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Microwave Pasteurization and Sterilization of Foods

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28.1 Introduction

Thermal processing has been a major processing technology in the food industry ever since the discovery of the process by Nicholas Appert and its subsequent commercialization. The purpose of thermal processing was to extend the shelf life of food products without compromising food safety. Various thermal treatments such as pasteurization and sterilization can be selected on the basis of severity of the heat treatment and the intended purpose [1]. Apart from inactivation of pathogens, thermal treatment can also result in some other desirable changes, such as protein coagulation, texture softening, and formation of aromatic components. However, the process has also got some limitation by way of partial destruction of quality attributes of food products, especially heat-labile nutrients, and sensory attributes. The technological revolution, nutritional awareness, and continuous demand of the new generation have necessitated search for new or improved food processing technologies. Presently, several new food processing technologies, including microwave and radio frequency heating, pulse-electric field treatment, high-pressure processing, ultrasonic applications, irradiation, and oscillating magnetic fields, are being investigated to improve, replace, or complement conventional processing technology.

Microwave heating of foods is attractive due to its volumetric origin, rapid increase in temperature, controllable heat deposition, and the easy clean-up opportunities. It is currently being used for a variety of domestic and industrial food preparations and processing applications. It has been used successfully for finish drying of potato chips, precooking of chicken and bacon, proofing and frying doughnuts, tempering of frozen foods, and drying pasta products. Microwave processing for fresh filled pasta has become common in Italy since the 1990s, and the technology has been applied to ready-to-eat meals, pasta-based products, and a variety of other foods throughout Europe, Japan, and South America [2]. Recently, microwaves have been used to heat foods in commercial pasteurization and sterilization applications to enhance microbial destruction and promote better product quality. Some European and Japanese food processing companies have utilized the technology for commercial pasteurization and sterilization of foods, while their North American counterparts have been still hesitating to accept these processes [3].

Microwave heating is preferred for pasteurization and sterilization over the conventional heating for the basic reason that the process is fast and requires minimum come-up time (CUT) to the desired process temperature. To process liquid foods, high-temperature short-time (HTST) processes have been accepted by the food processing industry to reduce the adverse thermal degradation in food quality while ensuring food safety [4]. However, the HTST process is not suitable for solid foods processed by conventional methods due to slow heat conduction, which often causes overheating at the solid surface during the time needed for the heat to be transferred to the slowest heating point of the food [4,5]. Microwave heating has the advantage to overcome the limitation imposed by the slow thermal diffusion process of conventional heating [5]. The volumetric heat generated by microwaves can significantly reduce the total heating time and severity at the elevated temperatures needed for commercial sterilization [6] whereby bacterial destruction is enhanced, but thermal degradation of the desired components is reduced.

Study of the destruction kinetics of microorganisms by microwave heating has had considerable interest since the 1940s when the first work by Fleming [7] was reported and the argument between nonthermal and thermal effects was born. Several theories have been proposed to explain how electromagnetic fields might kill microorganisms without heat as summarized in a review by Knorr [8]. On the contrary, some researchers [9] refute any molecular effects of electric fields compared with thermal energy using classical axioms of physics and chemistry. Palaniappan and Sastry [10] advocated that the effects of microwave and dielectric heating are clearly the fields where there is a knowledge gap, and further studies are needed.

28.2 Principles of Microwave Heating

Microwaves are electromagnetic radio waves that are within a frequency band of 300 MHz to 300 GHz. Microwave heating refers to dielectric heating due to polarization effects at a selected frequency band in a nonconductor. It differs from capacitive heating by the placement of sample. In capacitive heating the sample is placed between the electrodes, while the food material is commonly housed inside a closed cavity in the microwave heating. Microwave heating applications have been limited to a few narrow frequency bands (Table 28.1) for industrial, scientific, and medical use to avoid interference with the

TABLE 28.1

Frequencies Assigned by the Federal Communications Commission for Industrial, Scientific, and Medical Use

Frequency
13.56±6.68 kHz
27.12±160 kHz
40.68±20 kHz
915±25 MHz
2450±50 MHz
5800±75 MHz
24125±125 MHz

radio frequencies used for telecommunication purposes. The typical bands are 915±25 MHz and 2450±50 MHz with penetration depths ranging from 8 to 22 cm at 915 MHz and 3–8 cm at 2450 MHz depending on the moisture content [6]. The latter, in particular, is used more often in domestic microwave ovens while both frequencies are used for industrial purposes. It is worthwhile to note that outside of the United States, frequencies of 433.92, 896, and 2375 MHz are also used.

Microwave heating in foods occurs due to coupling of electrical energy from an electromagnetic field in a microwave cavity with the food and its subsequent dissipation within food product. This results in a sharp increase in temperature within the product. Microwave energy is delivered at a molecular level through the molecular interaction with the electromagnetic field, in particular, through molecular friction resulting from dipole rotation of polar solvents and from the conductive migration of dissolved ions [11]. The principal mechanisms involved in microwave heating are therefore dipole rotation and ionic polarization. Water in the food is the primary dipolar component responsible for the dielectric heating. In an alternating current electric field, the polarity of the field is varied at the rate of microwave frequency and molecules attempt to align themselves with the changing field. Heat is generated rapidly as a result of internal molecular friction. The second major mechanism of heating with microwaves is through the polarization of ions as a result of the back and forth movement of the ionic molecules trying to align themselves with the oscillating electric field. Microwave heating is also affected by the state of the constituents, whether they are bound or free, e.g., bound ions have much lower microwave absorptivities [12,13].

The volumetric heating rate (Q) of microwave at a particular location is related to the electric field strength by

$$Q = 2\pi f \varepsilon_o \varepsilon'' E^2 \tag{28.1}$$

where f is the frequency of microwaves, E the strength of electric field of the wave at that location, ε_0 the permittivity of free space (a physical constant), and ε'' the dielectric loss factor (a material property called dielectric property) representing the material's ability to absorb the wave. In addition to ε'', there is another dielectric property parameter called the dielectric constant (ε'), which affects the strength of the electric field inside the food.

28.2.1 Microwave Generation

The magnetron is the heart of the microwave oven. Microwaves are generated by a magnetron, which is attached to the applicator controlled by a waveguide. The magnetron consists of the two elements of an electron tube—a cathode and an anode—each of which is in a circular form with anode resonant cavities (anywhere from four to eighty). A magnet (permanent or temporary) is placed around the anode to provide a magnetic field. When the cathode is heated by means of an electrical filament, it gives off negatively charged electrons, which are attracted by the positively charged anode. The magnetic field around the anode causes the electrons to move in an orbital fashion rather than a straight line as they jump from the cathode to the anode under an electrical pressure of 4000–6000 volts. As the electrons approach the anode, they pass by the resonator cavities of the anode, and this causes the electrons to oscillate at a very high frequency (2450 or 915 MHz). The high-frequency oscillations of the electrons in the magnetron are picked up by a small antenna on the top the magnetron tube. These oscillations are transmitted through a waveguide to a feed box from where they are distributed into the oven cavity.

28.3 Advantages of Microwave Heating

Microwave has been successfully used to heat, dry, and sterilize many food products. Compared with conventional methods, microwave processing offers the following advantages: (i) microwave penetrates inside the food materials and, therefore, cooking takes place throughout the whole volume of food internally, uniformly, and rapidly, which significantly reduces the processing time and energy; (ii) since the heat transfer is fast, nutrients and vitamins contents, as well as flavor, sensory characteristics, and color of food are well preserved; (iii) ultrafast pasteurization or sterilization of pumpable fluids minimizes nutrient, color, and flavor losses; (iv) minimum fouling depositions, because of the elimination of the hot heat transfer surfaces, since the piping used is microwave transparent and remains relatively cooler than the product; (v) high heating efficiency (80% or higher efficiency can be achieved); (vi) perfect geometry for clean-in-place (CIP) system; (vii) suitable for heat-sensitive, high-viscous, and multiphase fluids; (viii) low cost in system maintenance; (ix) heating is silent and does not generate exhaust gas; (x) flat radial temperature profile for most products; and (xi) can be combined with other technologies, such as regenerative heat exchangers and infrared heating for better process performance.

28.4 Factors Affecting Microwave Heating

Some physical, thermal, and electrical properties determine the absorption of microwave energy and simultaneous heating behavior of food materials in microwave processing. These properties/factors are briefly discussed below.

28.4.1 Frequency

For food application, only two frequencies are allocated for microwave heating (915 and 2450 MHz) and, therefore, these frequencies are of special interest. The corresponding wavelengths of these frequencies are 0.328 and 0.122 m, respectively. The wavelength has special significance as most interactions between the energy and materials take place in that region and generate instantaneous heat due to molecular friction. Food constituents except moisture, lipids, and ash are relatively inert to prescribed microwave frequencies. In addition, frequency (or wavelength) dictates equipment components such as magnetron, waveguide, and to some extent heating volume.

28.4.2 Dielectric Properties

The electrical properties of materials in the context of microwave and radiofrequency heating are known as dielectric properties, which provide a measure of how food materials interact with electromagnetic energy. Biological materials may be viewed as nonideal capacitors in that they have the ability to store and dissipate electrical energy from an electromagnetic field and the properties can be expressed in terms of a complex notation. The complex notation is characterized by dielectric permittivity with a real component, dielectric constant, and an imaginary component, dielectric loss [13]. The dielectric properties of materials are governed by the following equations:

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{28.2}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{28.3}$$

where ε' is the dielectric constant, ε'' the dielectric loss factor of the material, and j the complex constant. The dielectric constant is a measure of a material's ability to store electric energy, and the loss factor is a measure of its ability to dissipate the electrical energy in the form of heat. Complex permittivity is a measure of a material's ability to couple electrical energy from a microwave power generator (magnetron). The dielectric properties of materials mostly govern the heating behavior of food materials during microwave heating. The power dissipated per unit volume in the dielectric field is directly related to loss factor (Equation 28.1); however, it may also be dependent on the dielectric constant subject to geometry and field configuration [14]. The ratio of the dielectric loss to the dielectric constant, defined as the loss tangent (Equation 28.3), is related to the material's susceptibility to be penetrated by an electrical field and dissipate (attenuate) electrical energy as heat. Materials are classified on the basis of loss tangent. Those that are highly lossy absorb microwave energy efficiently, while highly transparent materials, such as Teflon, glass, and kerosene, have low loss factors.

28.4.3 Moisture Content

The moisture content significantly affects the dielectric properties of the food product and consequently the penetration depth of the microwave. Uneven heating rate is observed in high-moisture foods because of low microwave penetration depth. Low-moisture foods will have more uniform heating rate because of the deeper microwave penetration [15]. The initial moisture content of the product and the rate of moisture evaporation play important roles during microwave heating. The heating behavior of water is phase dependent (liquid water versus solid ice phase) and also depends on the available free water content. At constant temperature, the dielectric behavior of free water remains constant in the lower frequency range (static region) and water dipoles have enough time to reorient themselves with not much absorption of energy, while a significant decrease in dielectric behavior can be observed at the higher frequency (optical region) with no field reversal by the water dipoles. Dielectric constant decreases exponentially with frequency (critical frequency) in between the static and optical regions. Phase change results in a significant change in the dielectric properties and, therefore, these properties for water and ice largely differ in their magnitude.

28.4.4 Mass

A direct relationship exists between the mass and the amount of absorbed microwave power, which should be applied to achieve the desired heating. For a smaller mass, batch oven is suitable, while a larger throughput would often be better in large capacity conveyorized equipment. Such equipment have the added advantage of providing greater heating uniformity by moving the product through the microwave field. Each microwave oven has a critical (minimum) sample mass for its efficient operation. It is usually around 250 mL water load in a 1 kW oven. Below this level, significant amount of microwave power is not absorbed into the product, and at very low loads they may damage the magnetron.

28.4.5 Temperature

Microwave heating is significantly affected by the level of sample temperature. Dielectric properties may vary with temperature, depending upon the material. Both temperature and moisture content can change during heating and, therefore, those may have a combined effect on the dielectric constant, dielectric loss factor, loss tangent, and subsequently on the heating behavior. Freezing has a major effect on a material's heating ability because of the vastly different dielectric properties of ice and water. Water has significantly higher magnitudes of dielectric constant and loss as compared to ice, and these properties are also dependent on the microwave frequency [16].

The initial temperature of the food product being heated by microwaves should either be controlled or known, so that the microwave power can be adjusted to obtain uniform final temperatures. If the microwave oven is preset to increase the product temperature from 20°C to 80°C, it will practically reach a target temperature of 95°C with an initial product temperature of 35°C. To compensate the effect of higher initial temperature, the power of MW oven should be reduced or a higher sample mass should be used or the product should be heated for a shorter duration.

28.4.6 Geometry and Location of Foods

The shape of the food product does play an important role in the distribution of heat within the product heated in a microwave oven. It affects the depth of microwave penetration, and the heating rate and uniformity. Irregular-shaped products are subjected to nonuniform heating due to the difference in product thickness [15]. The closer the size (thickness) is to the wavelength, the higher will be the center temperature. Smaller particulates require less heat than larger ones. In addition, the more regular the shape, the more uniform will be the heat distribution within the product. A food of a spherical or cylindrical shape heats more evenly than a square. A higher surface-to-volume ratio enhances the heating rate. Therefore, the heating rate for a sphere will be different from that of a cylinder with the same volume. The relationship between load geometry, load orientation, and oven cavity parameters such as cavity size and geometry, however, is not fully established. For most foods, size and geometry in combination with energy of a relatively small wavelength such as 2450 MHz would result in nonhomogeneous but predictable heating profiles. Recently, it has been advocated that microwave heating uniformity of multicomponent foods is dependent on food component, placement, and geometry of products and packages [17]. Placement has the most significant effect. The temperature distribution could be balanced partly by taking advantage of edge and corner heating intensification.

28.4.7 Thermal Properties

The heating characteristics of foods are dependent to a greater or lesser extent on some thermal properties such as thermal conductivity, density, and heat capacity. Thermal conductivity of food plays a significant role in microwave heating. Materials with higher thermal conductivity dissipate heat faster than the ones with lower conductivity during microwave heating. Food with high thermal conductivity will take lesser time to attain uniform temperature during holding period. The thermal conductivity of frozen food is higher due to high thermal conductivity of ice, while freeze-dried foods have lower thermal conductivity. Heat capacity of food measures the temperature response of food as a result of heat input or removal. Heat capacity can be raised by increasing solid content by adding components like salt and protein. Heat capacity along with thermal conductivity and thermal diffusivity constitutes thermal properties of the material. Combination of heat capacity with thermal conductivity and density is represented by thermal diffusivity, defined as the ratio of thermal conductivity to the product's volumetric heat capacity

$$\alpha = \frac{k}{\rho c_{\mathrm{p}}} \tag{28.4}$$

28.4.8 Secondary Flow in Curved Pipe

Thermal processing requires the coldest point to experience a target minimum temperature for a specified residence time. The coldest point in a continuous-flow process is the region where fluids exhibit the maximum velocity, which is the central axial position in a straight tube. The maximum velocity can vary in a helical coil; therefore, the flow characteristics should be determined. The use of helical coils creates a secondary flow due to the momentum transfer in the radial direction, which ensures better mixing and stabilizes the laminar flow [18]. Dean number (De) quantifies this phenomenon and therefore is the dimensionless parameter to characterize flow in helical coils [18].

$$\mathrm{De} = \mathrm{Re}\sqrt{D_{\mathrm{tube}}/D_{\mathrm{coil}}} \tag{28.5}$$

$$\mathrm{Re} = \frac{V D_{\mathrm{tube}} \rho}{\mu} \tag{28.6}$$

where Re is the Reynolds number, ρ the density of the fluid, η the viscosity of the fluid, D_{tube} the inside diameter of tube, and D_{coil} the coil diameter. The secondary flow enhances heat and mass transfer rates in addition to the rate of momentum transfer, the latter one resulting in an increased pressure drop [18]. The heat transfer rates are found to increase by few percentage to several-fold in a helical coil; however, they are a function of the types of flow regime (laminar or turbulent), fluid properties, and helix configuration. Recently, the concept of Dean number has been used in microwave heating of fluid foods and Dean number exceeding 100, normally exhibiting a plug-flow behavior, has been found to be suitable for heating liquids in a microwave oven where fluid particles with maximum velocity span across most of the tube [19].

28.5 Industrial Applications of Microwave Heating

The major industrial applications of microwave heating are tempering of frozen meat and poultry products; precooking of bacon for foodservice; sausage cooking; drying of various foods; baking of bread, biscuit, and confectionery; thawing of frozen products; blanching of vegetables; heating and sterilizing of fast food, cooked meals, and cereals; and pasteurization and sterilization of various foods. Brief accounts of individual applications are given below followed by a detailed account on pasteurization and sterilization applications.

28.5.1 Tempering of Fish, Meat, and Poultry

The largest use of industrial microwave processing of food has been for tempering of meat for further processing [3]. Microwave tempering is the process where the temperature of the product is raised from storage temperature (generally below −18°C) to a temperature just below freezing point.

In meat processing industry, the meat used is usually obtained in thick frozen blocks below −18°C. The first operation on the frozen meats usually is to dice, slice, or separate individual sections into smaller pieces. The mechanical operation requires that the blocks be tempered from their solid frozen state to a point where cutting or separation can be carried out easily without damage to the product. Conventional tempering techniques either with water or air, subject the outer surfaces of the product bulk to warmer temperatures for long periods, for the heat to penetrate to the center. This results in large temperature gradients. In addition, the conventional tempering process takes a long time (several days) with considerable drip loss especially resulting in loss of protein, which represents an economic loss. Microwaves can easily penetrate the whole frozen product, thus effectively reaching the inner regions within a short time. The microwave tempering can be performed in few minutes for a large amount of frozen products (5–10 min for 20–40 kg). The temperature to which a product must be tempered depends upon the type of cutting, slicing, and chopping, and also upon product compositions such as the combinations of water, salts, proteins, and fats.

As microwaves are absorbed by the material, its intensity is attenuated by the penetration depth. Surface layers retain more energy and heat up faster compared to the inner regions of the product. The loss factor increases with the temperature, the product surface heats up faster and faster, and the penetration depth simultaneously decreases. The lower frequency (915 MHz band) has an advantage for tempering of thick products because of its deeper penetration and longer wavelength compared to the higher frequency (2450 MHz) microwave. Presently, most food industries use microwave at 915 MHz for tempering purposes except where the law does not permit the use of this frequency. Tempering of frozen foods is carried out either in batch- or continuous-type microwave system (25–120 kW). Presently, manufacturers design the system as per customers' choice, type of food products, and applications. The process has been successfully used by meat, fish, and poultry industries for further processing while the dairy industry has exploited the technology to reduce the chances of rancidity during bulk freezing of butter.

28.5.2 Precooking of Bacon

Precooking of bacon is the second-largest application of microwave heating in the food industry [3]. Microwave heating is found to be an ideal system for cooking bacon compared to conventional grilling. It is reported that about half of the total bacon usage is in foodservice and virtually all foodservices bacon is precooked in microwave ovens. In addition, about 10% of the bacon sold in the supermarket is microwave precooked.

As two-component food, bacon loses the fat component, and the desirable characteristics/quality, rapidly during grilling. Microwave heating of bacon produces better structure with less shrinkage. Bacon cookers have changed with time and demand. Earlier, a combination of microwave energy and hot air was used in a microwave environment [6]. Hot air was used to trap the moisture evaporated during cooking of bacon. A combination of steam, hot air, and microwave energy is also used to cook the bacon. Sufficient amount of fat along with trapped moisture is removed during heating of the bacon at temperatures in the range of 70°C–80°C using steam. The trapped moisture does not convert to steam and is, therefore, removed along with fat. A complete microwave system has also been used for bacon cooking where series of magnetrons (equal input) are used to heat and cook the bacon. The placement of the magnetrons varies among manufacturers.

28.5.3 Cooking Sausage

The third largest application of microwave processing is sausage cooking [3]. The sausage patty quality could be improved along with better yield by using the microwave process. In sausage cooking also, microwave processing is used to reduce drip loss—loss of water, fat, nutrients, and flavor. Various laboratory-scale systems have been developed for microwave processing of sausage, but not with much commercial success.

28.5.4 Baking

The first commercial success of microwave/radio frequency energy was in the baking industry [6]. Baking ovens use radiant energy and operate in an unspecified frequency to dry the surface and make porous crust of bread. The first bread baking (proofing) was reported by Fetty (1966) [20] at 2450 MHz. A combination of microwave and thermal energy was also used to produce brown and crusted loaf in a short time. Schiffmann et al. [21] patented a bread-baking technique in which a conventional heat source along with microwave energy was used and it was claimed to reduce the baking time by 50%. The unit operations associated with baking, especially proofing and baking, led themselves toward microwave processing since the heat transfer problems encountered by conventional means were easily overcome by microwave heating. Numerous reports are available on baking of cakes, doughnut processing, and frying.

28.5.5 Drying

Microwave heating offers distinct benefits in dehydration because of its penetration depth, and the uniform heating results in water vaporizing from throughout the product. This induces an inner pressure that maintains puffed character of the dried product and preserves color, flavor, and nutritional value. Microwave drying is rapid and more energy-efficient compared with conventional hot-air drying [6]. In microwave drying, the removal of moisture is accelerated and, furthermore, heat transfer to the solid is slowed down significantly owing to the absence of convection. The usual practice of applying microwaves to drying of food materials is at the falling rate period where the migration of water from the center of the products is significantly reduced and the drying rate is comparatively slow in conventional drying process. A two-stage drying process involving initial forced-air convective drying followed by microwave finish drying has been reported to give better product quality with considerable savings in energy and time. The bakery industry conventionally uses the microwaves for finish drying of biscuits and cookies. Moreover, the moist bakery products exhibit higher loss factor (ε''), resulting in more heat generation compared to drying at a later stage with minimum water content.

Potato chips have been recognized as a global fast food. The first large-scale application of microwave energy in food processing industry was in finish drying of potato chips. Conventional drying technology cannot rapidly achieve the desired low moisture levels of potato chips and, in addition, browning creates another quality problem for the product due to presence of sugars. Drying of potato chips up to 6%–8% followed by finish drying by microwave overcomes the difficulty of the process industry.

Application of microwave energy in vacuum results in an increase in product temperature; however, the temperature rise is limited to the boiling point of the water at the lowered pressure. At a pressure of 3 kPa, free water boils at 22°C. This maintains a product temperature at a level below the temperature used under atmospheric conditions. Microwave vacuum dehydration was first used for concentration of citrus juice in France [6]. Microwave vacuum drying of agricultural commodities includes various cereal grains, and further this technology has been adapted to grapes for production of Grape Puffs™ using zoned microwave vacuum dehydration [22]. Applications of microwaves for drying of fruits and vegetables are plenty in the literature. The drying of pasta products and noodles at 915 MHz is a commercial success in many countries.

28.5.6 Blanching of Vegetables

Blanching, a unit operation practiced in canning, dehydration, and freezing industry, involves short-time exposure of the product to boiling water, steam, or microwave for the primary purpose of inactivating the oxidative enzymes, which otherwise would cause undesirable change in color, flavor, and texture of the product during storage. In canning, it also serves to reduce the microbial load, eliminate dissolved oxygen from the product, and facilitate better packing of the product into cans. It has also been shown to improve color, flavor, and sensory characteristics of the product. Water and steam are the media commonly used for blanching. Convectional steam blanching is currently the most commonly used method in the food industry. It is relatively energy intensive, and retains minerals and water-soluble vitamins better than water blanching. The first microwave blanching was reported by Proctor and Goldblith [23] using 3000 MHz for some green vegetables, and it was found to retain maximum amounts of vitamin C. Most of the results indicate that microwave blanching was more effective in retaining water-soluble vitamins in vegetables compared to conventional blanching methods.

28.5.7 Microwave Effects on Enzyme

Enzymes are probably the simplest system to consider for studying bioelectromagnetic effects in living systems. The effect of microwaves (0.3–300 GHz frequency range) on living matter has been widely studied, and most of the observed effects have been generally explained on the basis of purely bulk heating, i.e., temperature increase induced by the electromagnetic field, according to the classical theory of lossy dielectrics [13]. On the other hand, evidence of microwave effects not only related to temperature, as measurable by ordinary means, has accumulated over recent years, but the mechanisms involved are still largely unknown due to experimental and modeling difficulties. Inactivation of various enzymes such as wheat germ lipase and soybean lipoxygenase, and pectin methylesterase (PME) at various temperatures using conventional and microwave batch heating have been studied and found to have higher enzyme destruction rates under microwave heating conditions [24–26]. This difference is believed to be due to some contributory enhanced thermal effects of microwaves for enzyme inactivation.

28.5.8 Puffing and Foaming

Ultrarapid internal heating by microwaves causes puffing or foaming when the rate of heat transfer is made greater than the rate of vapor transfer out of the product's interior. Microwaves are ideal for producing puffed snack foods.

28.5.9 Concentration

Microwave heating has also been used to concentrate heat-sensitive solutions and slurries at relatively low temperatures. The process is also applicable to highly corrosive or viscous solutions.

28.6 Recent Development in Microwave Food and Packaging

Recently, food processors have developed many new-generation microwaveable foods with suitable packaging materials to meet these demands. The foods are microwaveable and for use at home as well as away from home, via convenience store or office microwave. In many cases, the products' success hinges on a combination of product reformulation and package redesign.

High-density polypropylene (HDPP) is a low-cost solution for microwave process over other materials that can withstand the target temperature. For sterilization, PET, HDPP, and various polyester-based materials are available as high-quality trays, pouches, and bags. Glass also is a possibility. The metal cap in glass jar actually proved to be an advantage.

Some of the new products now available in the market include Eggology's On-the-go 100% egg whites, and Marks and Spencer's Steam Cuisine [29]. The microwaveable product expands during cooking and the lid automatically pops up. Steam Cuisine fresh prepared meal requires 6 min to cook from raw stage. Another claim is to develop "intelligent double pressure cooking technology," where in the first cooking steps the microwave passes through the specially developed packaging and the frozen food materials. The frozen water becomes steam and cooks the food from inside out. In the next phase, as the steams comes out of the food tissues, it is held and retained inside the packaging. During the steam pressure builds, the food cooks from the outside in.

Packaging has played a significant role in microwave processing of foods. Big names like Kraft have developed many new packaging materials that can be used in microwave heating of pizza [29]. Another development in microwave foods has been reported by introducing aroma in the packaging material. The aroma is released during microwave heating of packaged material. In the future, we may expect more revolution in microwave package design to satisfy the never-ending demands of the consumer.

28.7 Microwave Pasteurization and Sterilization

Pasteurization is the process that uses relatively mild heat treatment to foods to kill key pathogens, and inactivate vegetative bacteria and enzymes to make food safe for consumption. Most frequently, milk and fresh fruit juices are pasteurized where minimum process is necessary to eliminate health-associated hazards. However, the thermal treatment given does not kill bacterial spores, and hence the product is not stable at room temperature. Under refrigerated storage conditions, one can expect 2–6 weeks of shelf life. Recently, the process has been upgraded to remove the potential health hazards due to *Salmonella, Escherichia coli,* and *Listeria monocytogenes*. Pasteurization of milk is achieved by 30 min heating at 63°C or 15 s at 72°C. Much higher temperatures have also been used for a shorter period in HTST and ultra-high temperature (UHT) processes. The temperatures and times are determined by what is necessary to destroy pathogenic, heat-resistant, disease-causing microorganisms that may be found in the food. Subsequent to pasteurization, the product is then quickly cooled to 4°C. Pasteurization temperatures and times vary, depending on the product nature and the target organism.

Sterilization is a more severe thermal treatment of foods. Traditionally, the process is designed to achieve commercial sterility of the products, giving it long-term shelf stability. The magnitude of thermal treatment is a function of pH, and it accounts for the effects of pH on the thermal resistance of the microbial spores. Foods with high pH (>4.5) support the growth of *Clostridium botulinum* that produces an exotoxin. It is generally recognized that a thermal process sufficient to eliminate toxin-producing *C. botulinum* from the food should make the food commercially sterile if adequately packaged under vacuum, recontamination prevented, and appropriately stored at room temperature (at <30°C to prevent the growth of thermophilic bacterial spores). Commonly, saturated steam at elevated pressures (135°C–140°C) and steam-heated hot water are used as heating media for food sterilization. Microwave sterilization has been studied for potential commercial applications. However, the commercialization has faced several problems with some limited success [27].

Both pasteurization and sterilization are based on time–temperature combination processes applied to food products to achieve intended target lethality. In most cases, target microorganisms are chosen for specific types of food. The death kinetics of the microorganisms play a major role in selecting the target lethality, and therefore the quantification and accommodation of microbial destruction kinetics are important steps in establishing the thermal process.

28.8 Kinetics of Microbial Destruction

The destruction of microorganisms and inactivation of enzymes are generally expressed by the *n*th-order chemical reaction as

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -kC^n \tag{28.7}$$

where $\mathrm{d}C/\mathrm{d}t$ is the change in concentration C or microbial population (change C to N) with time t, k the reaction rate constant, and n the order of reaction. Generally, the destruction of microorganisms is described by a first-order reaction kinetics. The thermal resistance of microorganisms is also conventionally characterized in food processing by means of a decimal reduction time (D value, which is the heating time at a given temperature that achieves 90% destruction of the existing microbial population) and the thermal resistance constant (z value, the temperature range between which the D values change by an order of 10) [30].

$$D_{T_{\mathrm{ref}}} = \frac{2.303}{k} \tag{28.8}$$

$$z = \frac{T_2 - T_1}{\log D_1/D_2} \tag{28.9}$$

The equivalent time necessary for thermal treatment with known thermal resistance of a microorganism is calculated by integration of the time–temperature history using Equation 28.10

$$F = \int_0^t 10^{\frac{T(t)-T_R}{z}}\,\mathrm{d}t \tag{28.10}$$

This approach has been commonly used in the thermal process calculations. A similar concept can be applied for determining kinetics parameters during microwave heating; however, nonisothermal heating conditions are involved in this case. Resulting D values can be computed using Equation 28.11

$$D = \frac{t_{\text{eff}}}{\log(C_o/C)} \tag{28.11}$$

where t_{eff} is an effective time (similar to F as in Equation 28.10) with T_R as exit temperature of the product, obtained using either model predicted or experimentally determined time–temperature profiles; and C_o and C are initial and final concentrations of microbial cells. The use of this approach is rather limited in studies relating to microwave effects. Only few studies reported in the literature describing kinetics during microwave heating make use of the transient temperature profiles [26]. However, as in thermal destruction, microwave destruction kinetics of food constituents such as quality characteristics, enzymes, and microorganisms are required for establishing microwave processing.

28.8.1 Come-Up Time and Come-Down Profile Corrections

Continuous-flow microwave heating has advantages over batch processing where the presence of nonuniform temperature in the product has seriously limited its use. Continuous-flow liquid systems allow maintaining the time and temperature achieved in steady state, record average temperatures during heating, minimize temperature gradient by mixing of the liquid, and cool liquid immediately at the exit. Microwave heating involves a nonisothermal CUT inside the oven or cavity. The holding and come-down phases take place generally outside the MW oven. More details on evaluating kinetic parameters during nonisothermal continuous-flow heating are detailed in Tajchakavit and Ramaswamy [25]. From a regression of log residual numbers of survivors versus residence time (uncorrected heating time), a first estimate of D values at the exit temperatures can be obtained, and using them at different temperatures one can get an estimate of z value. Using this estimated z value and the time–temperature profile, a more effective heating can be computed from Equation 28.10. These effective times can then be used to recalculate D and z. These two steps are repeated several times for the convergence of z value. The come-down period contribution occurs outside the microwave oven and this should be subtracted from total destruction to estimate the destruction due to MW heating. To do this, the effective cooling time (t_c) can be computed using the same Equation 28.10 with the z value obtained from conventional thermal destruction studies. The extent of logarithmic thermal destruction (LTD) during cooling can be estimated following the relationship

$$\text{LTD} = \frac{t_c}{D} \tag{28.12}$$

where D is the D value at the exit temperature obtained from thermal destruction studies. This calculated value is then subtracted from the combined destruction of microbial population due to microwave heating and cooling. Microbial destruction data of test samples can thus be corrected for both come-up and come-down period contribution to lethality. This approach has been used in some studies for comparative evaluation of microbial lethality under conventional and microwave heating.

28.8.2 Microwave Heating Systems

28.8.2.1 Batch Heating

In the batch process, the magnetron-based microwave ovens are commonly used for the heating purpose. The food sample is placed in the oven for a predetermined time to achieve a target temperature. The power level is normally adjusted to achieve a certain desired temperature difference in a given time frame. The volumetric heat absorbed by the food material during microwave heating can be calculated by using the following relationship assuming that there is no surrounding heat loss

$$Q = mC_p(T_f - T_i) \tag{28.13}$$

where m is the mass of food (kg); C_p the specific heat (kJ/kg°C); T_f the final temperature (°C), and T_i the initial temperature (°C). The absorbed microwave power (P) can be calculated by volumetric heat divided by heating time. P is compared with the nominal microwave output to compute the efficiency, and generally over 90% of the nominal power can be accounted by a large sample.

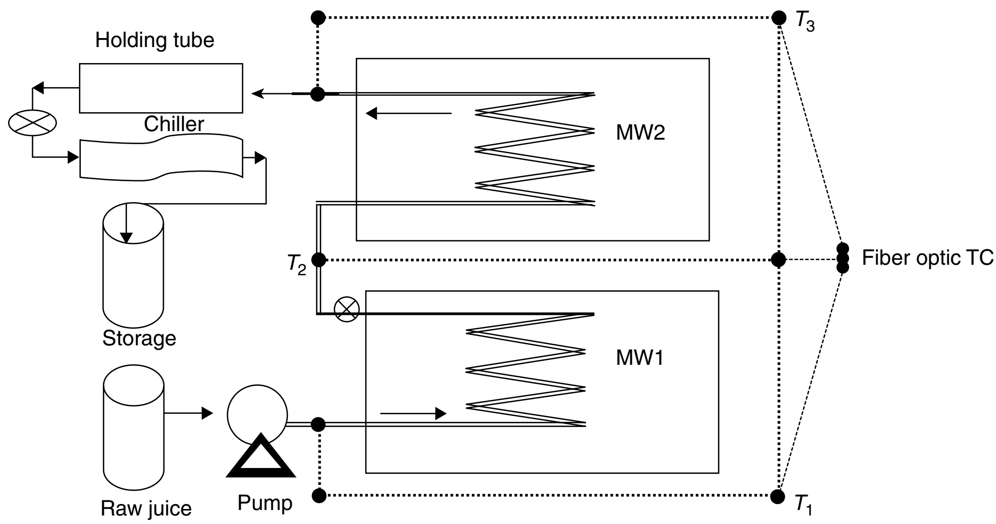

FIGURE 28.1 Continuous-flow microwave pasteurizer.

28.8.2.2 Continuous-Flow Heating

The thermal processing using microwaves has been reported to offer potential benefits to the food processing industry due to rapid heating and the ability of microwaves to penetrate the food and thereby achieve more effective bulk heating. Continuous systems have advantages over batch ones with increased productivity, easier clean up, and automation. Several laboratory-based continuous-flow microwave heating systems have been used for fluid foods with different configurations [19,25,31–33]. The schematic diagram of a basic continuous-flow microwave heating is shown in Figure 28.1. The raw fluid is pumped (peristaltic pump) through Teflon or glass helical coils placed inside one or several microwave ovens connected in series for heating (alternately several magnetrons can be arranged in one oven). Outside the microwave oven, the fluid then passes through a holding section to allow a predefined holding time followed by chilling in some form of a tubular heat exchanger. Thermocouples are used for gathering sample temperatures at the entry and exit sections (external to the oven), while fiber-optic probes are used to monitor the temperature inside the cavity/oven.

To establish steady-state flow conditions for microwave heating, the fluid food is precirculated in the system after which the microwave ovens are turned on. The volumetric flow rates are determined for various pump settings. For pasteurization process, the flow rate is generally set so that the exit temperature of the fluid in the microwave oven maintains the required temperature in holding section. The temperature of the fluid in the holding section is maintained by external means [25], or in some cases the exit temperature is elevated to a slightly higher level than required to allow for the heat loss through the insulated holding tubes [19]. However, time–temperature profiles of most of the cases are generated by transit time–temperature measurement at selected regions.

28.8.3 Application to Food Systems

28.8.3.1 Milk

Milk is traditionally pasteurized in a heat exchanger before distribution. The application of microwave heating to pasteurize milk has been well studied and has been a commercial practice for quite a long time. The success of microwave heating of milk is based on established conditions that provide the desired degree of safety with minimum product quality degradation. Since the first reported study on the use of a microwave system for pasteurization of milk [31], several studies on microwave heating of milk have been carried out. The majority of these microwave-based studies have been used to investigate the possibility of shelf-life enhancement of pasteurized milk, application of microwave energy to inactivate milk pathogens, assess the

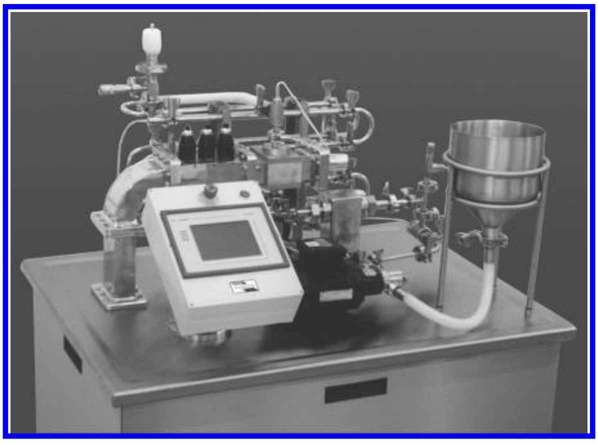

FIGURE 28.2 A typical microwave pasteurizer.

influence on the milk nutrients or the nonuniform temperature distribution during the microwave treatment [31,34–39].

Continuous-flow microwave treatment has been proposed for milk pasteurization due to its potential advantages over the conventional tubular and plate heat exchangers. Continuous milk pasteurization at 2450 MHz using a simple waveguide heat exchanger was first reported by Hamid et al. [31]. Raw milk was passed through a glass tube fitted across a waveguide, and milk was exposed to microwave energy during gravity falling. The plate counts were found to be negative while the temperature reached 82.2°C. Jaynes [34] developed an experimental continuous-flow microwave pasteurizer using a Teflon tube (12 cm/0.635 cm) placed across a 2450 MHz microwave guide. The system had a 15 s holding time. The adequacy of pasteurization was considered on the basis of inactivation of phosphatase enzyme, standard plate, and coliform counts.

HTST sterilization of raw milk has also been tested under microwave field at 2450 MHz. A typical microwave pasteurizer is shown in Figure 28.2. The process was done in free-falling stream of milk with pressure application. Heating was reported to be extremely rapid with a temperature rise of 200°C; holding was less than a second while the cooling was done by turbulent mixing with cold sterilized milk. However, the process was not considered economically feasible. Kudra et al. [35] used a domestic microwave oven for continuous-flow pasteurization of milk and its constituents. The protein in milk was found to be the contributing component to dictate the heating pattern in milk pasteurization, while effects of fat and lactose were considered negligible. Lopez-Fandino et al. [40] reported the effects of thermal treatment of milk in a continuous-flow microwave system by studying the denaturation of β-lactoglobulin and the inactivation of alkaline phosphatase and lactoperoxidase using a modified microwave oven at 2450 MHz. The results were compared with those obtained by conventional thermal treatment in a plate-type heat exchanger, and the degree of inactivation caused by the thermal treatment in both cases was found to be similar. Microwave pasteurization of milk was reported to result in lower levels of denaturation of whey proteins compared to conventional thermal processes and that the denaturation of β-lactoglobulin was almost similar in both processes [41]. Moreover, the process yielded lower microbial counts and lower lactose isomerization. The sensory characteristics of microwave-pasteurized milk were considered comparable to those achieved by traditional pasteurization after 15-day storage.

To overcome the nonuniformity of temperature distribution caused by microwave heating, Coronel et al. [42] experimented on continuous-flow microwave heating of milk at 915 MHz using a cylindrical microwave applicator. The microwave field inside the applicator generated a parabolic field distribution inside the tube for a fluid with constant dielectric properties, like those of milk at 25°C. The system was designed in such a fashion that the fastest moving particles residing at the center would receive maximum power for a shorter period, whereas the slowest moving particles at the wall side would receive minimum power for a larger period. The system was reported to exhibit a relatively even distribution of temperature for milk in the cross-sectional area of the tube at the exit of the applicator. Temperature distributions data revealed that the hottest temperature was found at the center of the tube, while the cooler temperature was close to the walls of the tube.

28.8.3.2 Effect on Milk Nutrients

Milk is a rich source of vitamins and heat treatment affects some of these nutrients. The effects of microwave heating on several vitamins in cows' milk have been studied by many researchers [40]. Most studies report an insignificant loss in vitamin A, β-carotene, vitamin B_1 or B_2 in microwave-pasteurized milk, while a loss of approximately 17% for vitamin E and 36% for vitamin C have been found.

Sierra et al. [43] compared the heat stability of vitamins B_1 and B_2 in milk between continuous microwave heating and conventional heating having the same heating, holding, and cooling steps. No significant losses in the vitamins were reported during microwave heating at 90°C without holding period, while vitamin B_2 was found to decrease by 3%–5% during 30–60 s of holding. The authors concluded that the microwave process does not offer any additional advantage with respect to vitamin retentions as compared to conventional heating process. Microwave heating of milk does not affect protein or fat components. Volatile components of conventionally treated and microwave-treated (continuous flow) milk have differed significantly.

28.8.3.3 Effect on Microbial Inactivation

The inactivation of *Streptococcus faecalis, Yersinia enterocolitica, Campylobacter jejuni,* and *Listeria monocytogenes* in milk by microwave energy has been reported by Choi et al. [37,38]. The complete inactivation of *Y. enterocolitica, C. jejuni,* and *L. monocytogenes* occurred at 8, 3, and 10 min when the cells were heated at a constant temperature of 71.1°C using microwaves with initial microbial loads of 10^6–10^7 K/mL [37,38].

28.8.3.4 Fruit Juices

Generally, acidic products like fruit juices are not considered vehicles for foodborne illness; however, recent reports demonstrate that three pathogens, namely, *Salmonella enterica, E. coli* O157:H7, and *Crytosporidium parvum* have been associated with foodborne illness in fruit juices. Pasteurization of fruit juices is traditionally carried out by HTST heating process using plate heat exchanger followed by a brief holding period and cooling. However, fouling is the major problem in such processes. Inactivation of microorganisms and enzymes of fruit juices, e.g., citrus juices by microwave pasteurization, especially in continuous-flow systems, has created interest among juice processor manufacturers due to lower thermal exposure, elimination of fouling in the pipe line, and retention of juice quality.

In orange juice, pectin methyl esterase (PME), an undesirable enzyme, causes spoilage and cloud loss during storage. In addition, the enzyme is more heat resistant than spoilage microorganisms and, therefore, has been considered as an index of the adequacy of pasteurization. Nikdel et al. [44] described a continuous-flow microwave system to pasteurize orange juice using PME inactivation and microbial count as indices. However, the system did not consider the time requirement for achieving the microwave exit temperature, or the CUT and come-down time (CDT) contributions. The inactivation of PME and *Lactobacillus plantarum* was found to be more pronounced using microwaves as compared to conventional heating. The kinetics of PME inactivation in orange juice during microwave heating in continuous as well as batch mode were compared with those during conventional heating by Tajchakavit and Ramaswamy [25,26], and they found largely enhanced inactivation of PME while employing microwave heating. In batch process, orange juice in glass beakers, with good mixing, was heated in a microwave oven for a preselected time to achieve the desired temperature. In the continuous-flow system, the juice was pumped through a helical glass coil placed inside the microwave oven under full power heating conditions, and a target exit temperature was achieved based on juice flow rate and initial temperature. Under steady-state conditions, the increment of fluid temperature between inlet and outlet in continuous flow was found to be nonlinear along the tube length. Under both batch and continuous-flow microwave heating conditions, PME inactivation rate was significantly higher than in conventional thermal treatment at selected temperatures (D values at 60°C: batch microwave = 7.37 s; continuous microwave = 22 s and conventional = 150 s). The authors claimed some enhanced thermal effects during microwave heating largely contributing to greater PME inactivation.

Microwave pasteurization of apple juice has also been investigated by several researchers [19,45]. Tajchakavit et al. [45] studied destruction kinetics of *Saccharomyces cerevisiae* and *Lactobacillus plantarum* in apple juice under continuous-flow microwave heating conditions and compared it with conventional batch heating in a water bath. The z values under microwave heating for *S. cerevisiae* and *L. plantarum* were found to be 7 and 4.5°C, respectively, while the corresponding batch conventional heating values were 13.4 and 15.9°C, respectively. Microbial destruction thus was much more temperature sensitive under microwave heating than under thermal heating. Based on the computed D values, the authors again suggested some contributory enhanced effects to be associated with microwave heating.

However, Canumir et al. [46] reported that exposure of *E. coli* to microwave treatments at 2450 MHz resulted in a reduction of the microbial population in apple juice and that the inactivation is solely due to heat. The pasteurization was carried out at different power levels (270–900 W), and it was reported that 2–4 log reduction in the microbial population was achieved at 720–900 W for 60–90 s with *D* values ranging from 0.42 min at 900 W to 3.88 min at 720 W. Recently, Gentry and Roberts [19] developed a continuous-flow microwave pasteurizer using helical coils distributed through a large cavity oven to produce uniform and reproducible heating of apple cider. Process lethality of apple cider was verified on the basis of inoculation of *E. coli* 25992 and 5D reduction was reported.

28.8.3.5 Ready-to-Eat Meals

Frozen ready-to-eat food processing technology is enormous and has been rapidly expanding over the years. The growth of the industry has been generated by the consumer demand for ready-to-eat meals, which can be reheated easily before eating. Pasteurization schedule of ready-to-eat meals needs to be established through the same guidelines that are used for commercial sterilization and cannot be simply specified in terms of a time–temperature combination. Pasteurization of ready-to-eat meals using microwaves to enhance their shelf life has been recognized for many years, and the potential of the method has been verified in pilot-scale systems [47]. Pilot- and commercial-scale microwave pasteurizers are available presently for this purpose. However, the adoption of the technology by the food processing industry has been slow due to the uncertain trends in the markets for chilled foods with extended shelf life and also because of the technical limitations linked to the process. Ideally, the product should be heated to specified levels without overcooking, then cooled quickly, and properly stored and distributed. All along, the product should remain microbiologically safe while its shelf life is extended.

Various procedures of overcoming the technical problems have been considered, including the use of a liquid circulating around the packs of food to restrict edge heating, pressurized systems for elevating temperatures, or using partially open packs to prevent the bursting of packages, moving the waveguides, hot filling of product components to produce more uniform product temperatures, or incorporating metallic structures into the cavity to modify the field distribution. Many of these changes increase the complexity and cost of the equipment and may impede flexibility of product types. Improving the design procedures for microwave systems, including the design of the microwave cavity, food packaging, and food composition should lead to better processes. An efficient engineering approach requires methods that are capable of predicting the electric and magnetic fields and temperature distributions in foods during microwave heating. Heat processing at 80°C–85°C for a few minutes is considered sufficient, with a margin of safety, to inactivate vegetative pathogenic microorganisms such as *Salmonella* and *Campylobacter,* but not bacterial spores. However, most bacterial spores do not multiply at low temperatures below 4°C. The growth from spores needs to be considered only when they are known to be present in the product ingredients and prolonged storage periods are expected.

Effect of various combinations of microwave ovens (domestic, pilot-scale tunnel) and frequencies (2450, 896 MHz) has been studied for pasteurization of ready-to-eat spaghetti bolognaise meals in retail packaging to extend the shelf life [48]. It was reported that mean product temperatures above 80°C could be achieved using any of the systems, but only the tunnel operating at 896 MHz heated all the products in a pack above that temperature.

Ryynanen and Ohlsson [17] studied the importance of chemical and physical modifications in four-component chilled ready meals during uniform microwave heating. The food component placement and geometry of products and packages were reported to play a significant role in providing microwave heating uniformity of multicomponent food systems. The temperature distribution could be balanced partly by taking advantage of edge and corner heating intensification. In contrast, chemical modifications, such as saltiness, did not notably affect the heating uniformity. However, interaction effects could sometimes be important.

28.9 Sterilization Systems

Pasteurization of packaged bread, pasta, and pizza has been reported. In some European countries, the whole loaf of the packaged bread is treated with microwave energy to enhance the shelf life. Microwave-treated fresh pasta in pack further needs controlled-atmosphere storage to increase shelf life. Microwave processing for fresh filled pasta became common in Italy in the 1990s, and the technology has been applied to ready-to-eat meals, pasta-based products, and a variety of other foods. Some of the leading global food manufacturers are applying the technology, including Unilever and Barilla SpA in Italy and Morinaga in Japan. However, both the products have limited success due to excessive cost of the process.

In the 1970s, Kenyon developed a high-quality shelf-stable ration as a replacement for the U.S. Army's C-ration by using a fiberglass-reinforced polyester pipe, which was installed in a 10 kW microwave oven. The system was similar to the equipment shown in Figure 28.3. A pair of butterfly valves at the product entry allowed pouches to be introduced into the processing system on a narrow conveyor belt through the microwave field. The pouches dropped off at the end of the belt into a cold-water tank from which they could be removed periodically. Radiation heat losses were minimized by wrapping the pouches in microwave transparent insulation. However, the temperature difference from the edge to the center of the pouches was reduced to 5°C or less from 30°C or more. Another contemporary study of microwave packaged food carried out by Alfa Laval, Sweden, was found to establish a decreasing temperature gradient from edge to center by introducing a cooling step to lower the temperature at the edges. Another modification of microwave sterilizer was carried out based on microwave heating of water by conveying packages of product through water. The water temperature was progressively adjusted by conventional heating means to provide edge heating control without expending too much energy in microwave heating of the water. The system was installed in a Swedish food plant [6].

HTST processing of pouches by conventional retorting has clearly proven the benefit of such processing on a number of quality parameters. According to Ohlsson and Bengtsson [49], there is no reason to believe a microwave HTST process would be any less successful. The authors [49] made a comparison of canning, retorting foil pouches, and microwave sterilization of plastic pouches in terms of the cook value (in an integrate value describing the effect of time and temperature on product quality). The quality of a variety of products processed using microwave sterilization was clearly superior. A typical commercial microwave reheating and sterilization system is shown in Figure 28.4.

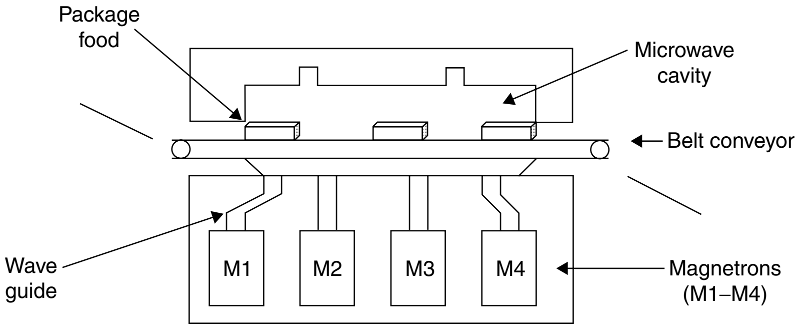

FIGURE 28.3 Multimode microwave tunnel cavity for packaged food pasteurization and sterilization.

FIGURE 28.4 Microwave pasteurizer.

Limited publications of data on processing two- and three-component ready meals are available. Processing meals presents a more complex problem—differential heating pattern of various components. The problem could be solved by accounting for the energy requirements of each component. Several patented references are available on the topic while public information is generally lacking. Data availability on the effect of storage time at room temperature on the quality factors of microwave-sterilized foods is scarce. However, there are some results in which microwave-sterilized (2450 MHz) vegetables were compared with foil pouch sterilization at 121°C and a frozen reference. The microwave product was comparable with the frozen product for sensory characteristics even after 6 months at 25°C [50]. In another study with chicken a la king, the appearance of microwave-sterilized product compared favorably with the frozen reference even after 12 months' storage.

28.10 Marker Formation as an Index of Microwave Sterilization

The implementation of microwave sterilization process can vary significantly among process design and manufacturers. The applicability of the process in the food industry, especially in the United States, depends on the FDA approval of the dielectric sterilization process as a reliable procedure to establish and validate the required lethality for heat treatments to ensure microbiological safety. To design a new thermal process, which ensures adequate sterility for shelf-stable foods, it is necessary to locate the cold spot in packaged foods [51]. Once the cold spot is determined, accurate time–temperature data can then be gathered from the slowest heated point and used for developing suitable thermal processes.

Numerous biological integrators have been found in the literature and most of these have been used as relative indicators for food safety. None of these are really adequate for identification of the coldest point of thermally processed foods. Microbiological assays are good indicators to determine effectiveness of a process; however, the procedure has limitations, as the process is time consuming, expensive, subject to recovery and contamination problems, and requires large population changes as evidence of the process. The use of effective chemical marker techniques developed by the U.S. Army Natick Research Center has been reported to be an alternative technique to quantify the time–temperature history of food products to assess heating uniformity in sterilized foods. Three markers have been in use for food systems, namely, 2,3-dihydro-3,5-dihydroxy-6-methyl-(4H)-pyran-4-one (M-1), 4-hydroxy-5-methyl-3(2H)-furanone (M-2), and 5-hydroxymethylfurfural (M-3) [52]. The marker yield can be correlated with the time–temperature effect within food systems, provided the kinetic information is obtained. Formation of intrinsic chemical markers is described as first-order reaction kinetics considering an excess source of either the protein or ribose/glucose precursor in food materials [52]. Since both marker formation and the bacterial destruction are functions of time–temperature profile, verification of calculated marker formation using experimental studies is analogous to verification of bacterial destruction in sterilization. The marker formation kinetics of ham and whey proteins has been well compared between experimental and mathematical models by Zhang et al. [28].

The yield of M-2 in whey protein gels as model foods was used to quantitatively assess the heating uniformity of microwaves at 915 and 2450 MHz [53]. M-2 predicted the HTST process well, while M-1 was found to be more relevant for longer thermal processes [54]. Kim and Taub [52] evaluated the kinetics of M-1 in broccoli extract at sterilization temperatures (116°C–131°C) practiced in the food industry. Zhang et al. [28] evaluated concentration of marker compound formed (M-2) during heating of whey protein concentrate solution and ham, and experimental data combined with numerical analysis were reported to result in an accurate and comprehensive study of the sterilization process. The marker yield increased beyond a temperature of 100°C and was maximum at 121°C. Lau et al. [54] studied the chemical marker formation of 4-hydroxy-5-methyl-3(2H)-furanone (M-2) in a model food system (20% whey protein gel) to identify cumulative time–temperature effects in HTST processes at 915 MHz. The formation of M-2 occurs from D-ribose and amines through nonenzymatic browning reactions and enolization under low acid conditions ($pH > 5$). M-2 formation follows the first-order reaction kinetics and can be used for determining the cumulative heating effect in a model food system subjected to microwave heating.

However, the main limitation of using chemical marker technique in real foods is the inconsistency of food composition in the food system leading to potentially large variations in the measurements of the marker yields. In addition, heating pattern changes with food materials, placement of foods in ovens, oven design and therefore a combination of coupled thermo-electromagnetic model along with experimental measurement of marker formation could provide a better picture of microwave sterilization.

28.11 Limitations and Future of Microwave Heating

Microwave sterilization has been studied extensively in academic and industrial sectors. However, the commercialization of the process has only limited success [27]. The major drawback in the microwave sterilization is the nonavailability of actual temperature profiles. Measurement of temperatures at few locations does not guarantee the real temperature distribution of the product during microwave heating, as the heating pattern can be uneven and difficult to predict, and change during heating. Therefore, researchers in the field have found inconsistent outcomes.

Secondly, it is not always true that the microwave-assisted process results better quality retention of food products. The degradation kinetics of either quality, sensory, or nutrients depend upon many factors like nature of the food products, food geometry, dielectric properties, and oven designs as compared to conventional thermal processing. The dielectric properties of the food product significantly vary during heat processing and especially at above 80°C for protein and starches, and simultaneously the heat absorption process. These changes in dielectric properties could affect the heating pattern qualitatively, while such factors are not serious in conventional thermal processing. Coupling of heat transfer and electromagnetics could serve to account for changes in dielectric properties during thermal treatment [28].

The novelty of the microwave sterilization process depends on the proper selection of equipment and packaging, which could assure its success in food processing industries. Laboratory processing equipment is also essential for process refinement and to study the effect of process and storage time on product quality attributes, and microbiological safety factors. It is well recognized that microwave sterilization can produce high-quality shelf-stable food products. Only the most recent work had the benefit of suitable barrier packaging material. However, the earlier work recognized the need for suitable barrier material. Recently, few packaging material suppliers showed serious interest in this process.

28.12 Recommendations for Microwave Pasteurization and Sterilization

Based on views and research outcome of several experts in the field of microwave technology applied to food, the U.S. Food and Drug Administration published the following recommendations in 2002 for better heat transfer and temperature management in microwave heating:

1. Temperature distribution in food during and after microwave heating is different from that using conventional heating method. Therefore, temperature should be measured with various techniques for a more reliable record of temperature distribution. The temperature should be measured in as many places as possible to predict more accurate information and time–temperature history of the product during microwave thermal processing.
2. Information on the coldest point and its location is of primary importance for the microbial safety of sterilized food. As heating patterns can change dramatically for various food materials, different placements in the oven, and different oven designs and, since, the patterns can also change during heating, a combination of a coupled thermal–electromagnetic model complemented with experimental measurement of marker formation are needed for comprehensibility and repeatability of microwave sterilization.
3. Microwave heating uniformity of multicomponent food systems is dependent on food component placement and geometry of products and packages. Placement has the most significant effect. The temperature distribution should be balanced partly by taking advantage of edge and corner heating intensification.
4. A combination of thermal–electromagnetic model and marker formation kinetics should be used to describe microwave sterilization in a comprehensive way. Coupling of heat transfer and electromagnetics is important while considering significant changes in dielectric properties during

heating of foods. The model predictions should be verified by obtained experimental data involving chemical marker yields that are functions of the time–temperature history in the material.

5. The time–temperature history and thus the sterilization vary spatially in a very significant way. Additionally, the heating changes the relative spatial variation in sterilization. The spatial nonuniformity of sterilization and its transient changes can be improved significantly by changing the material's dielectric properties, which are a function of its composition. The effect of salt content was found to be particularly pronounced.
6. To improve the microwave heating efficiency and desirable sensory characteristics of foods, combining microwaves with other modes of heating such as infrared heating (IR) and jet-impingement can be used.
7. Applying microwave energy at a lower frequency e.g., 900 MHz would show higher penetration depths in materials such as foodstuffs.

28.13 Conclusions

Microwave energy has advantages over conventional heating. The application of microwave energy for pasteurization and sterilization has been studied for about half a century with some commercial success. Some researchers have claimed nonthermal or enhanced thermal effects to be associated with microwave heating on the destruction of microorganisms and inactivation of enzyme, but the issue still remains controversial. Continuous-flow microwaveable pasteurizers could be used for milk and juice processing. Microwave pasteurization of ready-to-eat meals has also been found to be a commercial success in the European countries although US industries are still reluctant to adopt the technology. Replacement of conventional heating by microwave energy source is not possible before fully understanding the real heating and inactivation mechanisms, temperature distribution in multilayered foods, and other critical factors. The qualitative and significant change in heating pattern has to be taken into consideration in the calculations of marker yields by coupling the electromagnetics with energy transfer in microwave sterilization. Currently, more emphasis has been given on sterilization of solid foods using microwave energy. Commercial size microwave equipment is now readily available for pasteurization and sterilization applications. Some reasons cited for the lack of commercial success in the operation are complexity, high expenditure, nonuniformity of heating, inability to ensure sterilization of the entire package, lack of suitable packaging materials, and unfavorable economics when compared to prepared frozen foods in the developed countries.

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