governed by Maxwell's equations for electromagnetic waves, on the interactions between microwaves and foods determined by dielectric properties, and on heat dissipation governed by basic heat and mass transfer theories. This chapter will provide a general review and discussion on the interactions between microwaves and food materials and give a brief introduction of the current commercial applications of microwave heating in food processing. It will also describe some recent research results on microwave drying, pasteurization, and sterilization at Washington State University.

MECHANISMS OF MICROWAVE HEATING

Food materials are, in general, poor electric insulators. They have the ability to store and dissipate electric energy when subjected to an electromagnetic field. Dielectric properties play a critical role in determining the interaction between the electric field and the foods (Buffler, 1993). The dielectric properties of a material are given by:

$$\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| e^{-j\delta} \qquad (1)$$

where ε = the complex relative dielectric constant
ε' = the relative dielectric constant
ε'' = the relative dielectric loss factor
δ = dielectric loss angle ($\tan \delta = \varepsilon'' / \varepsilon'$)
$j = \sqrt{-1}$

ε' is related to the material's ability to store electric energy (for vacuum $\varepsilon' = 1$), while ε'' indicates dissipation of electric energy due to various mechanisms.

The magnetic permeability for most biological materials is the same as that of free space ($\mu_o = 4\pi \times 10^{-7}$ W/Am). Therefore, those materials do not interact with the magnetic field component of electromagnetic waves. Magnetic materials such as ferrite, often used in susceptors and browning dishes, however, interact with the magnetic field, which results in substantial heating (Buffler, 1993).

Conversion of the electric component of microwaves into thermal energy in a lossy material (Goldblith, 1967) can be calculated by:

$$Pv = 5.56 \times 10^{-11} \times f\varepsilon'' E^2 \qquad (2)$$

where P_v = the power conversion per unit volume (W/m^3)
f = frequency (Hz)
ε'' = relative dielectric loss factor
E = electric field (V/m)

In theory, electric conduction and various polarization mechanisms (including dipole, electronic, atomic and Maxwell-Wagner) all contribute to the dielectric loss factor (Metaxas and Meredith, 1993; Kuang and Nelson, 1998). But in the microwave frequency range of practical importance to food applications (e.g. 2450 MHz and 915 MHz in North America), conduction and dipole rotation are the dominant loss mechanisms (Fig. 1). That is:

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\varepsilon_0 \omega} \quad (3)$$

where subscribes "d" and "σ" stand for contribution due to dipole rotation and due to ionic conduction, respectively; ω represents angular frequency of the microwaves, and ε_0 is the permittivity of free space (8.85×10^{-12} F/m). In the frequency range between 1 kHz to 100 MHz, Maxwell-Wagner[1] polarization plays a very important role, but it is usually not considered in microwave heating.

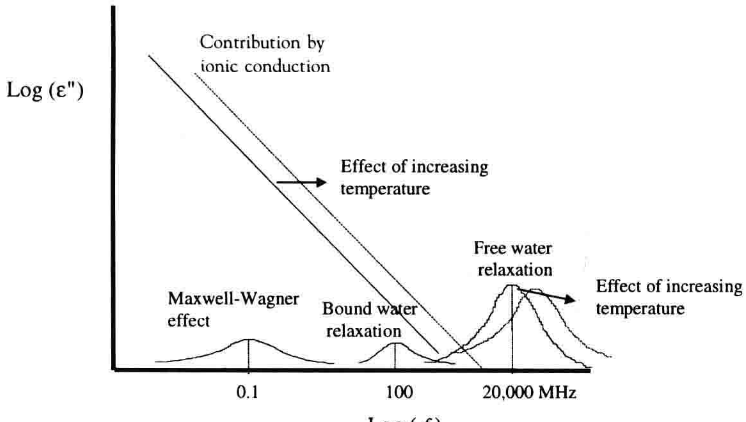

Fig. 1 Contributions of various mechanisms to the loss factor of moisture materials as a function of frequency and temperature (based on Roebuck and Goldblith, 1972; Harvey and Hoekstra, 1972; Metaxas and Meredith, 1993; Kuang and Nelson, 1998).

[1]Maxwell-Wagner polarization arises from charge build-up in interface between components in heterogeneous systems (Metaxas and Meredith, 1993). It peaks at about 100 kHz at room temperature of 20°C.

FACTORS AFFECTING DIELECTRIC PROPERTIES OF FOODS

Dielectric properties of food materials are affected by many factors, including frequency of the microwaves, food temperature, moisture content, salt content, and other constituents.

Effects of Frequency and Temperature

In a food system, the change of dielectric properties with respect to temperature depends upon frequency, bound water to free water ratio, ionic conductivity, and composition of the material. For example, at microwave frequencies used by the food industry, both the dielectric constants and the loss factor due to polarization of bound water in foods would increase with temperature. On the other hand, these two properties of free water would decrease when temperature increases (Calay *et al.*, 1995). An important concept in understanding how frequency and temperature affect dielectric properties due to dipole rotation, ε_d'' in Eq. (3), is the relaxation time τ. It is defined as the time required for preferentially oriented molecules, under a static external electric field, to relax back to 1/e (or 36.8%) of the original condition on sudden removal of the external field. In general, the larger the molecules, the longer the relaxation time. For a pure liquid, such as water, the dielectric loss factor ε_d'' reaches the maximum at the relaxation frequency ($f_c = \frac{1}{2\pi\tau}$). The relaxation time τ of free water at 20°C was measured to be between 0.0071 to 0.00148 ns, which corresponds to a peak in ε_d'' at around 16 GHz (Mashimo *et al.*, 1997). Water molecules are polar and are the most important constituent that contributes to the dielectric properties of moist foods. Water molecules bound to the surface of food solids in mono- or multi-layers have much longer relaxation times than free water molecules. For example, the relaxation time of bound water in different food materials at 20°C was determined to be between 0.98 ns to 2.00 ns, which corresponds to a peak in ε_d'' at about 100 MHz. Harvey and Hoekstra (1972) found that ε_d'' of monolayer bound water in lysozyme peaked at 200 MHz (2×10^8 Hz) and ε_d'' for the second layer bound water peaked at about 10 GHz (10^{10} Hz) (Figs. 2 and 3).

Debye related the relaxation time for the spherical molecule to viscosity and temperature as a result of randomized agitation of the Brownian movement (von Hippel, 1954):

$$\tau = V\frac{3\upsilon}{kT} \tag{4}$$

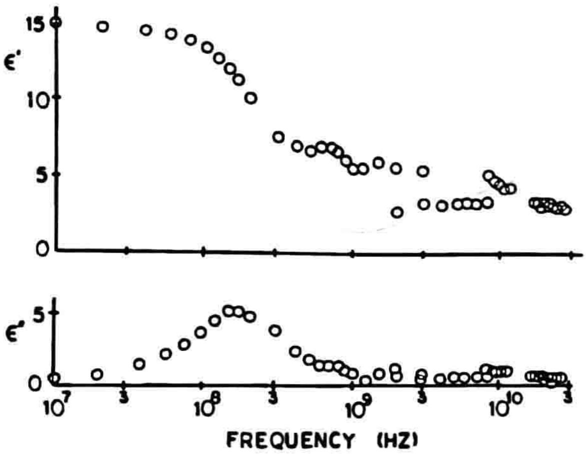

Fig. 2 Dielectric constant (ε') and loss factor (ε'') as a function of frequency for packed lysozyme samples containing slightly more than one monolayer of bound water at 25°C (Harvey and Hoekstra, 1972).

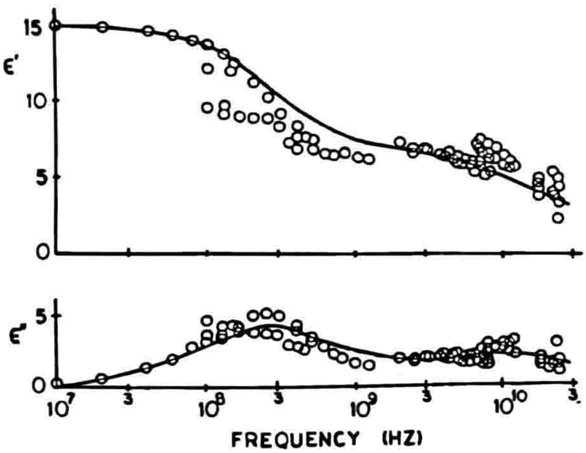

Fig. 3 Dielectric constant (ε') and loss factor (ε'') as a function of frequency for packed lysozyme samples containing nearly two layers of bound water at 25°C (Harvey and Hoekstra, 1972). The two dispersions correspond to the first and second layers of bound water, respectively.

where v is viscosity, T is absolute temperature, V is volume of the sphere, and k is a constant. For non-spherical water molecules, we may have the following relation:

$$\tau \propto \frac{v}{T} \tag{5}$$

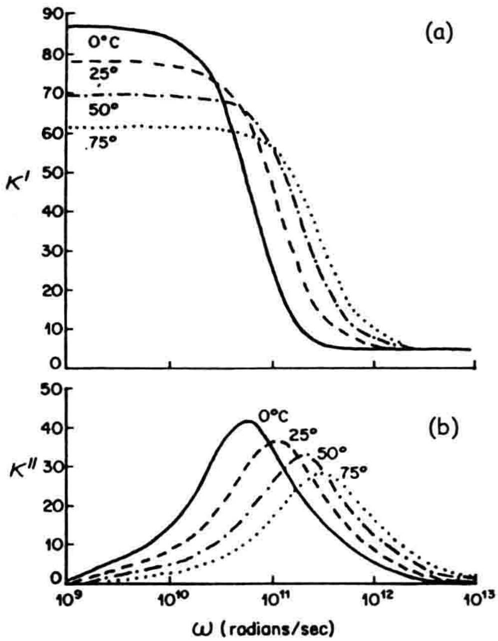

Fig. 4 Effect of temperature on dielectric behavior of free water ($\omega = 2\pi f$, f is frequency in Hz) (from Mudgett, 1985).

while the viscosity of all fluid decreases with increasing temperature (Macosko, 1994):

$$v = v_o e^{\frac{Ea}{RT}} \tag{6}$$

where E_a is activation energy and R is the universal gas constant. Therefore, as temperature rises, relaxation time for water decreases. The shifting of the relaxation time toward a smaller value (thus the frequency at the maximum ε_d'' shifts toward a larger value as temperature increases) reduces the value of ε_d'' for water at a fixed microwave frequency (Fig. 4). For example, as the relaxation time τ decreases with increasing temperature, the dispersion peak moves to higher frequencies, and the loss factor of pure water at 2450 MHz (2.45×10^9 Hz) decreases with increasing temperature.

The dielectric constant ε' of free water also decreases with increasing temperature as the result of increased Brownian movement.

The dielectric loss factor ε_σ'' due to ionic conduction decreases with increasing frequency as shown in Eq. (3). The contribution of ε_σ'' to the overall loss factors is smaller at 2450 MHz (2.45×10^9 Hz) than at 915 MHz (0.915×10^9 Hz) (Fig. 5).

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