# Innovative Food Processing Technologies: Advances in Multiphysics Simulation

# Chapter 1

# Introduction to Innovative Food Processing Technologies: Background, Advantages, Issues, and Need for Multiphysics Modeling

Gustavo V. Barbosa-Cánovas, Abdul Ghani Albaali, Pablo Juliano, and Kai Knoerzer

## 1.1. Introduction

In a world that is demanding environmental sustainability and food security, innovation is a key requirement for the sustained growth of the food industry. Furthermore, product innovation is the response to the growing demand for value addition along with more sophisticated and diverse food products. Modern food technology provides a handful of novel processing options to explore, which could provide more diverse food industry products and more competitive and efficient processes. Many of these innovative technologies can provide new opportunities for the development of new foods and for the improvement of safety and quality of more conventionally manufactured foods through milder processing.

This book discusses innovative technologies that take advantage of physical forces and phenomena such as high hydrostatic pressure, electric and electromagnetic fields, and pressure waves, for example, high-pressure processing (also in combination with heat), microwave processing, ohmic heating, pulsed electric field (PEF) processing, ultrasound processing (liquid and airborne), and ultraviolet light (UV) processing. Innovative processing technologies present a number of hurdles that need to be addressed from concept development to implementation. In particular, proper application, development, and optimization of suitable equipment and process conditions require a significant amount of further knowledge and understanding. In this book, the basic principles, current research, challenges, and commercial applications of the respective technologies, as well as the development and application of computational fluid dynamics (CFD) and, more broadly, Multiphysics modeling as a tool for characterizing, improving, and optimizing innovative food processing technologies are covered.

Most innovative processing technologies have a common challenge, that is, to achieve a sufficient uniformity of the treatment or the process. This challenge is often already an issue at laboratory scale and it can become progressively worse when scaling up to pilot plants and, subsequently, to commercial equipment. Among other potential technology-specific issues, nonuniformity of the treatment is most commonly encountered. In fact, the nonuniformities of the process and the lack of process validation of innovative processes are the greatest limitations for industrial uptake.

Nonuniform treatment is, however, not specific to innovative processing technologies; conventional

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processing technologies often encounter the same problem. For example, in conventional heat treatment processes such as canning, the temperature at the product surface is significantly higher than at the product center during most of the processing time, and only after prolonged holding times are temperature gradients throughout the product diminished. Another clear example of nonuniformity in conventional processing is the drying process of particulates. In this case, spatial and temporal heterogeneities in temperature and water content in the food product can be even more pronounced. The product goes (1) through an initial linear drying phase with water removal from the product surface, (2) over the falling rate period with moisture flux from the inside of the product to its surface, and (3) to a stage of product and drying medium (moisture) equilibrium with almost no further change in water content. In drying food products other important factors often come into play, increasing the degree of nonuniformity: product shrinkage and reduced moisture transport (increasing viscosity of contained liquids) up to a stage where pores are blocked. In the case of many innovative processing technologies as described throughout this book, nonuniformities may be reduced through technology-specific effects. However, these nonuniformities may be more pronounced due to increased complexities influenced by additional Multiphysics phenomena.

This introductory chapter outlines the range of innovative food processing technologies covered in this book and gives a short overview of their benefits and advantages over traditional technologies. Some additional background information on the technologies, not covered in the respective technology-specific chapters, is provided. Furthermore, this chapter makes a case for the need for applying Multiphysics modeling in these technologies for their design, including scale-up and optimization. The chapter summarizes the problems and challenges faced by the modelers, particularly with respect to the prediction of temperature, flow and technology-specific field distributions (e.g., sound intensity and electric or electromagnetic fields), and the extent of microbial or enzymatic inactivation and their distribution in equipment and products.

## 1.2. Multiphysics Modeling

### *1.2.1. Definition*

Multiphysics modeling is an extension of classical CFD. By definition, CFD is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. The geometry of the modeled scenario, including all components, is discretized into finite cells on which the governing partial differential equations (PDEs), namely the continuity, momentum, and energy conservation equations, are solved. This is detailed in the chapters specific to the respective technologies. Because these are PDEs, they cannot be solved analytically. Numerical techniques, such as finite differences, finite volumes, or finite element methods, must be applied to achieve an approximated solution (Sun 2007).

Multiphysics modeling is based on the same principles as conventional CFD, that is, geometry discretization, and solving the PDEs is performed in a similar manner. However, Multiphysics modeling comprises additional physical phenomena such as electromagnetic waves, electrical fields, and acoustic waves related to the innovative technologies discussed further in this chapter. These phenomena can also be described by physically based PDEs (specific to each innovative technology), which have to be solved simultaneously with the ones from classical CFD. In some cases, the expression of the process outcome based on the attributes of the processed food, that is, the remaining microbial load, enzyme activity, and chemical reaction products, is required. Within Multiphysics modeling, reaction kinetics (i.e., microbial inactivation, quality degradation, chemical reaction, and structural responses) can be coupled with the specific differential equations to provide the spatial distributions of reaction response.

Multiphysics models that concurrently solve the PDEs of classical CFD and the additional technology-specific physical phenomena and the differential equations describing the reaction response require significantly greater computational resources. The increase in affordable computational power in recent years has allowed the simulation of innovative processes.

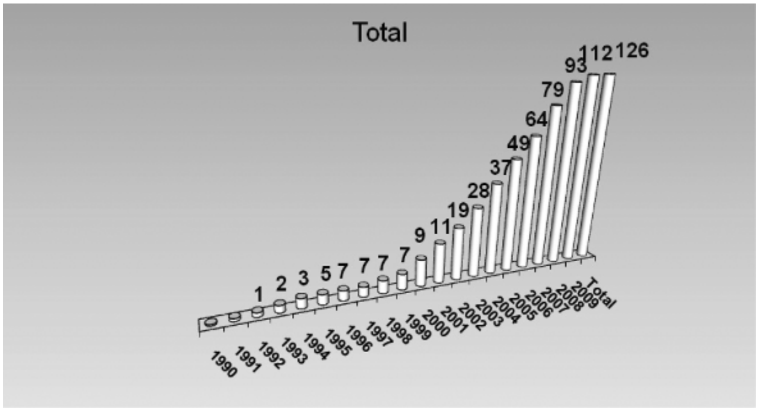

**Figure 1.1.** Number of commercial high-pressure equipment units around the world as of 2009 (Tonello 2010).

## 1.3. Innovative Food Processing Technologies

### 1.3.1. Background

This section presents a brief description of each technology covered in this book. The major design problems and application limitations of these technologies are highlighted as an introduction to subsequent chapters. Ways in which Multiphysics modeling of innovative food processing technologies can assist in their development will be discussed.

*1.3.1.1. High-Pressure Processing (HPP) and High-Pressure Thermal Sterilization (HPTS)* HPP has demonstrated wide applicability for producing high-quality foods. HPP has become accepted as an attractive alternative to traditional preservation methods utilizing preservatives or thermal processing (Hernando Saiz et al. 2008, Chapters 3–5).

HPP is commonly referred to as a nonthermal process of liquid and solid foods through application of high pressure in the order of 100–800 MPa (1,000 to 8,000 bar) and holding times of several minutes. HPP of foods is of increasing interest because it allows the inactivation of vegetative organisms at low or moderate temperature with minimum degradation (Abdul Ghani and Farid 2007). HPP offers opportunities for increased shelf life and preservative-free stabilization of meats, seafood, vegetable products, and juices. HPP can be used not only for preservation, but also for modifying the physical and functional properties of some foods.

More than 70 companies currently utilize HPP, producing more than 170,000 tons of products (Tonello 2010). Several HPP-treated food products, including juices, jams, jellies, yogurts, ready-to-eat meat, and oysters, are already widely available in the United States, Europe, Japan, New Zealand, and Australia. These successful applications have led to a pronounced increase in commercial-scale HPP units around the world during the past 10 years, as shown in Figure 1.1.

In addition to inactivation of microorganisms and some spoilage enzymes (Seyderhelm et al. 1996; Yen and Lin 1996), promising results have been obtained with respect to the application on gelation of food proteins (Ohshima et al. 1993), improvement of digestibility of proteins, and tenderization of meat products (Ohmori et al. 1991; Jung et al. 2000a, 2000b; Buckow et al. 2010b). These changes in proteins have been used successfully in fish meat; in *Carpaccio* and *Carpaccio*-like products, high pressure allows the "processing" of the product, while still maintaining its raw characteristics. However, because of the application of high pressures, these products have retained "fresh-like" qualities and texture compared with heat-processed food, are microbiologically safe, and have an extended shelf life compared with raw food. Gomez-Estaca et al.

(2009) investigated HPP on fish products (such as salmon, tuna, and cod), showing superior sensory results.

If the aim of the process is the inactivation of microbial spores, high pressure alone is not sufficient. However, a combination of high pressure and elevated temperatures, also referred to as HPTS or pressure-assisted thermal sterilization, can result in synergistic inactivation of these spores at potentially lower temperatures or shorter processing times, thus improving the quality of the processed foods while potentially reducing energy consumption (Bull et al. 2009). In this application, the increase in pressure is used as a means to increase the temperature evenly and fast in the product.

There are two approaches to achieve high-pressure conditions. In the direct approach, a piston is utilized, which compresses the content of the high-pressure chamber. In the indirect approach, a pressure-transmitting liquid (e.g., water) is pumped into the treatment chamber (high-pressure vessel) using a high-pressure pump followed by a "pressure intensifier." Liquids at extremely high pressures are compressible, requiring extra fluid to be pumped into the vessel.

During compression, the temperature of the processed food and the pressure-transmitting fluid increases due to the compression force working against intermolecular forces. The magnitude of the adiabatic temperature increase depends on a number of factors, such as the pressure medium and food product thermophysical properties (density, thermal expansion coefficient, and specific heat capacity) and initial temperature (see, e.g., Chapters 2, 4, and 5).

Higher fat content of the food and higher initial temperature, for example, lead to an increase in compression heating. The phenomenon of increasing compression heating at elevated initial temperatures is important; for example, in HPTS, the product and the pressure medium are preheated to achieve higher process temperatures, which in turn allows inactivation of microbial spores (Wilson et al. 2008).

In HPP, the greater the pressure level and time of application, the greater the potential for changes in the structure and appearance of the treated foods. This is especially true for raw high-protein foods, where pressure-induced protein denaturation may be visually evident. High pressures can also induce significant structural changes (or damages) in some sensitive foods, such as strawberries or lettuce. Cell deformation and cell membrane damage can result in softening and cell serum loss. Usually, these changes are undesirable because the food will appear to be processed and no longer fresh or raw.

**Limitations of HPP and HPTS** Although great progress has been made in the development of economically viable high-pressure applications, the scientific community and the food industry recognized in the early 2000s that engineering fundamentals, including CFD models, were required to design, evaluate, optimize, and scale up high-pressure processes of foods (Hendrickx and Knorr 2001).

The limitation of HPP to date mainly lies in the limited throughput and, relative to heat processing, the high cost of equipment, labor (HPP is not yet a fully automated process), and maintenance. High maintenance costs are caused mainly by the extreme processing conditions. Furthermore, there are only a few large-scale commercial high-pressure equipment suppliers worldwide that have expertise in the food industry, including Avure Technologies, Inc. (Kent, WA), Kobelco (Kobe Steel Ltd., Kobe, Japan), and NC Hyperbaric (Burgos, Spain).

A common issue in both HPP and HPTS is the nonuniformity of some aspects of the treatment. HPP generates pressure waves in liquids, which travel at the speed of sound (sound in water travels at 1,500 m/s). Therefore, pressure is commonly assumed to be transmitted instantaneously and uniformly. However, treatment nonuniformities can occur during HPP not only as a result of different compressibilities of the various substances in the food product, including trapped air (also headspace), but also because of the food packaging material. In addition, if the purpose of the process is the inactivation of the vegetative microorganisms, a nonuniform treatment can occur because some microorganisms are supposedly more resistant to the pressure when embedded in a fat matrix. Foods with higher fat or oil content may, therefore, protect the microorganisms in some areas in the food where fat is contained.

In the case of processing above room temperature (initial temperature), for example, in HPTS, nonuniform treatment temperature is likely to be more pronounced. In addition to pressure, temperature is an important process variable. In heterogeneous food materials, with the contents exhibiting differences in compression heating, temperatures may not be uniformly distributed in the food products. Furthermore, the packaging material, the material of the product carrier, and the steel of the high-pressure vessel are not heated to the same extent as the food; therefore, temperature gradients are developed throughout the system, leading to heat flux from the products to the cooler areas (which are mainly the steel walls). These spatial temperature heterogeneities increase over the process time. Although, theoretically, the preheated product heats up uniformly during compression to sterilization temperatures, during pressure holding time temperatures may decrease in certain areas of the vessel. This can affect spore inactivation, and spores may survive the process if temperature loss is not prevented. Product carriers have been developed as a means of retaining heat throughout the vessel during both pressure come-up and holding times (Chapter 5). Multiphysics modeling can greatly assist in the characterization of temperature distribution, subsequent microbial distributions, and other quality changes as a result of temperature inhomogeneities. These models can also be applied to the redesign and optimization of equipment and determination of adequate processing conditions for optimum process/product performance.

*1.3.1.2. Microwave and Radio Frequency Processing* Microwave heating refers to the use of electromagnetic waves of certain frequencies to generate heat in a material (Metaxas and Meredith 1983; Roussy and Pearce 1995; Metaxas 1996). Typically, microwave food processing uses frequencies of 2,450 and 915 MHz. In domestic ovens, 2,450 MHz frequency is commonly utilized, while in industrial heating application both frequencies are used, depending on the product to be treated, that is, product size and composition, associated with the relevant thermophysical properties (Chapters 2, 6, and 7).

Microwave heating has been proposed as an alternative to traditional heating methods in many food manufacturing processes, such as (re)heating, baking, (pre)cooking, tempering of frozen food, blanching, pasteurization, sterilization, and dehydration (Metaxas and Meredith 1983; Decareau 1985; Buffler 1993; Metaxas 1996; Schubert and Regier 2005; Tang et al. 2008).

Microwave and radio frequency heating for pasteurization and sterilization are rapid; therefore, less time is required for come-up to the desired process temperature compared with conventional heating. This is particularly true for solid and semisolid foods that depend on slow thermal diffusion process in conventional heating. Microwave and radio frequency heating can approach the benefits of high-temperature short-time (HTST) processing, whereby bacterial destruction is achieved, while thermal degradation of the desired components is reduced.

Heating with microwaves primarily involves two mechanisms. Water in the food is often the main component responsible for dielectric heating. Due to their dipolar nature, water molecules follow the alternating electric field associated with electromagnetic radiation. The second major mechanism is through the oscillatory migration of ions in the food under the influence of the alternating electric field. Such oscillatory motion of water molecules and ions and the associated intermolecular friction lead to a conversion of electromagnetic energy to thermal energy.

The dielectric properties, namely the dielectric constant and the loss factor (Chapter 2), determine the strength of the electric field inside the food and its conversion into heat. These properties strongly depend on the composition (or formulation) of the food, with moisture and salt being the two primary determinants of interest (Mudgett 1985, 1986; Sun et al. 1995; Nelson and Datta 2001). The subsequent temperature rise in the food depends on the duration of heating, the location in the food, convective heat transfer at the surface, and the heat conduction and extent of evaporation of water inside the food and at its surface.

Although the final objective of each process differs, an increase in product temperature is seen as a common theme. There has also been some speculation on the so-called nonthermal effects of electromagnetic waves in the microwave frequency range. Four theories have been proposed to explain "nonthermal" or nondirect thermal effects of microwaves on, for example, microorganisms: selective heating, electroporation, cell membrane rupture, and magnetic field coupling (Kozempel et al. 1998). The selective heating theory states that solid microorganisms are heated more effectively by microwaves than the surrounding medium and are thus killed more readily. Electroporation is caused when pores form in the membrane of the microorganisms due to electrical potential across the membrane, resulting in leakage (this is similar to one of the theories on the effect of PEF processing for cold pasteurization). Cell membrane rupture is related to the voltage drop across the membrane, which causes it to rupture, which is also a theory in PEF processing. In the fourth theory, cell lysis occurs due to coupling of electromagnetic energy with critical molecules within the cells, disrupting vitally important internal cell components.

Although researchers have repeatedly reported nonthermal effects of microwave processing, the general consensus (Heddleson and Doores 1994; Heddleson et al. 1994) is that the reported nonthermal effects are likely to be due to the lack of precise measurements of the time–temperature history and its spatial variations. A number of studies have shown that thermal effect is the essential contributor to the destruction of microorganisms (Goldblit and Wang 1967; Rosen 1972; Fujikawa et al. 1992). Therefore, to date, it is presumed that only thermal effects on microbial inactivation are effective, and microbial inactivation caused by microwave processing is essentially the same as in conventional thermal processing. Of course, the rates of heating and temperature distributions are quite different.

**Limitations of Electromagnetic Heating** Volumetric microwave and radio frequency heating is theoretically more uniform than conventional heating (Datta and Hu 1992). There are, however, a number of microwave-specific factors that induce nonuniform heating patterns. First, electromagnetic field distribution inside a microwave cavity is, in most cases, not uniform. Placing dielectrics (i.e., food products) into the microwave field leads to a change in the field distribution. Therefore, differences in the products, for example, product size, shape, and particularly composition with varying dielectric properties, will almost certainly lead to changes in process outcomes. However, not only do the field variations in the cavity cause nonuniform processing, the field characteristics inside the product are also heterogeneous.

The heterogeneous composition of the different food components (and different dielectric properties) is an important factor in the heating of foods. Differences in dielectric properties lead to differences in temperature increases, even in a perfectly homogeneous microwave field. As these properties are in most cases strongly temperature-dependent, changes in temperature may compensate or may increase the nonuniformity. In particular, in cases where increasing temperatures lead to increasing loss factors (the imaginary part of the complex dielectric permittivity; Chapter 2), a so-called thermal "runaway" phenomenon can occur. With increasing temperature the rate of converting the electromagnetic energy into thermal energy increases as well; therefore, the gradients between hot and cold areas in the product become more pronounced.

Another important factor in heating is the so-called focusing effect of the microwaves into specific areas in the product. This phenomenon is strongly dependent on the geometrical properties of the product. For example, a spherical product that does not exceed a certain size (due to limited penetration) can exhibit a pronounced hot spot in its geometrical center.

Other phenomena causing uneven heating patterns include edge and corner overheating (caused by the penetration and absorption of the microwaves from more than one direction) and the development of standing waves inside the product (which is mainly dependent on the dielectric constant (the real part of the complex dielectric permittivity; Chapter 2).

The time–temperature history at the coldest point for a conventional thermal process is generally predictable for a food that is all solid or all fluid. For example, for a conduction-heated (solid) food, it is usually the geometric center. In microwave heating, even for a solid food, it is less straightforward to predict the coldest point and it can change during the heating process depending on temperature-dependent material properties and oven characteristics (Fleischman 1996; Zhang et al. 2001).

A number of approaches have been proposed to improve the uniformity associated with microwave heating. These include rotating and oscillating the food in the microwave cavity (Geedipalli et al. 2007), providing an absorbing medium (such as hot water) surrounding the product (Chen et al. 2008; Chapter 6), equilibrating after heating (Fakhouri and Ramaswamy 1993), and cycling the power (Chapter 7). Success to date is limited due to the dependence of the materials' properties on temperature and the nonuniform distribution of the electromagnetic field inside the food and the microwave cavity. Utilizing a lower microwave frequency of 915 MHz and radio frequencies to improve uniformity of heating have the potential to improve the evenness of heating (Chen et al. 2008), as the penetration depth into the food is greater and the field nonuniformities are less pronounced. Combinations of microwave and conventional technologies in many different configurations (e.g., hot air, vacuum, or infrared heating) have also been used to improve treatment uniformity; (Contreras et al. 2008; Turabi et al. 2008; Abbasi and Azari 2009; Kowalski and Mierzwa 2009; Kowalski and Rajewska 2009; Seyhun et al. 2009; Uysal et al. 2009). These approaches can be successful for some applications, especially where the cold spot is located at the food surface (Chapter 7); however, in food products with high salt or sugar content, the cold spot is usually within in the food, as the penetration depth of the electromagnetic waves is reduced.

It remains a challenge to uniformly treat food products with microwaves and to achieve the targeted process outcomes; Multiphysics models, however, will greatly assist in designing microwave processes by evaluating process performance and developing appropriate control strategies (Chapters 6 and 7). Accordingly, Multiphysics models (including temperature-dependent properties of foods) need to be developed and subsequently validated to ascertain the location of the point of lowest integrated time–temperature history (Chapter 7).

*1.3.1.3. Ohmic Heating* Ohmic heating is defined as a process wherein electric currents are passed through foods or other materials with the primary purpose of heating them. The heating occurs in the form of internal electric energy dissipation within the material. Ohmic heating is distinguished from other electrical heating methods by the presence of electrodes contacting the food, the frequency of the current, or the waveform. The main purpose for the development of ohmic heating processes was to allow for HTST sterilization of solid–liquid mixtures (Chapter 8).

Applications of ohmic heating in the food industry to date are scarce, although there are a number of advantages over other (conventional) heating methods. The main advantages for ohmic heating are the associated rapid and relatively uniform heating of the food product, depending on the electrical conductivity of the food components. This is expected to reduce unwanted thermal effects on the product that often occur in conventional heating applications, caused by the need to heat the product by the transfer of thermal energy from a heating medium to a low temperature product, where excessive treatment times are necessary for sufficient heat penetration from the surface of a solid product to its core.

Potential applications for ohmic heating include its use in blanching, evaporation, dehydration, fermentation, and extraction. At present, the primary type of application is a heat treatment for microbial control, for example, for the pasteurization of milk, and also for processing of sauces, fruits, and tomatoes (Chapter 8).

The principal mechanisms of microbial inactivation in ohmic heating are thermal in nature. Recent literature, however, indicates that a mild electroporation mechanism may occur during ohmic heating (similar to the effects utilized in PEF processing (Lebovka et al. 2005; Kulshrestha and Sastry 2006). The principal reason for the additional microbial inactivation effect to heating of ohmic treatment may be its low frequency (50–60 Hz), which allows cell walls to build up charges and form pores. This is in contrast to high-frequency methods such as microwave or radio frequency heating, where the electric field is essentially reversed before sufficient charge buildup occurs at the cell walls.

Nevertheless, temperature is the principal critical process factor in ohmic heating. As in conventional thermal processes, the key issue is identifying the slowest heating zone. Fundamentally, there is only one critical factor: the temperature–time history of the coldest point. Since the primary critical process factor is the thermal history and location of the cold spot, the effects on microbial inactivation are the same as for thermal processes. Locating the slowest heating zones during ohmic heating, however, cannot be extrapolated from current knowledge of conventional heating, and requires special consideration.

Several factors significantly affect the temperature within an ohmic process. The critical parameters in continuous flow ohmic heating systems include electrical conductivities of the respective phases of the food, temperature dependence of the electrical conductivity, design of the heating device (e.g., location and orientation of the electrodes), extent of interstitial fluid motion, residence time distribution, thermal properties of the food, and electric field strength (Chapter 8).

**Limitations of Ohmic Heating** The main limitation of ohmic heating is the heterogeneous nature (in composition) of the food products and their corresponding electrical conductivities that leads to differences in the conversion of the electrical current into thermal energy. As in microwave heating, in ohmic heating, thermal runaway can also occur, because electrical conductivity, which is the property that influences electrical energy dissipation, usually increases with increasing temperature. Therefore, especially in stationary (i.e., not moving in a stream) solid products, there may be areas that are very hot (usually areas close to the electrodes), which in some instances may even be burned, while in other areas (with initially lower electrical conductivities, or farther away from the electrodes) almost no heating occurs.

Uniform heating with ohmic processing is theoretically possible, but at the same time challenging due to the various factors impacting on the slowest heating zone and the time–temperature history throughout the product. Multiphysics modeling (including the temperature-dependent properties of the foods: mainly the electrical conductivity) can greatly assist the evaluation and optimization of ohmic heating systems to achieve heating uniformity (Chapter 8).

*1.3.1.4. PEF* PEF processing is an innovative nonthermal processing technology mainly for liquid and pumpable foods (including emulsions, suspensions, and semisolids such as sausage meat), predominantly used for the inactivation of microorganisms at ambient or mild temperatures, thereby preserving the fresh flavor, color, functional properties, and integrity of heat-sensitive compounds (Chapters 9–11). PEF can also be used to enhance extraction yield of juices and bioactives from plant sources. PEF is one of the most appealing nonthermal technologies for preservation of liquid foods due to reduced heating effects compared with traditional pasteurization methods (Barbosa-Cánovas et al. 1999).

In PEF processing, a liquid or other pumpable material is passed through an electrode arrangement where the PEF is applied. For microbial inactivation, foods are processed by means of brief pulses of a strong electric field with field strengths of around 15–40 kV/cm. For extraction of plant materials and pretreatment of meat for processing, only about 0.7 to 3 kV/cm is required (Toepfl et al. 2006). The utilization of PEF leads to the formation of pores (the so-called electroporation [temporary or permanent]), in the membranes of microbial or plant cells, which disturbs and damages the membrane's functionality, leading to inactivation of the cells and the partial release of the cell contents to make extraction or other processing more efficient.

Membrane disruption occurs when the induced membrane potential exceeds a critical value of 1 V in many cellular systems, which, for example, corresponds to an external electric field of about 10 kV/cm for *Escherichia coli* (Castro et al. 1993). The most relevant factor affecting microbial inactivation and extraction enhancement by PEF is, therefore, the electric field intensity. The combination of electric field intensity, total treatment time during PEF and pulse shapes, and the associated temperature increase determine the extent of membrane disruption in bacterial and plant cells (Hamilton and Sale 1967). Other factors affecting the performance of the PEF process include the microbial entity to be inactivated (type, concentration, and growth stage of microorganism) and the treatment media (pH, antimicrobials, and ionic compounds, electric conductivity, and medium ionic strength).

PEF produces products with slightly different properties from conventional pasteurization treatments. Most enzymes are not affected by PEF. The fact that the maximum temperature reached is lower than in thermal pasteurization means that some of the flavors associated with the raw material are not destroyed. Spores, with their tough protective coats, and dehydrated cells are mostly able to survive PEF processing. The survival of spores and enzymes means that products have to be refrigerated after passing through PEF processing in order to slow the action of the enzymes and keep pathogens from growing; PEF alone is generally not capable of producing ambient shelf-stable products. However, acidic well-packaged products may have a useful ambient shelf life.

As indicated before, another potential application of PEF, which is gaining increasing interest, is the utilization of the technology for enhanced extraction of plant cell material. Because PEF induces electroporation in cell walls at relatively low energy inputs, allowing the cell contents to leak out, it holds promise as an efficient way of getting useful components out of cells and cell membranes (Corrales et al. 2008; Lopez et al. 2009a, 2009b; Loginova et al. 2010; Puertolas et al. 2010).

To date, however, PEF has been mainly researched to preserve the quality of foods, such as to improve the shelf life of orange juice, apple juice, milk, and liquid eggs, as well as the fermentation properties of brewer's yeast. Martín-Belloso and Soliva-Fortuny (2010) have summarized the work of several researchers on food-borne pathogenic microorganisms in different food products.

**Limitations of PEF Processing** Issues that may arise with PEF include electric arcing, dielectric breakdown of the treated food, and a pronounced temperature increase (caused by ohmic heating). Several factors play a role here, including the material's electrical conductivity, the frequency of the pulses, their duration (width), adequacy of deaeration, back pressure, and the flow rate of the liquid (laminar or turbulent flow regime; residence time in the treatment chamber). Because the pulse duration is only in the range of microseconds and, therefore, the overall treatment time is short, temperature increases during treatment are often assumed to be minimal and temperature effects neglected in inactivation studies.

In processing liquids with PEF, a nonuniformity of the treatment can be a result of the interaction between the flow, heat transfer, electric field phenomena, and effects on microbial or plant cells. Predictions of the increase in temperature caused by the electric field are similar to ohmic heating and less complicated compared with the dissipation of electromagnetic energy in microwave processing. Moreover, the property influencing this dissipation effect, that is, the electrical conductivity, is easier to measure, and usually shows a less complex behavior with temperature than the two dielectric properties in microwave processing, that is, the dielectric constant and the loss factor (Chapter 2).

However, the purpose of the pulsed (potentially alternating) electric field is, unlike in microwave processing, not an increase in temperature. The temperature increase should be minimized in most PEF applications. The main aim is a nonthermal inactivation of vegetative microorganisms for cold pasteurization or a nonmechanical means of opening cells for enhanced extraction. In particular, for the purpose of cold pasteurization, a great degree of electric field uniformity is needed to ensure a similar treatment of the entire liquid product. Ideally, the same number of electric pulses and electric field strength is applied to all microorganisms present in the liquid. Typically, pasteurization requires inactivation of up to 99.999%, that is, 5 log of the target organism. If only a small fraction of microorganisms bypass proper treatment through regions of low electric field strength, it is not possible to reach the required extent of inactivation.

Achieving this uniformity, however, is very challenging; the electric field distribution is strongly dependent on the configuration of the treatment chamber (and to a lesser extent on the electrical conductivity and other thermophysical properties of the processed media). PEF chamber designs such as co-field, coaxial, or colinear electrode arrangements (Chapters 9–11) exhibit pronounced nonuniformities in flow, temperature, and electric field distributions. Uniform fields can be achieved in parallel plate configurations, which are mainly applied for batch processing. If the field is not uniform, the induced temperature increase is also uneven across the volume of the treatment chamber. Often, several treatment cells are arranged to process in series, which reduces the effects of imperfections in single treatment cells.

Thus, in processes for inactivation of specific microorganisms that show synergistic effects of temperature and electric field on inactivation, temperature nonuniformities will lower the performance of the process. Nonuniformities can be minimized, but to some extent will always occur.

To enable a comparable treatment history of the entire product, the flow pattern is very important. Laminar flow conditions, which can be found in low-throughput laboratory-scale systems, are to be avoided. In laminar flow, each microorganism follows a more or less straight path through the treatment chamber; therefore, pronounced differences in exposure to varying electric field strengths and temperatures will occur. Modifying the treatment chamber with grids (Chapter 10) or increasing the flow rate to give turbulent flow (Buckow et al. 2010a) can improve the uniformity of exposure of the product to the important treatment variables (e.g., temperature and electric field strength) and furthermore improve temperature uniformity due to increased (turbulent) thermal conduction and convective flows.

For characterizing process performance, information on the field distributions is essential. However, such local information inside the chambers is difficult and near to impossible to obtain experimentally. For further development of the PEF technology, numerical simulations can be applied to improve the fundamental understanding of the physical phenomena in the process and to optimize it with respect to the chamber design and operating conditions (Gerlach et al. 2008; Chapters 9–11).

*1.3.1.5. Ultrasound Processing* This technology is based on pressure waves at frequencies exceeding 20 kHz, that is, more than 20,000 vibrations per second. It is considered as another innovative process that has been investigated for many different purposes over the last decades. While in the earlier work mainly the lower frequencies of around 20 kHz were studied, research and applications currently include frequencies of several hundred kHz, to several MHz (Chapter 12).

Ultrasound systems consist of a generator for turning electrical energy into high-frequency alternating current, a transducer for converting the alternating current into mechanical vibrations, and a delivery probe for conveying the sonic vibrations into a medium to couple sonic vibrations to the treated material. The transducers may take the shape of a rod, plate, bar, or sphere, and are usually manufactured from titanium, aluminum, or steel.

The ultrasonic transducer can be mounted outside on the wall of a vessel or flow cell and be in indirect contact with foods, or it can be inserted into a treatment chamber or flow cell of specified geometry to transmit energy directly into a food system with better energy efficiency (Feng and Yang 2005). There are also transducers that are designed for effective transmission into air (Chapter 13).

Ultrasound has attracted considerable interest in the food industry due to its useful effects in food structure modification (e.g., emulsification, extraction, crystallization, and viscosity alteration), food preservation, and enzyme modulation (Patist and Bates 2008). As one of the innovative and advanced food processing technologies, it can be applied to develop gentle but targeted processes to improve the quality and safety of processed foods and, thus, offers the potential for improving existing processes as well as for developing new process options.

Ultrasound alone has some effects on the inactivation of vegetative organisms in liquid food products. The bactericidal effect of ultrasound is generally attributed to intracellular cavitation (Hughes and Nyborg 1962). It is proposed that micro-mechanical shocks and jet streaming are created by microscopic cavitation bubbles induced by the fluctuating pressures under the ultrasonication process (Chapter 12). These shocks and microjets disrupt cellular structural and functional components up to the point of cell lysis.

Positive effects have been observed when ultrasound is used in combination with temperature (thermo-sonication) or pressure (mano-sonication) or both (mano-thermo-sonication) in the inactivation of pathogenic bacteria, spoilage microorganisms, and enzymes (Cameron et al. 2009; Demirdoven and Baysal 2009; Lee et al. 2009). The use of temperature and ultrasound together has been successful in reducing the enzymatic activity in some target products such as juices, providing better stability during storage (Terefe et al. 2009). Sonicated milk is the most explored product; it shows positive results in pasteurization standards, better homogenization and color, as well as new physical properties for the development of dairy products (Chouliara et al. 2010).

Most developments of ultrasound for food applications are nonmicrobial in nature, that is, their main aim is not inactivation of microorganisms (Hoover 1997). High frequencies in the range of 0.1 to 20 MHz, pulsed operation, and low power levels (100 mW) are used for nondestructive testing (Gunasekaran and Ay 1994). These industrial applications include texture, viscosity, and concentration measurements of many solid and fluid foods; composition determination of eggs, meats, fruits and vegetables, dairy, and other products; thickness, flow level, and temperature measurements for monitoring and control of several processes; and nondestructive inspection of egg shells and food packages.

Apart from testing applications, process improvements have been observed in applications such as cleaning surfaces (Tolvanen et al. 2009), enhancement of dewatering, drying and filtration, inactivation of microorganisms and enzymes, disruption of cells, degassing of liquids, emulsification, accelerating heat transfer and extraction processes (Patist and Bates 2008; Vilkhu et al. 2008), enhancement of processes dependent on diffusion (e.g., enzyme activity, targeted infusion of small compounds into porous food matrices), and also targeted movement of two-phase systems, such as oil droplets or particles dispersed in a continuous aqueous phase (Doblhoffdier et al. 1994; Hawkes et al. 1997; Groschl 1998). It is evident that ultrasound technology has a wide range of actual and future applications in the food industry.

More recently, research activities related to the sonochemistry in certain foods products have gained interest, involving the reactions that ultrasound generates in food during processing. Jambrak et al. (2009) show that these chemical reactions can be used to generate new compounds in food for specific purposes such as the modification of proteins. Hydroxylation of phenolic compounds to enhance their antioxidant properties has also been studied by Ashokkumar et al. (2008).

Another interesting application is the use of airborne ultrasound for enhanced drying of food products. Difficulties in the propagation of ultrasound waves in air and the impedance mismatch at the transducer/air interface have led to the development of especially adapted transducers that have been applied, for example, to drying of carrots, lemon peel, and other food products (Garcia-Perez et al. 2009; Chapter 13).

**Limitations of Ultrasound Processing** Although potential applications of ultrasound processing are many and diverse, the uptake by industry to date is not widespread. Reasons for this include a lack of knowledge of ultrasound intensity distribution in tank systems and, particularly, in flow-through systems, where the forced convection disturbs the ultrasound field, as well as the effect of the pressure waves on the food product. Depending on the equipment, with the generators, the transducers, treatment cells, the frequency and power of the ultrasound waves, and the product properties, the effect of ultrasound can differ significantly.

Ultrasound processing comprises another Multiphysics phenomenon: the acoustic field. Several factors must be considered, for example, ultrasound frequency, intensity, the associated speed of sound and sound absorption, and impact on the acoustic field. Although the speed of sound in a homogeneous medium is independent of the sound wave frequency and intensity, varying composition of the treated product strongly impacts the speed. The sound absorption is dependent on the composition as well as the frequency and intensity of the ultrasound waves. In addition to this, occurring cavitation (Chapter 12) significantly influences the speed of sound, the sound absorption and, therefore, the acoustic field distribution. The speed of sound in a cavitating medium can, for example, decrease from a value of 1,500 m/s to values as low as 20 m/s.

As discussed in Chapter 12, the ultrasound waves in a cavitating medium can be completely absorbed by the cavitation bubbles in the close vicinity of the ultrasound transducer and, therefore, large parts of the sonoreactors may not undergo ultrasound treatment. Although this pronounced absorption leads to the conversion of the sound energy into motion and the formation of a turbulent jet, which could in turn result in the treated liquid being well-mixed and, therefore, undergoing a similar treatment over time, the presence of solid products, which due to size and different densities cannot completely follow the flow, may induce further treatment nonuniformity.

During ultrasound processing, standing waves (the so-called bands) can occur. This formation of bands can be an intended desirable effect, for example, for separating multiphase products such as emulsions. In other cases, where the sound waves are meant to induce other effects, such as cell disruption, sono- or biochemical reaction, the standing waves can unintentionally impair the process performance.

Hence, generic Multiphysics models, including acoustics, heat and fluid flow and, potentially, coupling to the kinetics of food transformation, enhanced diffusion, microbial interaction, and enzyme modulation need to be developed. Such models can assist in process design, scale-up and optimization and subsequent uptake of the technology by the food industry.

*1.3.1.6. UV Processing* UV light for food processing has been investigated for many years but is still considered as an innovative technology in food processing. In this technology, UV-C light (wavelength of 254 nm) is predominantly being used as a disinfection method to inhibit or inactivate foodborne microorganisms, mainly in liquid food products (Chapters 14 and 15). Fresh produce can be processed using UV light, which has a germicidal effect on many types of microorganisms (bacteria, viruses, protozoa, molds, and yeasts). However, the effect of UV light on microorganisms in liquids depends on variables such as density of the liquid, types of microorganisms, UV-C absorptivity of the liquid, and the solids (suspended or soluble) in the liquid.

Although the use of UV light is well established for air and water treatment and surface decontamination, its use for treating liquid foods is still limited. Recently, interest in using UV has increased as a viable alternative to thermal pasteurization for a range of liquid foods and ingredients (fresh juices, fruit purees, soft drinks, raw milk, liquid eggs, liquid sugars and sweeteners, etc.) (Koutchma 2009). Pumpable fruit and vegetable products are generally very suitable for processing by UV light to reduce the microbial load (Guerrero-Beltran and Barbosa-Cánovas 2004) as long as sufficient fluid mixing allows the entire product to be exposed to a certain required dose of UV radiation. The germicidal properties of UV irradiation are mainly due to DNA damage induced through absorption of UV light by DNA molecules. This mechanism of inactivation results in a sigmoidal curve of microbial population reduction (Bolton 1999).

UV treatment can be used for primary disinfection or as a backup for other purification methods such as carbon filtration, reverse osmosis, or pasteurization. As UV has no residual effect, the best position for a treatment system is immediately prior to the point of use. This ensures that any incoming microbiological contaminants are destroyed and that there is little chance of post-treatment contamination.

In addition to UV-C light, UV light with wavelengths other than 254 nm can also be used as a radiation source to inactivate microorganisms in foods (liquids or solids). In general, wavelengths ranging from 100 (UV-V, vacuum UV light) to 400 nm (UV-A) are suitable for UV light processing (Bintsis et al. 2000; Sastry et al. 2000).

UV disinfection has many advantages over alternative methods. Unlike chemical treatment, UV does not introduce toxins or residues into the process and mostly does not alter the chemical composition, taste, odor, or pH of the water or liquid being disinfected. As a physical method, UV irradiation has a positive consumer image and is of interest to the food industry as a low-cost nonthermal method of preservation. Recent advances in the science and engineering of UV light irradiation have demonstrated that this technology holds considerable promise as an alternative method to traditional thermal pasteurization for liquid foods and ingredients, fresh juices, soft drinks, and beverages.

**Limitations of UV Processing** Compared with water, liquid foods have a range of optical and physical properties, diverse chemical compositions, and solid-phase characteristics (particle size and size distribution, shape and volume fraction), influencing UV light transmittance (UVT), dose delivery, momentum transfer (laminar or turbulent flow), and consequently microbial inactivation (Koutchma 2009; Chapter 14). As there is no practical method for evaluating the spatially resolved performance experimentally and predictions of the process performance are not straightforward for liquid foods (compared with water), Multiphysics modeling is essential for evaluating particles and fluid velocities in the UV reactor, particle mixing, particle location, residence times, UV fluence rate (irradiance) distribution and resulting changes in bacterial count.

As mentioned, UV is mainly useful for surface decontamination (e.g., on fresh produce) and for disinfection of liquids transparent to the UV light to a certain extent. Although consisting of electromagnetic waves, the penetration of UV light into opaque substances is limited at these wavelengths. Therefore, microorganisms on the surface of products can be protected by the so-called shadowing effect, caused, for example, by overlapping parts of the products. Treating opaque liquids is impossible under laminar flow conditions as the product flowing through the center of a UV transparent glass tube will not "see" the UV light. Providing a highly turbulent flow, however, can allow sufficient treatment uniformity, as all particles will likely be close to the glass walls at least for a certain period of time. Residence time in such a flow reactor must be sufficiently long to ensure similar treatment histories of the entire liquid product. Multiphysics modeling can assist in the UV chamber design and optimizing process conditions according to the absorptivity and other properties of the fluid, while assuring a similar treatment history of all portions of the liquid or dispersion.

In all technologies and their associated specific issues regarding nonuniformity discussed in the previous sections, Multiphysics modeling can assist in providing insights into the internal distribution of processes in treatment chambers and products. It can be utilized to improve the systems design, performance, optimization, and scale-up to commercial applications by reducing inhomogeneities and for the process to become acceptable and viable.

## 1.4. Modeling Challenges

Previous sections have described a number of limitations encountered in innovative food processing technologies and how Multiphysics modeling can assist in overcoming them. However, there are practical complexities in modeling and validating models for these technologies that will be covered in this section.

### *1.4.1. Modeling Complexity in Innovative Processing*

As mentioned earlier in this chapter, modeling innovative processing involves additional physics phenomena to conventional CFD. This implies that the fundamental conservation equations from thermofluiddynamics need to be coupled with the PDEs to describe the respective field phenomena (i.e., electromagnetic, electric, and acoustic fields), thereby providing considerably increased complexity.

Developing a Multiphysics model requires the same steps as developing a CFD model (Sun 2007), for example, the geometry definition, where all objects in the model scenario are constructed and assembled in the modeling software package or imported from a computer-aided design (CAD) drawing of the system (treatment chamber, peripheral devices, piping, food, packages, etc.). In particular, the materials forming the complete computational domain (i.e., the processing system), commonly referred to as subdomains, may include solids, liquids, and gases. The next step is discretization, that is, approximating the computational domain by finite cells. Next, material specific thermophysical properties need to be allocated to each subdomain as functions of the process variables (e.g., temperature and pressure; Chapter 2) and initial conditions and boundary conditions need to be defined. Furthermore, the model needs to specify time dependency, whether they are transient or stationary.

The main differences between conventional CFD and Multiphysics modeling are as follows:

- The geometry discretization step often needs more details than in conventional CFD. For example, in electromagnetics modeling with the finite difference method 15 cubic cells per wavelength have been recommended (QWED Sp.z o.o. 2003). In microwave processing at 2.45 GHz, with a wavelength in vacuum of around 12 cm, the maximum mesh cell size should therefore be below 1 mm (edge length). Furthermore in modeling an acoustic field with the finite element method, the resolved three-dimensional (3D) mesh should have at least 12 degrees of freedom per wavelength for each possible direction of the wave (i.e., the degrees of freedom of the complete mesh in three dimensions should be 1,728 times the model volume in wavelengths). Higher frequencies, with shorter wavelengths, therefore, limit the feasible volume of the model scenario (COMSOL Multiphysics 2007).
- As discussed in Chapter 2, there is a lack of thermophysical property data of foods, in particular expressed as a function of the process variables needed for model accuracy. As will be shown, more properties are needed to model innovative processes than conventional processes.
- Each boundary condition will have to be defined for each Multiphysics phenomenon as a requirement to solve PDEs at the interface of each subdomain.
- In most cases, when relatively high frequencies are involved (PEF, ultrasonic processing, ohmic heating, microwave, UV), time resolution of the respective waves is not feasible due to the short time scales (i.e., a higher frequency gives smaller time scales) across the domain. Therefore, an integrated value from the steady-state solution of the wave equation is often used as a source term in the conservation equations for momentum and energy.

Multiphysics models are highly nonlinear mathematical problems. With each additional PDE, the degree of nonlinearity increases. Depending on the mesh, the thermophysical properties (as functions of the process variables), and the number of physics phenomena being coupled, the difficulty for convergence of the model may increase. When that is the case, models may not be as robust as those developed utilizing classical CFD PDEs.

### 1.4.2. Validation of Multiphysics Models

Validation is an essential step to complete the modeling process. Models used for prediction of process variables and their distributions may converge, suggesting solutions that might be plausible, but in fact are not accurate (Nicolaï et al. 2001). Therefore, particularly in the case of highly nonlinear Multiphysics problems, the numerical solutions must always be validated before using them for further studies, such as equipment and process redesign, optimization, or scale-up. The validation process involves the comparison of predicted data (i.e., temperature, velocities, inactivation extent, and chemical or physical change) with measured data. This can be done using two approaches: (1) direct validation of process variables; or (2) indirect

**Table 1.1.** Tools for the validation of Multiphysics models.

| Technology | Process variable or outcome to validate | Direct (D)/ Indirect (I) | Method | Chapter or reference |
|---|---|---|---|---|
| High-pressure processing | Temperature | D | Thermocouples, wireless temperature logger | Chapter 5 |
| | | I | Enzymatic or other temperature time integrator (TTI), liquid crystals | (Pehl et al. 2000; Grauwet et al. 2010a, 2010b) |
| | Fluid velocity | D | High-pressure PIV | (Pehl and Delgado 1999) |
| | Indicator | D/I | Enzymatic, microbial, colorimetric determination methods among others | (Denys et al. 2000) |
| Microwave, ohmic heating | Temperature | D | Thermocouples, fiber-optic probes | Chapters 7 and 8 |
| | | I | MRI, infrared thermography, microwave radiometry, time temperature integrators, liquid crystals | Chapters 6–8 |
| | Fluid velocity | D | PIV (particle tagging), LDA | Chapter 8 |
| | Indicator | D/I | Enzymatic, microbial, colorimetric determination methods among others | Chapter 6 |
| Pulsed electric field (PEF) | Temperature | D | Thermocouples (not in the area of high-electric field strength), fiber-optic probes | Chapter 10; (Buckow et al. 2010a) |
| | | I | Enzymatic TTI | — |
| | Indicator | D/I | Enzymatic, microbial, colorimetric determination methods among others | Chapter 11 |
| Ultrasound | Temperature | D | Thermocouples (type K) | — |
| | Fluid velocity | D | PIV, LDA | Chapter 12 |
| | Acoustic intensity | D | Hydro- and microphones | Chapter 13 |
| | | I | Qualitative visual (cavitation fields, band formation of particles), chemical markers | (Klima et al. 2007; Sutkar and Gogate 2010) |
| | Indicator | D/I | Enzymatic, microbial, colorimetric, determination methods among others | — |
| Ultraviolet (UV) | Fluid velocity | D | PIV, LDA | (Hofman et al. 2007) |
| | Indicator | D/I | Microbial (also referred to as biodosimetry), colorimetric, determination methods among others | Chapters 14, 15 |

validation by means of a (bio)chemical or microbial indicator. Table 1.1 classifies the indirect and direct validation tools to determine the process variables or outcomes for each technology.

Direct measurements include:

- temperature measurements by utilizing resistance thermometers, thermocouples, or fiber-optic sensors
- flow measurement by means of Laser Doppler Anemometry (LDA) or Particle Imaging Velocimetry (PIV)
- sound intensity by means of hydro- or microphones
- particle (size) change by measuring particle size distribution, for example, with a Focused Beam Reflectance Measurement (FBRM) device.

The direct measurement of other process variables, such as electric and electromagnetic field distribution, including, for example, microwave and UV light, is often not feasible in the constrained space of the respective processing equipment. However, the process outcomes, such as microbial inactivation, nutrient degradation, structural changes, and material separation, are the true process indicators. Unless they are spatially resolved, these only give overall outcomes and are of no or limited value to validate local variations in a treatment cell or zone.

An indirect measurement involves the evaluation of enzymatic, microbial, color, chemical, or any other biological or physical change that represents a change in temperature or any other process variable when typical measurement devices cannot be utilized. For example, temperature distribution changes after microwave sterilization can be measured using whey protein and measuring Maillard reaction components at different locations (Chapter 6). Another example is the use of magnetic resonance imaging (MRI) to measure the change in proton resonance frequency, referred to as chemical shift, to establish 3D temperature distribution changes (Chapter 7). Methods for validation will be covered in more detail in the following chapters.

Once the data of the measured process variables or process outcomes are gathered, there are different ways of comparing simulated with measured data. A common method to validate transient simulations is the comparison of profiles at specific points of the modeling domain, which are measurable. Another approach is to compare model and measured data at several specific time and location coordinates (in a 2D or 3D grid) throughout the process period in a parity plot, for example, represent measured temperature versus simulated ones at identical locations and selected times in a plot (e.g., Knoerzer et al. 2007, 2008). Comparison of 2D or 3D distributions requires working in matrices.

Distributions of inactivation or chemical or physical changes cannot be validated through direct measurements at selected points. The study of a certain volume in packages containing an initial amount of substance can partially resolve this problem. By this method overall averages for the whole vessel or vessel areas where packages are located are calculated from the predictions in the model. For example, Chapter 5 shows a case where a relative activity ratio (Eq. 5.16) is utilized to determine enzyme inactivation distributions after HPP.

## 1.5. Concluding Remarks

After examining the literature, we note that only some of the Multiphysics models developed to describe innovative processing technologies have been thoroughly validated. The overarching aim of the models is to represent a process outcome that will provide certain design or optimization aids. However, in practice, not all of the validation variables or outcomes in Table 1.1 have been measured to match a certain model. In the case of HPP, PEF, ultrasound, and ohmic heating, more outcome-related models need adequate validation to establish, for example, accurate predictions of microbial, enzymatic or chemical reaction distributions, or other outcome-related parameters. On the other hand, more complete outcome-related validated models have been developed for microwave processing. For example, the Multiphysics models presented in Chapter 6 have assisted in the filing of microwave sterilization processing in the U.S. Food and Drug Administration. As such, Multiphysics models will mainly be useful when reaching a stage of predicting process outcomes that leverage technologies to industrial levels. In order to achieve this, a more direct collaboration between processing equipment manufacturers, interested industry partners, and researchers is needed for successful design and implementation of innovative food processing technologies.

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