Chapter 1
The Beginning, Current, and Future of Food Engineering: A Perspective

Dennis R. Heldman and Daryl B. Lund

1.1 Introduction

Food engineering is a field of study that has emerged in rather recent history, but is based on concepts that have evolved over a significant period of time. In general, food engineering is the interpretation and application of engineering principles and concepts to any aspect of food manufacturing and operations, including the construction of the facilities for these operations. With this broad interpretation, almost any of the more traditional fields of engineering (electrical, mechanical, civil, chemical, industrial, and agricultural) would contribute to the successful operation of the facilities and processes dealing with food. Recent focus in food engineering has been on processes occurring within manufacturing operations, specifically on the influence of unique characteristics and properties of foods and ingredients in these processes.

The purpose of this paper is to review the history and current status of food engineering, and to provide a framework for discussion about its future. In addition to identifying some of the founding fathers and giants in food engineering, this review will include the development of educational programs and the role of food engineering within those programs. Attention will be given to evolution of research and the potential of food engineering research in the future. Finally, there will be an attempt to evaluate the impact of public sector research on research conducted within the food industry, as well as applications of research within the industrial sector.

D.R. Heldman (✉)
Heldman Associates, 5224 Kings Mills Rd; #314, 45040 Mason, OH, USA
e-mail: drheldman@earthlink.net

D.B. Lund
Department of Food Science, University of Wisconsin-Madison. 1605 Linden Dr., 53706 Madison, WI, USA
e-mail: dlund@cals.wisc.edu

J.M. Aguilera et al. (eds.), *Food Engineering Interfaces*, Food Engineering Series,
DOI 10.1007/978-1-4419-7475-4_1, © Springer Science+Business Media, LLC 2011

1.2 Scope of Food Engineering

As suggested, the term "food engineering" has many interpretations and the scope of this term has evolved over time. In addition, there are varied interpretations and meanings in different regions of the world. It is likely our attempt at a definition will fall short and not capture all of the various interpretations. However, the broadest interpretation of food engineering occurs in the industrial sector, where it is generally accepted on a global basis. This general interpretation includes applications of engineering in any aspect of production, handling, storage, processing, packaging, and distribution of food. This is certainly the interpretation accepted by the founding fathers of the International Congress of Engineering and Food (ICEF), who did not use "food engineering" in the title of the congress. Obviously, this broad interpretation is inclusive of the expertise associated with most of the engineering fields.

In development of food engineering curricula, a more narrow interpretation of food engineering has been applied within education institutions, so as to define the uniqueness of the discipline in teaching and research. As might be expected, these interpretations focus more on basic concepts and principles, and the impact of the product being handled on the application of engineering principles, with special emphasis on the word "food."

Undergraduate food engineering teaching programs incorporate both basic engineering principles and the unique chemical and microbiological characteristics of foods. These programs tend to integrate basic engineering, chemistry, and microbiology into process designs. It is clear that in most regions of the world, these programs have evolved at the interface between science and engineering. In the United States, two types of programs have developed in parallel: some with a clear alignment with engineering curricula (usually in chemical or agricultural engineering), and many with food science programs (associated with colleges of agricultural sciences). Graduate programs and research in food engineering have evolved with an evident focus on basic principles, mathematical models, and process simulations.

In summary, food engineering provides an essential link between engineering and the food sciences. The dimensions of this interface present unique challenges in education, research, and applications, and will continue to provide professionals associated with food engineering with opportunities in the future and a continuing evolution of scope.

1.3 Definitions of Food Engineering

There are many definitions of food engineering, and not one is universally accepted. One of the early definitions appears in the preface of the book *Elements of Food Engineering* (1952) by Parker, Harvey, and Stateler. Parker proposed that "Food Engineering is concerned with the design, construction, and operation of industrial processes and plants in which intentional and controlled changes in food materials are performed with due consideration to all economic aspects considered." Later in 1963, Charm suggested that the purpose of food engineering is "to illustrate the common relationship between basic engineering principles and the fundamentals of food processing." Finally, in 1966, Earle defined food engineering as "the study of the processes that transform raw materials into finished products, or preserves foods so they can be kept for longer periods." There are obvious similarities and differences in these early definitions. All three indicate that food engineering is the application of engineering to manufacturing and preservation of foods, but there are distinct differences, from more emphasis on basic principles to greater emphasis on applications of engineering in practice.

A more current definition of food engineering has been posted online (Wikipedia 2010; http://en.wikipedia.org/wiki/Food_engineering) as follows: "Food engineering refers to the engineering aspects of food production and processing. Food engineering includes, but is not limited to, the application of agricultural engineering and chemical engineering principles to food materials." However, given the evolution of research and industrial applications, the following definition should also apply, now and in the near future: Food engineering is both the identification and creation of the physical principles associated with foods and ingredients, and the applications of the principles to the handling, storage, processing, packaging and distribution of consumer food products. This definition attempts to include both the interests associated with engineering research and the applications of outcomes from research to ultimate applications in processes associated with the food industry. Undoubtedly, a better appreciation of the diversity of this unique field of study solicits more discussion of the subject.

1.4 Origins of Food Engineering

There are clear relationships between the origins of food engineering and food preservation processes. Design and prediction of the effect of preservation properties on food requires quantification and modeling. One of the most visible applications can be found in the book *Sterilization in Food Technology* by Ball and Olson (1957). This book provides numerous examples of applications of mathematics to heat transfer to foods in containers and the description of the kinetics of microbial destruction. Historically, food preservation evolved from an art to a science. Early preservation techniques (drying, salting, fermentation, and cooling) were based on "trial and error." Later, technologies such as canning and freezing were based on observations that provided the basis for science-based improvements in the processes. Many of these early scientific findings occurred in the basic sciences of chemistry, biology, and physics. One of the more significant outcomes from Louis Pasteur (1860) in response to food spoilage challenges was to provide the foundation for bacteriology and microbiology. Other contributions from basic science and mathematics were significant, such as the influence of temperature on reactions (Arrhenius 1889) and modeling heat and mass transfer (Carslaw and Jaeger 1946; Crank 1956).

There are several other early and significant contributions that have become the foundation of food engineering. The role of Nicholas Appert in demonstrating thermal processing of foods in the early 1800s is recognized as the basis for many current shelf-stable foods. The invention and development of mechanical refrigeration by von Linde (1896) was significant, followed by Birdseye (1930) who established the basis of the modern frozen food industry. Although dehydration has been recognized as a food preservation process for centuries, the contributions of von Loesecke (1943) advanced the process in a quantitative manner. These three processes (thermal processing, food cooling and freezing, and food dehydration) continue to be the most visible processes in the research literature on food engineering.

1.5 Evolution of Food Engineering

In general, food engineering was started by engineers who happened to have some acquaintance with the food industry. However, there were other engineers and scientists who appreciated the application of engineering principles to something as complex as food. At the risk of omission, here are some of the giants in food engineering and others who have made significant contributions to food engineering (in no particular order): Bird, Stewart and Lightfoot, Kessler, Thijssen, Leniger, Cheftel, King, Karel, Plank, Kuprianoff, Diendorfer, Humphrey, Hallstrom, Heldman, Labuza, Berk, Mizrahi, Morgan, Pflug, Earle, Goldblith, Proctor, Hayakawa, Ball, Zahradnick, Saravacos, Brody, Duckworth, Cheftel (J.C.), Loncin, Saguy, Ohlsson, Pham, Teixeira, Sastry, Hall, Farrall, Harper (J.C.), Nickerson, Mannheim, Harper (J.M.), Merson, Lund, Knorr, Singh (R.P.), Schluender, Schwartzberg, Bimbenet, and Lovric.

In addition to people, there are several events and developments that have contributed to the evolution of food engineering in the past 50 years. For professionals involved in teaching, there are several textbooks, including the following key books:

1952 – *Elements of Food Engineering* by Milton E. Parker, Ellery H. Harvey, and E. S. Stateler
1963 – *Fundamentals of Food Engineering* by Stanley E. Charm
1966 – *Unit Operations in Food Processing* by Richard Earle
1975 – *Food Process Engineering* by H.A. Leniger and W.A. Beverloo
1975 – *Food Process Engineering* by Dennis R. Heldman
1976 – *Elements of Food Engineering* by John C. Harper
1979 – *Food Engineering; Principles and Selected Applications* by Marcel Loncin and Larry Merson
1980 – *Fundamentals of Food Process Engineering* by Romeo Toledo
1984 – *Introduction to Food Engineering* by R. Paul Singh and Dennis R. Heldman

Although other textbooks have been published in this recent time period, these nine demonstrate the evolution of food engineering as a field of study. Parker et al.

(1952) placed significant emphasis on the description of manufacturing operations and the role of engineering in all aspects of the manufacturing facility. Charm (1963) introduced mathematics and an emphasis on process design and unit operations. Earle's book (1966) was ideal for undergraduate students pursuing a degree in food science, and the objectives in Harper's book (1976) were similar. Books by Leninger and Beverloo (1975) and Heldman (1975) were designed for students with a significant background in engineering concepts, and emphasized advanced analysis of unit operations. The book by Loncin and Merson (1979) provided even more emphasis on mathematical analysis of unit operations, and was suited to introductory graduate students in some dimension of food engineering. Both Toledo (1980) and Singh and Heldman (1984) developed textbooks for undergraduate students in food science with specific attention to topics identified in guidelines for food science curricula recommended by the Institute of Food Technologists.

During the past 25 years, several of these pioneering textbooks have been published in later editions. In most cases, emphasis has been on new information and technologies, as well as on advancement in tools available for conducting analysis. There has been a continuous trend toward more mathematical description of processes, and computer simulation of operations within the food industry. Further, there has been an obvious emphasis on the impact of processes on product quality attributes, including nutrients, as well as changes in process design to enhance the efficiency of processes.

Another measure of the evolution and development of food engineering as a field of study and research is the holding of national and international meetings that focus on food engineering. Some of the key meetings and events that have occurred during the last 50 years include:

1972 – *Food Engineering Conference*; organized by H.A. Leninger and Hans Thijssen, hosted at Agricultural University, Wageningen, The Netherlands.

1976 – *International Congress on Engineering and Food (ICEF1)*; 1st Congress was chaired by Dr. Joe Clayton, held in Boston, Massachusetts. The 11th Congress will be hosted in Athens, Greece on May 22–26, 2011.

1976 – *Food Engineering Division of IFT*; a petition signed by several food engineering members of IFT was approved by the Executive Committee; the Division continues to organize symposia and research programming at annual IFT meetings.

1981 – *International Conference in Fouling and Cleaning*; conference was organized by Bengt Hallstom, Lund University, and Daryl Lund, University of Wisconsin; subsequent conferences were held in 1985 (USA) and 1989 (Germany); now part of ICEF.

1991 – *Conference of Food Engineering (CoFE)*; first of nine conferences organized by Dr. Martin Okos, held in Chicago. The 11th conference is being planned for 2011.

1996 – *CIBIA*; 1st Congreso IberoAmericano de Ingenieria de Alimentos (CIBIA) was hosted in Campinas, Brazil. The 6th Congreso was hosted in Bogata, Columbia, in 2009.

2007 – *European Workshop on Food Engineering and Technology*; first of series of workshops held with focus on applications of food engineering research.

Although many other meetings related to food engineering have occurred, the above list illustrates the continuing development of research programs in the past 35 years.

The historical evolution of food engineering can also be illustrated by the publication of research literature. Specific journals for publication of current food engineering research have been created with some of the more visible journals and reference books, such as:

1970 – *Journal of Food Science*; first issue published, which included a section titled "Applied Science and Engineering by the Institute of Food Technologists."
1976 – *Journal of Food Process Engineering*; first issue published by Food & Nutrition, Press.
1982 – *Journal of Food Engineering*; first issue published by Academic Press, Inc.
1992 – *Handbook of Food Engineering*; first edition published by Marcel Dekker, Inc.
1997 – *Handbook of Food Engineering Practice*; published by Academic Press, Inc.
2003 – *Encyclopedia of Agriculture, Food and Biological Engineering*; first edition published by Marcel Dekker, Inc.

Information about food engineering has been published in many other journals and references, but the above list illustrates the evolution within a relatively short time period.

All of the developments described have occurred during a period of significant change in the food industry and related industries. Bruin and Jongen (2001) suggested the following categories of significant change:

1. Mergers and acquisitions of companies in the food and related industries. These changes have caused significant reorganization within all companies, impacting the role of food engineers in the industry.
2. Expectations for innovation. Changes in consumer expectations have increased in frequency, forcing the identification and implementation of new, innovative processes.
3. Changes in industry expectations. Previously, expectations of the food industry were to deliver an abundant and safe supply of food to consumers. These expectations have evolved to include not only more abundant and safe foods but also foods with greater convenience, and eventually, foods with enhanced influence on health and wellness.
4. Advances in computer technology. These advances have provided the tools to accelerate the responsiveness of engineers to all types of challenges.

These changes have influenced the environment of food engineering activities, and have had an impact on the expectations of food engineers in the industry. Many of these changes also will be incorporated into future educational programs for food engineers. Thus, a challenge to educators will be to incorporate these changes into food engineering programs.

1.6 Evolution in Food Engineering Research

There have been significant advancements in food engineering research over the past 50 years. Although the research has been conducted over a broad range of applications, the unique focus of research that has evolved is the integration of reaction kinetics with transport phenomenon to accomplish process design. The research model concept is illustrated in Fig. 1.1.

The concept described by the model encourages research in three distinct areas: kinetic parameters, transport phenomenon, and process design. Research on kinetic models has expanded the availability of kinetic parameters and enhanced the investigation of appropriate models used for food products. Transport phenomenon research has improved our understanding of heat and mass transfer in foods, with specific attention to the unique properties of food products and the mathematic models needed to describe the phenomenon in a food system. Process design research integrates the kinetic models with appropriate transport phenomenon models to allow prediction of a parameter to quantify the quality of the food product. In general, the concept is ideal for optimization of the process through maximizing the product quality attributes, while identifying the best combination of process parameters.

1.6.1 Kinetic Models

The development of kinetic models for food systems is still evolving. A typical model used to describe changes in a food component or attribute is expressed as:

$$\mathrm{d}A/\mathrm{d}t = -kA \tag{1.1}$$

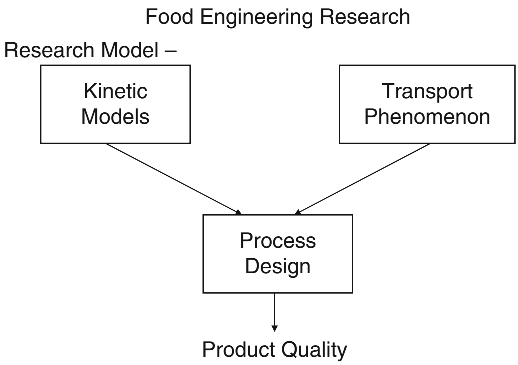

Fig. 1.1 A food process engineering research model

where A = the concentration or intensity of component, and k = the first-order rate constant.

There has been a significant increase in the measurement and publication of rate constants for an array of product component changes as a function of process or storage parameters, as illustrated by Villota and Hawkes (2007). Traditionally, the same model has been used to describe changes in microbial populations during preservation processes; the rate constants have been assembled in several locations, including the IFT Task Force Report (2000). These rate constants are evaluated and expressed as a function of parameters such as temperature, water activity, pressure, pH, etc. The evolution of more complex models has been explored by von Bockel (2008), with specific attention to variations from first-order kinetics.

1.6.2 Transport Phenomenon

Significant attention has been given to the development of models to describe heat, mass, and momentum transfer in food systems, expressed as follows:

$$\partial N/\partial t = \alpha \blacktriangledown^2 N \tag{1.2}$$

where N = intensity of a process parameter, and α = appropriate property of food structure.

Expressions of this type are used to predict distribution histories of the preservation process parameter. Typical parameters include temperature, moisture content, pressure, and other parameters used to accomplish reductions in microbial populations. Over the past 30–40 years, the availability of quantitative physical properties data has increased significantly (Rao et al. 2005). In addition, there has been increased emphasis on the development of prediction models for properties based on product composition.

1.6.3 Process Design

Integration of the appropriate kinetic model with transport phenomenon expressions leads to process design. In general, the outcomes are product quality attributes, predicted as follows:

$$A = \int k(N)\, \mathrm{d}t \tag{1.3}$$

where A = the intensity or concentration of a quality attribute.

The focus of process design is on the product, with impact of the process on reduction of the microbial population and/or the retention of a sensitive product quality attribute. Process design provides the opportunity to consider multiple attributes as long as the kinetic parameters and models are available. An even more important dimension of this approach is the potential for process optimization, which is the identification of the process parameters to achieve maximum retention of product quality attributes, while ensuring the desired reduction in microbial population for safety or shelf-life extension.

1.7 Contributions of Food Engineering Research

The process design approach has contributed to many positive products manufactured by the food industry. These contributions can be expressed in several different ways. In general, process design facilitates the quantitative prediction of process outcomes, while evaluating a range of process parameters without conducting time-consuming and costly experimental trials.

1.7.1 Safe and Wholesome Foods

Process design has had significant impact on the safety and wholesomeness of food products. The development of food canning by Nicholas Appert (1750–1841) took 14 years. Using the current process design approaches, processes can be developed within hours. These approaches ensure microbiological safety of products, along with the capability to maximize the retention of product quality attributes.

A current example of process design is illustrated in Fig. 1.2. Knorr (2006) has demonstrated that through measuring and understanding the kinetics of *Escherichia coli* population reductions at high pressures, the retention of product quality attributes in sausage are evident. These same approaches have been used to ensure maximum retention of nutrients in a food product using high temperatures to ensure microbiological safety and shelf-life of the product.

1.7.2 Affordable Food Supply

Food engineering research has contributed to keeping quantities of food available at a modest cost to the consumer. These contributions have been accomplished through overall improvements in the efficiency of food manufacturing. These improvements have occurred through a focus on specific processes, as well as an analysis of processing operations. Many of the improvements in efficiency have occurred through increased capacity of individual pieces of equipment and

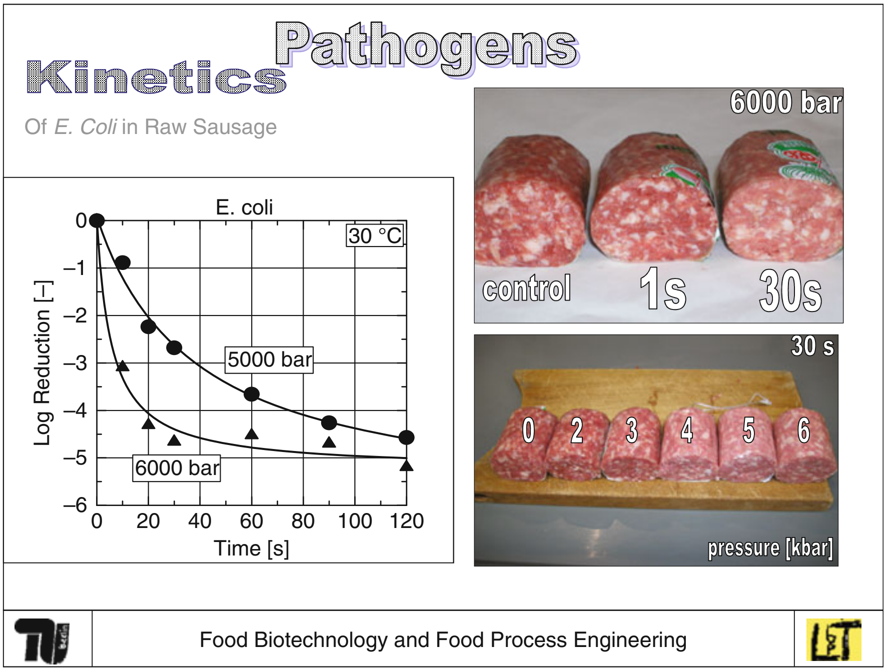

Fig. 1.2 Process design for pathogen reduction of *Escherichia coli* in sausage while retaining product quality attributes (Knorr 2006)

throughput of processing lines. Another contributor to a low-cost food supply has been the development of processes that allow foods to be transported for long distances without noticeable reductions in product quality attributes.

An example of process improvements for shelf-stable foods has been aseptic processing and packaging. This continuous process has been demonstrated as an excellent alternative to the more traditional batch retort process. As illustrated in Fig. 1.3, the process involves continuous processing of both product and packaging, before filling the product into the package. As illustrated by Bruin and Jongen (2001), improvements in the process have continued with capabilities to accomplish thermal processing of food particles within the carrier liquid.

1.7.3 Convenient Food Products

Process design has contributed to the development of convenient foods in a significant way. Examples include products with reduced preparation times, products with improved quality attributes, products with extended shelf-life, and a variety of shelf-stable products.

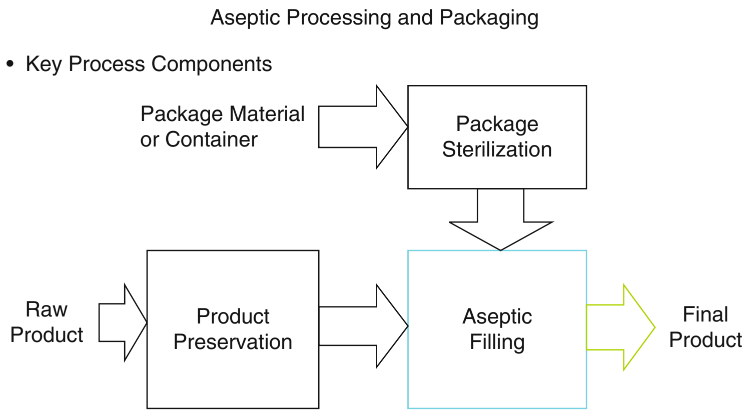

Fig. 1.3 The aseptic processing and packaging concept in an aseptic environment

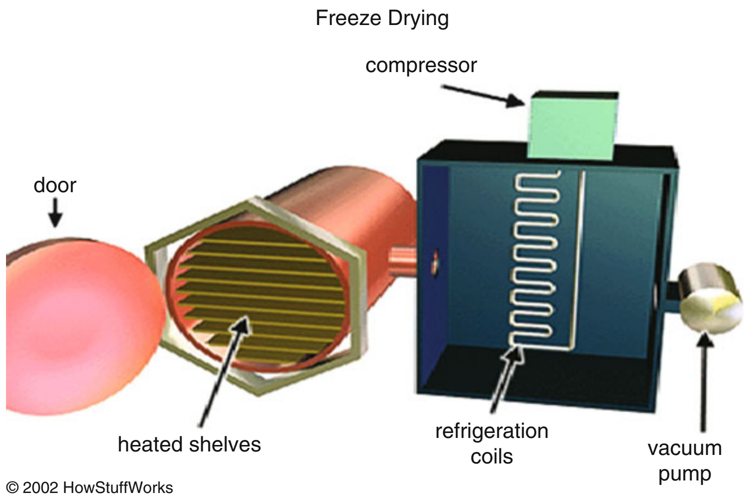

Fig. 1.4 The freeze-drying process

Freeze-dried foods are examples of products convenient for consumers. As illustrated in Fig. 1.4, the freeze-drying process produces high-quality dry foods by removing moisture from the product through sublimation at low temperature, and preserving the product's quality attributes. The freeze-drying process is not a new one, since the first application was to produce freeze-dried coffee in 1938. The process gained significant visibility in the 1960s during development of low-mass foods for space flights. Applications of the process to foods continue as efforts to reduce the costs associated with the process are evaluated.

1.7.4 Product Quality Improvements

Process design has contributed to food quality improvements in many different ways. These improvements have occurred as a result of new and unique ingredients manufactured using new processes created through process design. Product flavors are being enhanced with new technologies to preserve volatile flavors, with specific attention to encapsulation processes. Based on new physical properties knowledge, process design has created an array of new and improved product textures. Many of the recent improvements in food product quality can be traced to the "food stability map" (Fig. 1.5) as suggested by Labuza et al. (1970).

The concept of water activity has provided a unique basis for product and process development. Many new relationships between reaction rates in foods and water activity have guided the development of foods with extended shelf-life and unique quality attributes. These early developments have led to the more recent concepts of glass transition as illustrated in Fig. 1.6 (Roos and Karel 1991). The more sophisticated relationships between temperature and moisture content within a food provide even more opportunities for process development now and in the future. These state diagrams provide the ideal basis for evaluation of new ingredients and their impacts on response of a product to a process, and optimization of product quality attributes as a function of process parameters. These concepts will provide the basis for food engineering research and applications for many years into the future. All of these developments are based on the unique relationships between the process and the ingredients of the food products.

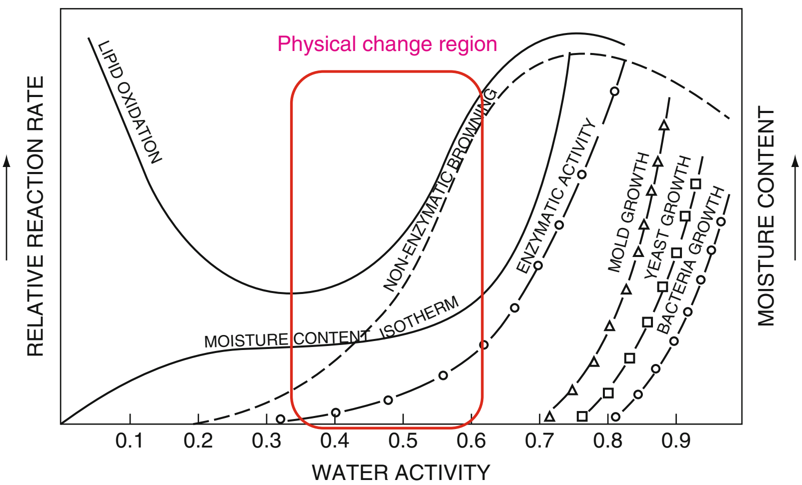

Fig. 1.5 The food stability map (Figure redone by T.P. Labuza based on Labuza et al. 1970)

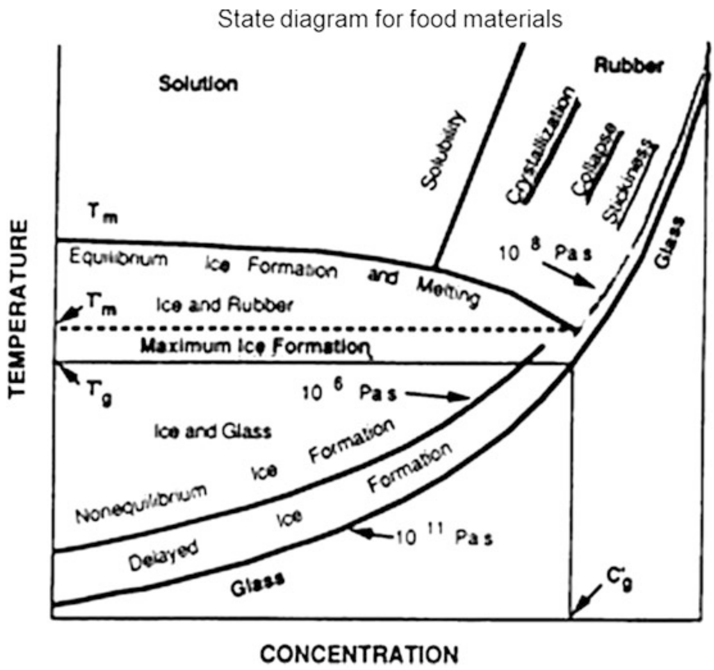

Fig. 1.6 The "state diagram" concept (Roos and Karel 1991)

1.7.5 Innovative Food Products

The development of many innovative new products has resulted from process design. As new process technologies are identified and applied to food manufacturing the opportunities for new and different products evolve. Similar opportunities occur as new packaging and packaging systems are developed. In many situations, these new process technologies are important to the enhancement of product quality.

An excellent example of a process technology with significant impact on food product development is extrusion. Extrusion is a process developed in the polymer industry, but it has been adapted to a range of applications in the food industry. The process combines the parameters of pressure, temperature, and time to produce products with unique characteristics and properties. By considering the significant range for each parameter, and the combinations of parameters for each one, the opportunities for product attributes are nearly unlimited.

The opportunities for future developments in food extrusion are emphasized by Bruin and Jongen (2001). By superimposing a typical cycle during an extrusion process on a state diagram (Fig. 1.7), the depth of understanding achieved from recent process design research is recognized.

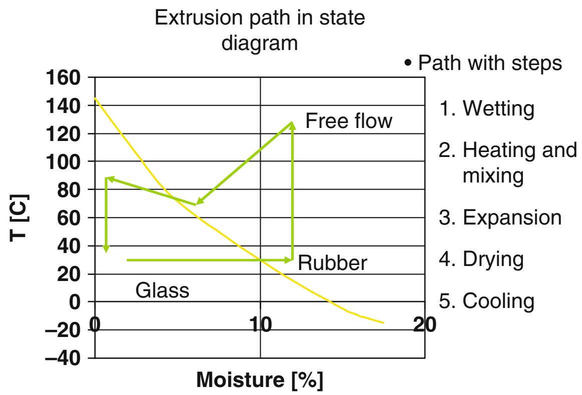

Fig. 1.7 The extrusion process on a state diagram (Bruin and Jongen 2001)

As is evident in Fig. 1.7, the steps associated with the extrusion process shift the product ingredients from a glass state to a rubber state, followed by elevation of temperature before expansion and drying back to a glass state. The final step of cooling returns the product to the same composition and temperature, but the final product has completely different properties and characteristics. Obviously, this understanding of the process and the product creates an unlimited array of opportunities for new and innovative products.

1.8 The Future of Food Engineering

The future of food engineering is very bright. It is evident that food engineering education will continue to evolve for both undergraduate and graduate students. It will continue to be an attractive field of study because of the unique characteristics of foods and ingredients, and the challenges associated with applications of engineering concepts and principles. The education of future students will be driven by the new information created by current and future research.

One of the currently evolving areas of research is nanoscale science and the translation of outcomes into applications in food systems. Bruin and Jongen (2001) have suggested that nanoscale adds another scale of consideration to existing scales that range from molecular scale to supply-chain scale. Although the visible applications are still evolving, there seem to be several potential outcomes. The shelf-life of foods is likely to be increased through a combination of nano-sensors used to detect the onset of product deterioration, followed immediately by intervention to prevent this deterioration. Through the study and understanding of food properties at the nanoscale, the texture of food products can be improved and new product textures are likely to evolve. Many of these improvements are likely to be the result of the creation of nano-structured particles and films. The encapsulation of flavors within nanoscale particles should ensure that food products retain optimum flavor intensity through processing steps and for longer periods of time during storage and distribution. Similar opportunities seem logical for bioactive compounds. Knowledge about packaging materials at the nano-scale should lead to the development of new and improved packaging materials for food products.

Food engineering will contribute to the goals of improved health and wellness of consumers through development of functional foods. The application of engineering concepts and principles to the metabolism of food will provide insights on the product and process development cycle. The potential for incorporating bioactive compounds into food products in a manner that ensures delivery of the compound to the appropriate site within the body during metabolism of the food is achievable through food engineering research.

An evolving challenge to food manufacturing and distribution is the constraint of sustainability. Food engineering should contribute to sustainability in many different ways. The basic concepts of material and energy balances will become standard tools in evaluation of all scales of operation from the point of raw material production to delivery of the product to the consumer and beyond. The transitions of new information from process design to commercial manufacturing operations will continue to be a significant challenge. These transitions must be accomplished in a more efficient manner.

1.9 Summary

Food engineering has a relatively brief history as a field of study. Educational programs for undergraduate and graduate studies have evolved over the past 50 years, with somewhat different approaches globally. Many engineering impacts on the food industry have a longer history, as indicated by the origin of several preservation processes, such as drying, canning, and refrigeration. More recently, food engineering research has brought a quantitative dimension to both product and process development. The future of food engineering research will continue to focus on technology transfer and attempts to accelerate the transition of new processes from the laboratory bench to operations scale in manufacturing. Future research must be directed toward meeting the expectations of the consumer for safe and convenient foods that will contribute to a healthy lifestyle for extended periods of time.

References

Arrhenius S (1889) Z Phyzik Chem 4:226, Title not available

Ball CO, Olson FCW (1957) Sterilization in food technology. McGraw-Hill, New York

Birdseye C (1930) Production of quick-frozen fish. US Patent #1773070

Bruin S, Jongen RG (2001) Food process engineering: the past 25 years and challenges ahead. The Food Engineering Division Lecture. Institute of Food Technologists Annual Meeting, New Orleans, LA

Carslaw HS, Jaeger JC (1946) Heat of conduction in solids. Oxford University Press, London

Charm SE (1963) The fundamentals of food engineering. The AVI Publishing Co., Westport, CT

Crank J (1956) The mathematics of diffusion. Oxford University Press, London

Earle RL (1966) Unit operations in food processing. Pergamon, London

Harper JC (1976) Elements of food engineering. The AVI Publishing Co., Westport, CT

Heldman DR (1975) Food process engineering. The AVI Publishing Co., Westport, CT

IFT Task Force Report (2000) Kinetics of microbial inactivation for alternative food processing technologies. JFS Special Supplement. pp 1–108

Knorr D (2006) Processing concepts for non-thermal modification of foods. 13th World Food Congress of Food Science & Technology. Nantes, France. Sept. 17–21

Labuza TP, Tannenbaum SR, Karel M (1970) Water content and stability of low moisture and intermediate moisture foods. Food Technol 24:543–550

Leninger HA, Beverloo WA (1975) Food process engineering. Reidel, Dordrecht, The Netherlands

Loncin M, Merson RL (1979) Food engineering. Principles and selected application. Academic, New York

Parker ME, Harvey EH, Stateler ES (1952) Elements of food engineering. Reinhold, New York

Rao MA, Rizvi SSH, Datta AK (2005) Engineering properties of foods, 3rd edn. CRC Press/Taylor & Francis, Boca Raton, FL

Roos YH, Karel M (1991) Applying state diagrams to food processing and development. Food Technol 45(12):68–71, 107

Singh RP, Heldman DR (1984) Introduction to food engineering. Academic, Orlando, FL

Toledo RT (1980) Fundamentals of food process engineering. The AVI Publishing Co., Westport, CT

Villota Ricardo, Hawkes James G (2007) Reaction kinetics in food systems. In: Heldman Dennis R, Lund Daryl B (eds) Handbook of food engineering, 2nd edn. CRC Press/Taylor & Francis, Boca Raton, FL

von Bockel MA (2008) Kinetic modeling of reactions in foods. CRC Press/Taylor & Francis, Boca Raton, FL

von Linde C (1896) Process and apparatus for liquefying gases or gaseous mixtures, and for producing cold, more particularly applicable for separating oxygen from atmospheric air. German Patent # GB189512528

von Loesecke HW (1943) Drying and dehydration of foods. Reinhold, New York