Thermal Principles and Kinetics

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2.1 Introduction

Thermal processing of food materials is one of the most widely used methods of food preservation. Foods may be thermally processed using numerous heating systems such as retorts (batch or continuous), direct heating systems (steam injection or steam infusion), indirect heating systems (tubular heat exchangers, shell and tube heat exchangers, plate heat exchangers, scraped surface heat exchangers), volumetric heating systems (microwave or ohmic heating), and combinations of these. The choice of the heating system is based on several factors, including the characteristics of the product (pH, water activity, composition, etc.), properties of the product (density, viscosity, specific heat, thermal conductivity, thermal diffusivity, electrical conductivity for ohmic heating, and dielectric properties for microwave heating), quality of the product, need for refrigeration, need or acceptability of moisture addition/removal, and cost.

The extent of thermal treatment required for a food product depends on whether it is an acid product, an acidified product, or a low-acid product. An acid food product is one with a natural pH of less than 4.6. Acid food products include apple juice, orange juice, ketchup, etc. An acidified food product is one with an equilibrium pH of less than 4.6 and a water activity (a_w) greater than 0.85. Examples of acidified foods include peppers treated in an acid brine, pickled foods (excluding foods pickled by fermentation), etc. Acidified food products are typically treated at 90–95 °C for a period of 30–90 sec to inactivate yeasts, molds, and bacteria (usually Lactobacillus species). A low-acid food product is any food other than alcoholic beverages, with a natural equilibrium pH greater than 4.6 and a water activity greater than 0.85. These food products include butter, cheese, fresh eggs, pears, papaya, and raisins (Skudder 1993). Low-acid food products are capable of sustaining the growth of Clostridium botulinum spores. Clostridium botulinum is an anaerobic, gram-positive, heat-resistant spore-forming bacterium that produces a potent neurotoxin. Food-borne botulism is a severe type of food poisoning caused by the ingestion of foods containing the potent neurotoxin formed during the growth of Clostridium botulinum. The spores of Clostridium botulinum must be destroyed or effectively inhibited to prevent germination and subsequent production of the deadly toxin, which causes botulism.

Low-acid food products come under the regulatory authority of either the Food and Drug Administration (FDA) or the United States Department of Agriculture (USDA), depending on the proportion of meat or poultry in the food product. The FDA regulates most food products, except those containing more than 3% raw or 2% cooked meat or poultry ingredients, which fall under the jurisdiction of the USDA. The general thermal process requirements of both regulatory agencies are similar and they are compiled in Code of Federal Regulations 21 CFR Parts 108 (emergency permit control), 113 (low-acid canned foods), and 114 (acidified foods) for the FDA, and 9 CFR Parts 308, 318 (meat products), 320, 327, and 381 (poultry products) for the USDA. The FDA requires registration of the processing facility (form 2541) and a detailed process filing (form 2541a for acidified and low-acid canned foods and form 2541c for low-acid aseptically processed foods) (Chandarana 1992).

2.2 Methods of thermal processing

There are several methods of thermal processing of foods, with pasteurization and sterilization being the two most widely used. The most common methods of thermal
processing include blanching, pasteurization, hot filling, and sterilization. These methods are now described.

### 2.2.1 Blanching

Blanching is a mild heat treatment commonly applied to fruits and vegetables prior to freezing, drying, or canning. Blanching is performed to inactivate enzymes, enhance drying and rehydration, remove tissue gases, enhance color of green vegetables, and reduce microbial load. The effectiveness of blanching is usually evaluated by assaying for peroxidase and catalase activity. Blanching is usually accomplished by bringing the product into contact with hot water, hot air, or steam for a specified period of time, depending upon the product and/or enzyme of interest. Water blanching can be conducted as a batch operation by dipping a batch of product in hot water for the required time. Continuous hot water blanching can be accomplished using a screw-type, drum-type, or pipe-type blancher. The screw-type blancher consists of a trough fitted with a helical screw. The drum-type blancher consists of a perforated drum fitted internally with a helical screw. The pipe-type blancher can be used for solid products, which can be pumped with water. Similar to water blanching, steam blanching can also be accomplished as a batch or continuous process. The heating time necessary to accomplish blanching depends on the type and size of fruit/vegetable, the method of heating, and the temperature of the heating medium. Typical blanching times at 100°C for commercial blanching range from 1 to 5 min (Lund, 1975).

### 2.2.2 Pasteurization

Pasteurization refers to the heat treatment of food products, mostly liquid or liquid with particulates, to inactivate vegetative pathogenic microorganisms. The temperature combination for the pasteurization of milk, for instance, is 63°C for 30 min, referred to as a low-temperature, long-time (LTLT) process, and 72°C for 15 sec, referred to as a high-temperature, short-time (HTST) process. The heat treatment in pasteurization is not sufficient to inactivate all spoilage-causing vegetative cells or heat-resistant spores. Therefore, the shelf life of pasteurized low-acid products such as milk and dairy products is approximately 2–3 weeks under refrigerated conditions. Ultrapasteurization refers to pasteurization at temperatures of 138°C or above for at least 2 sec, either before or after packaging. This process further extends the shelf life of the product. Ultrapasteurization results in destruction of a greater proportion of spoilage microorganisms, leading to an extended shelf life of about 6–8 weeks at refrigeration temperature. This process has been used for flavored milks and non-dairy creamers in portion pack cups (David et al., 1996).

The choice of heating system for pasteurization depends on the characteristics (rheological and thermal properties) of the product, potential for fouling, ease of cleaning, and cost of the heating equipment. A direct type heating system (steam injection and steam infusion) is used for homogeneous and high-viscosity products and is particularly suited for shear-sensitive products such as creams, desserts, and sauces. In a steam injection heating system, liquid product is heated by injection of culinary steam into the product. Rapid heating by steam, combined with rapid methods of cooling, can yield a high-quality product. A steam infusion heating system, similar to steam injection, involves infusing a thin film of liquid product into an atmosphere of steam, which provides rapid heating. A direct heating system (steam injection or steam infusion) adds water to the product due to the condensing steam. The amount of added water should be either accounted for in the product formulation or removed by pumping the heated liquid into a vacuum cooling chamber.

There are four main types of indirect heating systems: tubular, shell and tube, plate, and scraped surface heat exchangers. Tubular heat exchangers are used for homogeneous and high-viscosity products (soups and fruit purees) containing particles of sizes up to approximately 10 mm. The simplest tubular heat exchanger is a double pipe heat exchanger consisting of two concentric pipes. Shell and tube heat exchangers consist of a shell (typically cylindrical in shape) with one or more sets of tubes inside it. The tubes may be coiled in a helical manner or arranged in a trombone fashion. This type of heat exchanger is used when a greater degree of mixing than that achieved in a tubular heat exchanger is desired. Plate heat exchangers are used for homogeneous and low-viscosity (<5 Pa.s) products (e.g. milk, juices, and thin sauces) containing particle sizes up to approximately 3 mm. These heat exchangers consist of closely spaced parallel plates pressed together in a frame. They provide a rapid rate of heat transfer due to the large surface area for heat transfer and turbulent flow characteristics. Scraped surface heat exchangers are used for viscous products (e.g. diced fruit preserves and soups) containing particles of sizes up to approximately 15 mm. These heat exchangers consist of a jacketed cylinder housing with scraping blades on a rotating shaft. The rotating action
of the scraping blades prevents fouling on the heat exchanger surface and improves the rate of heat transfer. Fouling is the phenomenon of product build-up on the heat transfer surface caused when a liquid product comes into contact with a heated surface. Fouling increases thermal resistance and thus results in reduced rates of heat transfer. This type of heat exchanger is the best choice for viscous products containing particulates (Skudder 1993).

Apart from tubular, shell and tube, plate, and scraped surface heat exchangers, pasteurization can also be accomplished in a vat or tank-type heat exchanger. In a tank-type heat exchanger, product is pumped into a jacketed vat or tank, heated to pasteurization temperature, held for the required time, and pumped from the vat to the cooling section (Mitten, 1963).

Volumetric heating systems such as microwave and ohmic heating can provide very rapid heating throughout the product, which is desirable for aseptic processing. However, it is challenging to maintain a uniform temperature distribution within the product. Microwave heating systems apply a rapidly changing electromagnetic field to the product. Movement of charged ions and agitation of the small polar molecules within the product (mostly water molecules) due to the changing electromagnetic field generate heat. An ohmic heating system operates by directly passing electric current through a product. The electrical resistance of the product to the passing electric current generates heat (Coronel et al., 2008).

2.2.3 Hot filling

Acid/acidified products such as juices and beverages packed in hermetically sealed containers using an appropriate hot filling process yield commercially sterile shelf-stable products. Hot filling, also known as “hot fill and hold,” refers to filling unsterilized containers with a sterilized acid/acidified food product that is hot enough to render the container commercially sterile. A hermetically sealed container is a container that is designed and intended to be secure against contamination by microorganisms and thus to maintain the commercial sterility of its contents after processing.

2.2.4 Sterilization

Sterilization refers to killing of all living microorganisms, including spores, in the food product. Food products are never completely sterilized; instead, they are rendered commercially sterile. Commercial sterility means the condition achieved either by (1) the application of heat, which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution, and viable microorganisms (including spores) of public health significance, or by (2) the control of water activity and the application of heat, which renders the food free of microorganisms capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution. Commercially sterile food products are shelf-stable with a long shelf life (1–2 years) (Anderson et al. 2011; David et al. 1996).

Low-acid food products are rendered commercially sterile to prevent the growth of *Clostridium botulinum* spores (David et al., 1996; Lund, 1975). Commercial sterility can be achieved by in-container sterilization or in-flow sterilization. In-container sterilization generally refers to the retorting process whereas in-flow sterilization refers to aseptic processing.

2.2.4.1 Retorting

Traditionally, retorting has been used to process low-acid food products to ensure destruction of *C. botulinum* spores. Conventional retorting involves filling of the product in metal cans, glass jars, retortable semi-rigid plastic containers or retortable pouches, double seam or heat sealed, followed by heating, holding, and cooling in a pressurized batch or continuous retort. Retorting of foods in cans, invented by Nicholas Appert in the early 1800s, still remains the gold standard for preservation of foods. Retorts can be operated in either batch or continuous mode. Batch retort is the most versatile sterilization system, with the ability to handle different products (conduction heating and convection heating) and package types. Batch retort can further be classified into still/static (horizontal, vertical, or crateless) retort, and agitating/rotary (end-over-end or axial rotation) retort. When steam is used as the heating medium, it should be introduced into the retort with care such that all the air in the retort is displaced. Inadequate elimination of air may result in understerilization or non-uniform cooking of products in the retort. Removal of air by steam is also known as venting. Cooling is accomplished by shutting off steam and introducing cold water into the retort.

Overpressure is often used to prevent internal pressure inside the container from bursting containers. Thus, overpressure allows thermal processing of a wide variety of containers including glass, rigid plastics, and flexible pouches. The rotary retort agitates the product inside
the container by the movement of the air in the head-
space, resulting in enhanced heat transfer in the con-
tainer. A larger headspace results in faster heating/
cooling of a product due to efficient mixing. Different
heating media and heating methods used in various
batch retorts include steam, water, steam-air, water cas-
cading, water spray, or water immersion (Lund, 1975;
Weng, 2005).

Continuous retort can also be classified into static
(hydrostatic) retort and rotary (hydrolock, sterilmatic,
reel and spiral, etc.) retort. Continuous retorts increase
throughput and lower manpower costs. Hydrostatic
retorts are vertical systems, which use water legs for
preheating and cooling, with a central steam heating
chamber. Hydrostatic retort is well suited for products
that require long cook and cool times along with higher
throughput. A continuous rotary retort is a fully auto-
mated system designed for high throughput, lower energy
consumption, and uniform product quality. These sys-
tems require a cylindrical container with limited variation
in can diameter and height (Weng, 2005).

2.2.4.2 Aseptic processing

Aseptic processing offers an alternative to conventional
retorting to meet the demand for safe, convenient, and
high-quality foods. In aseptic processing of foods, the
product and the package are sterilized separately and
brought together in a sterile environment. This involves
sterilization of a food product, followed by holding it
for a specified period of time in a holding tube, cooling
it, and packaging it in a sterile container. Aseptic pro-
cessing uses high temperatures for a short period of time,
yielding a high-quality (nutrients, flavor, color, or texture)
product compared to that obtained by conventional can-
nning. Some of the other advantages associated with aseptic
processing include longer shelf life (1–2 years at ambient
temperature), flexible package size and shape, less energy
consumption, less space requirement, eliminating the
need for refrigeration, easy adaptability to automation,
and need for fewer operators. However, some of the dis-
advantages of aseptic processing include slower filler
speeds, higher overall initial cost, need for better quality
control of raw ingredients, better trained personnel, better
control of process variables and equipment, and stringent
validation procedures.

Products that are aseptically processed include fruit
juices, milk, coffee creamers, purees, puddings, soups,
baby foods, and cheese sauces (David et al., 1996).
Sterilization of products via aseptic processing can be
accomplished using tubular, shell and tube, scraped
surface or volumetric heating (microwave and ohmic)
systems.

2.3 Microorganisms

The microorganisms of importance in thermal processing
are bacteria and fungi because they can grow in foods and
cause spoilage or public health issues. Bacteria are a large
group of unicellular prokaryotic microorganisms that are
found in a wide range of shapes, such as spheres (cocci),
rods, and spirals. Bacteria reproduce asexually through
binary fission. Under favorable growth conditions, bacte-
ria can grow and divide rapidly. A typical growth cycle of
bacteria can be divided into four phases: lag, log, station-
ary, and death. During the lag phase, bacteria adapt to
their new surroundings and multiple slowly. During the
log phase, bacteria multiply at an exponential rate. During
the stationary phase, growth rate slows down, and event-
ually they stop multiplying, resulting in their death in the
death phase (Tucker & Featherstone, 2011).

Gram-positive bacteria are more resistant to changes
in environment because of the thick peptidoglycan layer
in the cell wall. The cell wall of gram-positive bacteria
consists of peptidoglycan and teichoic acids. Teichoic
acids are negatively charged acidic polysaccharides, which
may be involved in ion transport. The cell wall of gram-
negative organisms consists of a thin peptidoglycan layer,
periplasm, and a lipopolysaccharide (LPS) layer. LPS is
composed of a lipid A component and a polysaccharide
component. Pathogenicity of gram-negative bacteria is
usually associated with the lipid A component of LPS,
also known as endotoxin. Gram-negative bacteria are less
fastidious (grow faster) than gram-positive bacteria.

Some species of rod-shaped bacteria can form highly
resistant structures known as spores, which can survive
extreme stress conditions such as high heat and pressure.
Bacteria in this dormant state may remain viable for
thousands of years (Tucker & Featherstone, 2011).

Fungi are a group of eukaryotes that include yeasts and
molds. Fungi are neither plants nor animals, as they pos-
sess some properties (cell wall) similar to plants and some
properties (absence of chlorophyll) similar to animals.
Yeasts are unicellular fungi that derive their energy from
organic compounds and do not require sunlight to grow.
Yeasts (4–8 μm) are larger than bacteria (0.5–5 μm), but
smaller than molds (10–40 μm). Yeasts reproduce asexu-
ally by budding, when a small bud forms on the parent
yeast cell and gradually enlarges into another yeast cell.
Yeasts are either obligate aerobes or facultative anaerobes. They grow best in a neutral or a slightly acidic medium and are generally destroyed above a temperature of 50°C. Yeasts are used in the food industry for leavening of bread and production of alcohol. However, their ability to grow at low pH and water activity (a_w) makes them organisms of concern for spoilage in fruit products such as juices and jams (Tucker & Featherstone, 2011).

Molds are multicellular fungi that grow in the form of hyphae (multicellular tubular filaments). Molds reproduce sexually and asexually by means of spores produced on specialized structures or in fruiting bodies. All molds are aerobic, but some can grow in low oxygen conditions. They can also grow at extreme conditions (high acid, high salt, low temperature). Molds are used in the food industry for production of soy sauce and certain cheeses. They are also capable of consuming acids, which can remove the acidic conditions that inhibit the growth of *Clostridium botulinum*. Spoilage of food products by mold is primarily due to mycotoxins (aflatoxin, ochratoxin, Patulin, etc.), which are secondary metabolites produced by molds (Tucker & Featherstone, 2011).

### 2.3.1 Factors affecting microbial growth

Growth of microorganisms is dependent on several factors such as oxygen content, temperature, relative humidity, pH, water activity (a_w), redox potential, and antimicrobial resistance. These factors can be grouped into intrinsic and extrinsic factors. Characteristics of the food itself are known as intrinsic (pH, a_w, redox potential) factors whereas factors external to food are known as extrinsic (oxygen content, temperature, relative humidity) factors.

Most microorganisms grow best at neutral pH and only a few are able to grow at a pH value of less than 4.0. Bacteria are more selective about pH requirements than yeasts and molds, which can grow over a wide range of pH. Microorganisms that can withstand low pH are known as aciduric. Bacteria require higher a_w for growth compared to that required by yeasts and molds. Gram-negative bacteria cannot grow at a_w less than 0.95, whereas most gram-positive bacteria cannot grow at a_w less than 0.90. However, *Staphylococcus aureus* can grow at a_w value as low as 0.85 and halophilic bacteria can grow at a minimum a_w value of 0.75. Halophilic microorganisms are those that require a high salt concentration (3.4–5.1 M NaCl) for growth. Most yeasts and molds can grow at a minimum a_w value of 0.88 and 0.80, respectively. Xerophilic (microorganisms which can grow in low a_w conditions) molds and osmophilic (microorganisms which can grow in high solute concentration) yeasts can grow at a_w as low as 0.61.

Redox potential is the tendency of a substance to convert to its reduced state by acquiring electrons. It is measured in millivolts (mV) relative to a standard hydrogen electrode (0 mV). In general, aerobic microorganisms prefer positive redox potential for growth whereas anaerobic microorganisms prefer negative redox potential (Tucker & Featherstone, 2011). Based on oxygen requirements, microorganisms can be classified into aerobes, anaerobes, facultative anaerobes, and microaerophiles. Aerobes grow in the presence of atmospheric oxygen whereas anaerobes grow in the absence of atmospheric oxygen. Facultative anaerobes are in between these two extremes and can grow in either the presence or absence of atmospheric oxygen. Microaerophiles require a small amount of oxygen to grow (Montville & Matthews, 2008).

Based on the response to temperature, microorganisms can be classified into psychrophilic, psychrotrophic, mesophilic, and thermophilic. Psychrophilic microorganisms have an optimum growth temperature between 12°C and 15°C but can grow up to 20°C. Psychrotrophic microorganisms have an optimum growth temperature between 20°C and 30°C but can grow up to 0°C. Mesophilic microorganisms have an optimum growth temperature between 30°C and 42°C but can grow between 15°C and 47°C. Thermophilic microorganisms have an optimum growth temperature between 55°C and 65°C, but can grow between 40°C and 90°C.

Relative humidity is the amount of water vapor present in a mixture of air and water. Relative humidity of the storage environment can affect growth of microorganisms by changing the water activity of the food (Montville & Matthews, 2008; Tucker & Featherstone, 2011).

### 2.4 Thermal kinetics

#### 2.4.1 Destruction of a microbial population

When a homogeneous microbial population is subjected to a constant temperature, T, the rate of destruction of microbes follows a first-order reaction kinetics as is given by David et al. (1996):
where 

\[
\frac{-dN}{dt} = K_T N,
\]

(2.1)

where \( N \) is the number of microbes surviving after processing time \( t \) (s) and \( K_T \) is the reaction rate (s\(^{-1}\)). Integration of Equation 2.1 from time 0 to time \( t \) yields:

\[
\frac{N}{N_0} = e^{-K_T t},
\]

(2.2)

where \( N_0 \) is the number of viable microorganisms at time \( t = 0 \).

Equation 2.2 can be rewritten as:

\[
\log_{10}\left(\frac{N}{N_0}\right) = -\frac{t}{D},
\]

(2.3)

where \( D = 2.303/K_T \). The parameter \( D \) is the decimal reduction time, the time required to reduce the size of the surviving microbial population by 90%. The \( D \) value is a measure of heat resistance of microorganisms. Microorganisms with a higher \( D \) value have a higher heat resistance. The \( D \) value determined at a reference temperature \( (T_{ref}) \) is denoted by \( D_{ref} \). The effect of temperature on \( D \) value is generally described by the following expression (David et al., 1996):

\[
\log_{10}\left(\frac{D_T}{D_{ref}}\right) = \frac{T_{ref} - T}{z},
\]

(2.4)

where \( D_T \) is the \( D \) value at temperature \( T \) and \( z \) is the change in temperature (°C) required to reduce the \( D \) value by 90%. \( D \) and \( z \) values are the basis of thermal process calculations and are commonly used to design a thermal process. \( D \) and \( z \) values for most of the common microorganisms are given in Table 2.1. The choice of target microorganisms for designing a thermal process should take into account the characteristics of the product (\( a_w \), pH, etc.) and the storage and transportation conditions.

The ratio of \( D_{ref} \) to \( D \) is the lethal rate (\( L_r \)). Thermal death time (TDT) or \( F \) value of a process is defined as the process time at a given temperature required for stipulated destruction of a microbial population, or the time required for destruction of microorganisms to an acceptable level. The \( F \) value can be expressed as a multiple of the \( D \) value for first-order microbial kinetics. The \( F \) value required for a process depends on the nature of food (pH and water activity), storage conditions after processing (refrigerated versus room temperature), target organism, and initial population of microorganisms (Singh, 2007). The \( F \) value is usually expressed with a superscript denoting \( z \) value and a subscript denoting temperature. It can be computed in terms of lethal rate as:

\[
F_{T_{ref}}^z = \int_0^1 L_r dt = \int_0^1 \left(10^{-\frac{T_{ref} - T}{z}}\right) dt = -D_{ref} \log\left(\frac{N}{N_0}\right),
\]

(2.5)

<table>
<thead>
<tr>
<th>Microorganisms</th>
<th>Temperature (°C)</th>
<th>( D ) value (min)</th>
<th>( z ) value (°C)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacillus cereus</td>
<td>121.1</td>
<td>0.0065</td>
<td>9.7</td>
<td>Lund, 1975</td>
</tr>
<tr>
<td>Bacillus coagulans</td>
<td>121.1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacillus coagulans var. thermoacidurans</td>
<td>96</td>
<td>3</td>
<td></td>
<td>Holdsworth, 2004</td>
</tr>
<tr>
<td>Bacillus licheniformis</td>
<td>100</td>
<td>6.6–9</td>
<td></td>
<td>Cousin, 1993</td>
</tr>
<tr>
<td>Bacillus stearothermophilus</td>
<td>121.1</td>
<td>4</td>
<td>7</td>
<td>Lund, 1975</td>
</tr>
<tr>
<td>Bacillus steatorhophilus</td>
<td>150</td>
<td>0.008</td>
<td></td>
<td>Cousin, 1993</td>
</tr>
<tr>
<td>Bacillus subtilis</td>
<td>121.1</td>
<td>0.48–0.76</td>
<td>7.4–13</td>
<td>Lund, 1975</td>
</tr>
<tr>
<td>Bacillus subtilis</td>
<td>140</td>
<td>0.001</td>
<td></td>
<td>Cousin, 1993</td>
</tr>
<tr>
<td>Clostridium botulinum</td>
<td>121.1</td>
<td>0.21</td>
<td>9.9</td>
<td>Lund, 1975</td>
</tr>
<tr>
<td>Clostridium butyricum</td>
<td>85</td>
<td>8</td>
<td></td>
<td>Holdsworth, 2004</td>
</tr>
<tr>
<td>Clostridium sporogenes</td>
<td>121.1</td>
<td>0.15</td>
<td>13</td>
<td>Lund, 1975</td>
</tr>
<tr>
<td>Clostridium sporogenes (PA 3679)</td>
<td>121.1</td>
<td>0.3–2.6</td>
<td>10.6</td>
<td>Cousin, 1993</td>
</tr>
<tr>
<td>Clostridium thermosacharolyticum</td>
<td>121.1</td>
<td>16–22</td>
<td>1.7–2.2</td>
<td>Lund, 1975</td>
</tr>
<tr>
<td>Desulfotomaculum nigrificans</td>
<td>121.1</td>
<td>3–5</td>
<td></td>
<td>Holdsworth, 2004</td>
</tr>
<tr>
<td>Desulfotomaculum nigrificans</td>
<td>121.1</td>
<td>13–54.4</td>
<td></td>
<td>Cousin, 1993</td>
</tr>
</tbody>
</table>
where temperature $T$ is a function of time. For a constant temperature process (process temperature remains constant), the above equation for the $F$ value reduces to:

$$F_z^T = 10^{-\frac{T - T_{ref}}{z}}$$  \hspace{1cm} (2.6)

The $F$ value at a reference temperature of 121.1°C (250°F) and a $z$ value of 10°C (18°F) is referred to as the $F_0$ value. The main microorganism of concern for low-acid foods is $C.\text{botulinum}$, which has a $D_{121.1}$ value of 0.21 min (see Table 2.1). For processes where $C.\text{botulinum}$ is the target organism, the $F_0$ value represents the process time necessary to achieve a 12 log reduction (12D) in microbial population of $C.\text{botulinum}$ at 121.1°C. A thermal process designed to reduce the probability of $C.\text{botulinum}$ spore survival to $10^{-12}$, a 12D process, is referred to as the botulinum cook. The $F_0$ value for a botulinum cook is $2.52$ (12 × 0.21) min. An $F_0$ value of 2.52 min indicates that the process is equivalent to a full exposure of food to 121.1°C (250°F) for 2.52 min. Many combinations of time and temperature can yield an equivalent $F_0$ value of 2.52 min. The $F$ value can be written in terms of the $F_0$ value as:

$$F_z^T = \frac{F_0}{L_r} = F_0 \times 10^{-\frac{T - T_{ref}}{z}}$$  \hspace{1cm} (2.7)

The ratio of $F_0$ value of the process at a given process time to the $F_0$ required for commercial sterility is known as lethality. Thus, lethality must be at least 1 for commercial sterility of the product (David et al., 1996). All low-acid food products are processed beyond the minimum botulinum cook in order to eliminate spoilage from mesophilic spore formers. The organism most frequently used to characterize this food spoilage is a strain of $C.\text{sporogenes}$, a putrefactive anaerobe (PA), known as PA 3679. The $F_0$ value required to prevent mesophilic spoilage represents a 5-log reduction in microbial population of $C.\text{sporogenes}$. A more severe process may be necessary for situations where thermophilic spoilage could be a concern because of very high heat resistance of thermophilic spores. A 5-log reduction of Bacillus stearothermophilus has been used to establish a thermal process to prevent thermophilic spoilage (Teixeira & Balaban, 2011). For foods with a pH value between 4.0 and 4.6, the thermal process is less severe. The microorganisms of concern include Bacillus coagulans, Clostridium butyricum, and Clostridium pasteurianum. The thermal process for foods with a pH value less than 4.0 is designed to inactivate the most resistant yeast, mold, or acid-tolerant bacteria.

Molds and yeasts are easily inactivated by heat but ascospores of yeasts and molds may be more heat resistant (Cousin, 1993).

### 2.4.2 Destruction of quality attributes

The destruction of nutrients and inactivation of enzymes follow similar kinetics to that of the destruction of microorganisms, which is first-order kinetics. $D_e$ and $z_e$ values for enzymes and quality attributes are given in Table 2.2. Destruction of nutrients in food products is quantified by the term cook value (C), which has been defined (Mansfield, 1962) as:

<table>
<thead>
<tr>
<th>Enzyme or quality attribute</th>
<th>Temperature (°C)</th>
<th>$D$ value (min)</th>
<th>$z$ value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthocyanin (in grape juice)</td>
<td>121.1</td>
<td>17.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Thiamin (in whole peas)</td>
<td>121.1</td>
<td>164</td>
<td>26.1</td>
</tr>
<tr>
<td>Thiamin (in pea puree)</td>
<td>121.1</td>
<td>247</td>
<td>26.7</td>
</tr>
<tr>
<td>Thiamin (in peas in brine)</td>
<td>121.1</td>
<td>226.7</td>
<td>27.2</td>
</tr>
<tr>
<td>Thiamin (in lamb puree)</td>
<td>121.1</td>
<td>120</td>
<td>25</td>
</tr>
<tr>
<td>Lysine (in soya bean meal)</td>
<td>121.1</td>
<td>786</td>
<td>21.1</td>
</tr>
<tr>
<td>Chlorophyll a (in spinach: pH = 6.5)</td>
<td>121.1</td>
<td>13</td>
<td>51.1</td>
</tr>
<tr>
<td>Chlorophyll b (in spinach: pH = 5.5)</td>
<td>121.1</td>
<td>14.7</td>
<td>79.4</td>
</tr>
<tr>
<td>Peroxidase (in peas)</td>
<td>121.1</td>
<td>3</td>
<td>37.2</td>
</tr>
<tr>
<td>Chlorophyll (in blanched pea puree)</td>
<td>121.1</td>
<td>14</td>
<td>36.7</td>
</tr>
<tr>
<td>Chlorophyll (in unblanched pea puree)</td>
<td>121.1</td>
<td>13.9</td>
<td>45</td>
</tr>
<tr>
<td>Color (in peas)</td>
<td>121.1</td>
<td>25</td>
<td>39.4</td>
</tr>
<tr>
<td>Organoleptic quality (in peas)</td>
<td>121.1</td>
<td>2.3</td>
<td>28.3</td>
</tr>
<tr>
<td>Texture (in peas)</td>
<td>121.1</td>
<td>1.4</td>
<td>32.2</td>
</tr>
<tr>
<td>Overall quality (in peas)</td>
<td>121.1</td>
<td>2.5</td>
<td>32.2</td>
</tr>
<tr>
<td>Color (in green beans)</td>
<td>121.1</td>
<td>21</td>
<td>38.9</td>
</tr>
<tr>
<td>Color (in asparagus)</td>
<td>121.1</td>
<td>17</td>
<td>41.7</td>
</tr>
</tbody>
</table>
2.4.3 Process optimization

The objective of a food processor is to produce a safe product that retains nutritional and quality attributes at an acceptable level. Therefore, the appropriate combination of time and temperature used for processing is based on factors such as nutrient retention and enzyme inactivation in addition to safety. Dc and zc values for destruction of nutritional and quality attributes are generally larger than those for microorganisms. This implies that the rate of destruction of microorganisms at higher temperature will be much higher than the rate of destruction of nutritional and quality attributes. Thus, thermal processing of food products at higher temperature can achieve commercial sterility with better retention of nutritional and quality attributes (David et al., 1996).

2.5 Thermal process establishment

The goal in thermal processing is to ensure that the slowest heating point (cold spot) within a product container receives adequate thermal treatment. This involves measurement of product temperature at the slowest heating point. For in-container sterilization processes, there are two main stages in thermal process establishment: the temperature distribution (TD) test to identify the slowest heating zone in the retort and the heat penetration (HP) test to determine the temperature history at the cold spot in prepackaged foods. For in-flow sterilization processes, the TD test is not required.

2.5.1 Temperature distribution test

The temperature distribution inside a retort is not uniform. The location of the slowest heating zone in the retort is determined by performing a TD test. The first step in conducting the test is the selection of the test retort. A survey of the processing room should be done to select the test retort. The survey should include examination of the following factors: steam, air, and water supply to the retort, type and size of each retort in the retort room, purging, drainage, and retort loading considerations (container information, type of product heating, maximum number of containers, etc.). To conduct the TD test, the situation resulting in worst-case conditions for commercial operation should be selected. Containers may be filled with water for convection heating products. For conduction heating products, containers should be filled either with the product or other material that simulates the product (starch solution). Temperature measuring devices (TMD) in sufficient quantity should be used to monitor the temperature of the heating medium within the retort. The most commons TMDs used in thermal processing are duplex type T (copper-constantan) thermocouples with Teflon insulation. Pressure-indicating devices should be used to monitor pressure in the retort shell during the test. Flow meters should be used to measure flow rate of process water during come-up and heating.

The test should be conducted at the maximum retort temperature used during processing. The critical parameters that should be recorded during a TD test include the temperature controller set point, initial temperature (IT), time when steam is turned on, temperature of heating medium, flow rate of heating medium, time when the reference TMD achieves the process set point, and come-up time. Come-up time (CUT) is the time required by a retort to attain a minimum required process temperature with uniform temperature distribution in the retort (IFTPS, 2005; Tucker, 2001).

2.5.2 Heat penetration test

The goal of a heat penetration test is to determine the heating and cooling behavior of a specific product-package combination in a specific retort system for establishment of a safe thermal process. The HP study is conducted before starting production of a new product using a new process. The test involves locating the cold spot in food within the package and establishing the scheduled process time and temperature. For a conduction heating product in a cylindrical can, the cold spot is at the geometric center of the can. For a convection heating product in a cylindrical can, the cold spot is between the geometric center and the base of the container. A study should be conducted to determine the location of the cold spot for a specific product-package-process combination. The cold spot is usually determined by conducting a series of HP tests employing several containers with thermocouples inserted at different locations. The design of an HP test should consider all critical factors to deliver adequate thermal
treatment to the slowest heating point within the product. Box 2.1 lists the critical factors that should be considered during an HP study.

An HP test should include at least 10 working thermocouples from each test run. HP tests should also be replicated to account for product, package, and process variability. Once the cold spot and all critical factors are determined, two full replications of each test should be conducted. A third replication should be conducted if results from the first two replications show variation (IFTPS, 1995; Tucker, 2001).

Heat penetration data are evaluated by plotting a heat penetration curve (Figure 2.1). The data are plotted such that there is a linear relationship between the product temperature ($T_p$) and heating time. A plot of $\log (T_r - T_p)$ versus time, known as the temperature deficit plot, is linear (see Figure 2.1). $T_r$ is the retort temperature. Heat penetration curves, which are linear throughout the heating time, are referred to as simple heating curves, whereas heat penetration curves showing an abrupt change in heat transfer are referred to as broken heating curves. A heat penetration curve for a broken heating profile has two linear portions due to change in the heating mode from conduction to convection or vice versa. Heat penetration data can also be plotted as an inverted scale plot with $T_p$ on the right-hand axis (see Figure 2.1).

There are two important parameters that define a simple heat penetration curve. The negative inverse of the slope, known as the heating rate factor ($f_h$), is defined as the time required for the heat penetration curve to traverse one log cycle. A lower $f_h$ value indicates a faster heating rate. The subscript h indicates that the $f$ value is for a heating process. A similar cooling rate factor ($f_c$) is defined for

**Box 2.1 Factors affecting heating behavior during heat penetration (HP) study (Tucker, 2001)**

<table>
<thead>
<tr>
<th>Product factors</th>
<th>Formulations, fill weight, viscosity, solid components, preparation methods, rehydration of dried components, heating mode, pH, water activity, density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Container factors</td>
<td>Type (metal cans, glass jars, pouches, semi-rigid containers), size and dimension, vacuum, headspace, container orientation (vertical or horizontal), fill method, symmetry of rotation</td>
</tr>
<tr>
<td>Filling/sealing factors</td>
<td>Fill temperature, seal integrity</td>
</tr>
<tr>
<td>Retort factors</td>
<td>Type of heating medium (steam, steam/air, water immersion, water spray), come-up time, racking dividing systems, rotation for rotary retort systems</td>
</tr>
</tbody>
</table>

**Figure 2.1** Heat penetration curve.
the cooling curve. The other parameter is the intercept of the heat penetration curve. The intercept is obtained by linear extrapolation of the curve back to zero time. The intercept is \( T_r - T_{ih} \), where \( T_{ih} \) is pseudo initial product temperature determined by linearizing the entire heat penetration curve. The equation of the heat penetration curve can be written as (Lund, 1975):

\[
\log(T_r - T_p) = \left( -\frac{t}{f_h} \right) + \log(T_r - T_{ih}), \quad (2.9)
\]

where \( t \) is the heating time. A dimensionless heating lag factor, \( j_h \), is defined as (Lund, 1975):

\[
j_h = \frac{T_r - T_{ih}}{T_r - T_i}, \quad (2.10)
\]

where \( T_i \) is the initial temperature of the product. Substituting \( (T_r - T_{ih}) \) from Equation 2.10 in Equation 2.9 leads to the following equation:

\[
\log(T_r - T_p) = \left( -\frac{t}{f_h} \right) + \log[j_h(T_r - T_i)] \quad (2.11)
\]

At the end of the process time (\( B \)), if the temperature difference \( (T_r - T_p) \) is defined as \( g \), then Equation 2.11 can be written as (Lund, 1975):

\[
\log(g) = \left( -\frac{B}{f_h} \right) + \log[j_h(T_r - T_i)] \quad (2.12)
\]

or

\[
B = f_h \log\left( \frac{[j_h(T_r - T_i)]}{g} \right) \quad (2.13)
\]

Equation 2.13, known as the ball formula method, can be used to calculate process time if the value of \( g \) is known. The temperature at the cold spot is also determined for the cooling phase. The cooling curve can be characterized in a similar manner by using cooling rate factor \( (f_c) \) and cooling lag factor \( (j_c) \). Temperature of the cooling water \( (T_c) \) is used in place of \( T_r \) for plotting the cooling curve (Lund, 1975).

### 2.6 Thermal process calculation

Many different methods, based on Equations 2.5 and 2.13, have been proposed for thermal process calculations. The difference between them is the way the temperature at the cold spot is obtained. For some methods, temperature is physically measured whereas some methods use mathematical models for predicting the temperature. The process calculation methods can be divided into three categories: general method, formula method, and numerical method (Weng, 2005).

#### 2.6.1 The general method

The general method, developed by Bigelow in 1920, is the simplest of all methods for the calculation of thermal process. This method involves graphical or numerical integration of Equation 2.5 when the temperature distribution is known either from the heat penetration data or heat transfer equations. The time-temperature graph is converted into a lethal rate \( (L_r) \) versus time graph using Equation 2.5. The area under the \( L_r - t \) curve is the \( F \) value of the process. The area under the \( L_r - t \) curve can also be determined using numerical methods such as the trapezoidal rule or Simpson’s rule. Simpson’s rule is generally more accurate and requires an even number of areas. Thermal process developed by the general method is dependent on product-package-process parameters used during the test. The thermal process is established only for the actual conditions tested (retort temperature and initial temperature). Therefore, this method is not useful to determine \( F \) values for different retort temperatures and initial temperatures of product. Thus, the general method does not allow assessment of process deviations (Park, 1996; Weng, 2005).

The general method relies on time-temperature history at the cold spot. Thus, it can be used for both in-container sterilization and in-flow sterilization. For a fluid product in an in-flow sterilization process, process time \( \) (\( t \)) for a given \( F \) value and process temperature \( \) \( (\text{temperature } T \text{ of product at the exit of the hold tube}) \) can be calculated from Equations 2.5 and 2.6. The required process time must be achieved for the fastest moving portion of the fluid product. The length of the hold tube is calculated as:

\[
L = u_{max} t, \quad (2.14)
\]

where \( u_{max} \) is the maximum velocity of the product in the holding tube. Maximum velocity occurs at the center of the holding tube. For Newtonian fluids, the magnitude of \( u_{max} \) is given as:

Laminar flow conditions : \( u_{max} = 2 \bar{u} \)

Turbulent flow conditions : \( u_{max} = 1.2 \bar{u} \)
where $\bar{u}$ is the average fluid velocity, which is volumetric flow rate divided by cross-sectional area for flow. For non-Newtonian fluids under laminar flow conditions, the magnitude of $u_{\text{max}}$ is given as:

$$u_{\text{max}} = \frac{3n + 1}{n + 1} \bar{u},$$  \hspace{1cm} (2.16)

where $n$ is the flow behavior index. For most fluid products, the limiting case for design of holding tubes is based on $u_{\text{max}} = 2\bar{u}$ (Lund & Singh, 1993).

For multiphase food products, calculation of process time is more difficult than for fluid products. The challenges associated include determination of residence time distribution (RTD) of particles and the heat transfer coefficient between particles and fluid. The main problem in process establishment in a multiphase product has been the inability to measure the temperature of particles suspended in a carrier fluid and flowing in a continuous system (Sandeep & Puri, 2001).

### 2.6.2 The formula method

The formula method uses heat penetration data and mathematical models to establish the heating rate of the product in the form of an equation. Equation 2.13 is the basis for the formula method. The process time can be determined if $f_h$, $j_h$, $(T_r - T_i)$, and $g$ are known. The first three parameters can be obtained from a heat penetration curve. However, it is difficult to obtain the value of $g$ (Lund, 1975).

#### 2.6.2.1 The Ball formula method

To overcome the limitation of the general method, C.O. Ball proposed the Ball formula method in 1923. This method allows for extrapolation of process time for different retort temperatures and product initial temperatures. It is the most widely used and accepted method of thermal process calculation in the US. Ball related the value of $g$ to the dimensionless ratio $f_h/F_{T_r}$ ($T_r$, retort temperature) for various $z$ values and cooling lag factor $j_c$. If the $F$ value at $T_r$ is $U$, then the equation for TDT curve can be written as (Lund, 1975):

$$\log(U) = \log(F_{250}^z) - \frac{T_r - 250}{z}$$  \hspace{1cm} (2.17)

Ball defined a phantom or reference TDT curve as the one with the same slope as TDT curve, but that represents heat resistance of microorganisms if $F_{250} = 1$. By substituting $F_{250} = 1$ min in Equation 2.17, the equation of the phantom TDT curve can be written as (Lund, 1975):

$$\log(F_i) = -\frac{T_r - 250}{z}$$  \hspace{1cm} (2.18)

where $F_i$ is $F_{T_r}$ on the phantom TDT curve. Combining Equations 2.17 and 2.18 yields (Lund, 1975):

$$U = F_iF_{250}^z$$  \hspace{1cm} (2.19)

$F_i$, which is a function of $z$ value and $T_r$, can be found in literature (Stumbo, 1973). Thus, $U$ can be calculated if the value of $F_{250}$ is known. Once $U$ is determined, the $g$ value can be determined from $f_h/U$: $g$ correlations (for various $j_c$ values at a $z$ value of 18°C) in literature (Stumbo, 1973). Once $g$ is known, the process time ($B$) can be determined from Equation 2.13. The calculated process time is applicable to processes where the product comes in contact with steam at retort temperature without any lag. This situation holds true only for continuous retorts. In batch retorts, there is a time lag in getting the retort to process temperature. This time lag is known as the come-up time (CUT). The Ball method accommodates for 42% contribution of CUT to the process time. Thus, the process time ($P_t$) in a batch retort can be given as (Lund, 1975):

$$P_t = B - 0.42 \times \text{CUT}$$  \hspace{1cm} (2.20)

The following assumptions are made while calculating the process time using the Ball method: $j_c = 1.41$, $f_c = f_h$ for simple heating curve, no product heating occurs after cooling starts, constant retort temperature, and constant cooling water temperature (100°C below retort temperature for cans and 72.2°C below retort temperature for glass containers). These assumptions make the Ball method flexible, but decrease its accuracy. The Ball method often underestimates the $F$ value for conduction heating products. For products packed in thin pouches, the Ball method can overestimate $F$ value, as the $j_c$ value is substantially less than the assumed value of 1.41. The major limitation of the Ball formula method is its inability to handle variable process temperature (Park, 1996; Weng, 2005).

The Ball formula method has been modified by Stumbo and Hayakawa. Stumbo used the same heating factors. However, Stumbo’s modified model allowed for $j_c$ values other than 1.41 and considered variation in $z$ values and ($T_r - T_c$). Hayakawa’s modified method provided for a
range of $j_c$ values and unlimited range of $z$ value and $(T_r - T_c)$ combinations (Holdsworth & Simpson 2008; Stumbo, 1973). Although the Ball formula method was developed for in-container sterilization processes, it is applicable to in-flow sterilization as well. For in-flow sterilization systems using indirect heat exchangers, time-temperature profile can be described by Equation 2.11 after changing retort temperature to the temperature of the heating medium and product temperature to the mass average temperature of the product (Lund & Singh, 1993).

### 2.6.3 The numerical methods

The numerical methods have been widely used to establish thermal processes and evaluate process deviations since the 1970s. These methods are sophisticated and can handle variable process temperatures, which makes them very useful for thermal process deviation analysis. NumeriCAL™ and CTemp are two examples of software packages used in the food industry (Weng, 2005).

#### 2.6.3.1 NumeriCAL™

NumeriCAL™ is a software package offered by JBT Corporation (Chicago, IL), which performs thermal process calculations by using a finite difference method to solve partial differential equations of unsteady-state heat transfer. The main advantages of NumeriCAL™ are its accuracy and flexibility. The results obtained by using this software are accepted by both the FDA and USDA. NumeriCAL™ requires the use of heating factors and can be used for products with conduction, convection, or broken heating behavior. NumeriCAL™ consists of two modules: analyze and calculate. The “analyze” module analyzes heat penetration data and develops heating and cooling factors for the worst-case container. The “calculate” module is used for thermal process calculation and thermal process deviation analysis (Weng, 2005).

#### 2.6.3.2 CTemp

CTemp is another software package for calculating the internal temperature of products during thermal processing. It can be used to determine the F value for any in-container sterilization process, optimize the process, analyze process deviations, and efficiently establish process temperature and time (Weng, 2005).

### 2.6.3.3 AseptiCAL™

NumeriCAL™ and CTemp have been developed for thermal process calculation of an in-container sterilization process. AseptiCAL™ is a software package offered by JBT Corporation (Chicago, IL), which performs thermal process calculations by using advanced finite difference-based mathematical modeling for in-flow (aseptic process) sterilization process of low-acid and high-acid foods with or without particles. This software can be used to determine the center temperature of the fastest moving particle and calculates lethality values and the required length of the hold tube for safety of the process.

### 2.7 Thermal process validation

Once the thermal process is established, the designed process should be validated during actual process conditions. The methods most commonly used for thermal process validation are temperature measurement, microbiological validation, and the use of time-temperature integrators.

#### 2.7.1 Temperature measurement

The F value delivered during a process can be calculated using Equation 2.5 if the time-temperature history at the cold spot is known. Modern data loggers for temperature measurement are typically multichannel systems with digital output for display that can also record the data. Thermocouples based on type T (copper-constantan) with Teflon insulation are the temperature measurement devices most commonly used. Another type of temperature measurement device is the resistance temperature detector, based on change in electrical resistance with temperature (Tucker, 2001).

#### 2.7.2 Microbiological validation

Microbiological validation is a direct method of thermal process validation. Log reductions achieved during a process are measured using a non-pathogenic microorganism (surrogate microorganism). The log reductions are converted to the F value using Equation 2.5.

##### 2.7.2.1 Count reduction method

In the count reduction method, a known number of microorganisms are exposed to a thermal process.
After processing, the number of surviving microorganisms is determined. This method requires direct measurement of surviving microorganisms after the treatment in order to determine the F value of the sterilization process. Microbiological validation using count reduction can be conducted using either an inoculated pack or encapsulated spore method. In the inoculated pack method, the entire food is inoculated with a certain number of microorganisms of known heat resistance (D value). The containers are incubated after processing and the surviving microorganisms are counted. The F value received during the process can be calculated from Equation 2.5. For this method to be successful, some microorganisms should survive the process. Thus, a non-pathogenic microorganism with a high $D_{121.1}$ value (Bacillus stearothermophilus or Clostridium sporogenes) is usually used for an inoculated pack study. Typical levels of inoculum are between $10^3$ and $10^5$ spores per container (Tucker, 2001).

2.7.2.2 End point method
In the end point method, a known number of microorganisms are exposed to a thermal process. After processing, the presence or absence of surviving microorganisms is determined by cultivation in an appropriate medium. A binary response of growth or no growth is obtained. A no-growth result implies sterility of the sample.

2.7.3 Time-temperature integrators
Time-temperature integrators (TTIs) have received considerable attention as an alternative means of process evaluation to either temperature measurement or microbiological validation. A TTI can be an enzyme that is denatured during heating. If the reaction kinetics of temperature-induced enzyme denaturation match the death kinetics of the target microorganism, that TTI can be used as a non-biological marker of the safety of a process (Tucker, 2001).

2.8 Process monitoring and control

2.8.1 Critical factors in thermal processing
A critical factor is one that may affect the scheduled thermal process and attainment of commercial sterility. Once thermal process validation is done, critical factors should be monitored and controlled to ensure safety of the food product. Some of the critical factors related to the design of a thermal process include factors related to the product, process, and package. Some of the product-related critical factors include microbial load of the raw materials, additives and ingredients used in product formulation, product characteristics ($pH$, $a_w$, thermophysical properties, rheological properties, particle size, solid/liquid ratio), fill weight, and pretreatment (blanching, rehydration). Process-related critical factors include type (metal can, glass jars, pouches, semi-rigid containers) and size of the package, headspace, and vacuum. Process-related critical factors include rotation/agitation of containers, initial temperature, CUT, heating method (direct versus indirect), heating medium, process temperature, process time, temperature of cooling medium, residence time distribution (RTD), and flow rate (Zuber et al., 2011).

2.9 Emerging processing technologies

2.9.1 Ohmic heating
Ohmic heating, also known as joule heating, electric resistance heating, and electroconductive heating, is a process in which an alternating current is passed directly through a conductive food product. The heat is generated internally due to the resistance of the food product to the applied electric current. The heating is rapid due to volumetric generation of heat. The heat generated ($P$) is given as:

$$P = E^2 \sigma,$$

where $E$ is the electric field strength (V/m) and $\sigma$ is the electrical conductivity. Electric field strength can be varied by adjusting the electrode gap or the applied voltage. Electrical conductivity is the measure of how well a substance conducts electricity and is expressed in the units of Siemens per meter ($S\cdot m^{-1}$). The efficiency of ohmic heating is dependent on the electrical conductivity ($\sigma$) of the product (Coronel et al., 2008).

2.9.2 Microwave heating
Microwaves are part of the electromagnetic spectrum and have a frequency between 300 MHz and 300 GHz. They lie between the radio (3 kHz–300 MHz) and infrared (300 GHz–400 THz) frequencies of the electromagnetic spectrum. Microwave radiation has the ability to heat materials by penetrating and dissipating heat
in them. The important advantages of microwave heating compared with conventional heating include instant start-up, faster heating, and energy efficiency. The main disadvantage associated with microwave heating is non-uniform heating of food products. In the US, only four microwave frequencies (915 ± 13, 2450 ± 50, 5800 ± 75, and 24,150 ± 125 MHz) are permitted by the Federal Communications Commission (FCC) for industrial, scientific, and medical applications.

Interaction of microwaves with materials depends on their dielectric properties. Dielectric properties determine the extent of heating of a material when subjected to an electromagnetic field. Therefore, knowledge of dielectric properties is important for the design of a microwave heating system. Dielectric properties consist of the dielectric constant (\(\varepsilon'\)) and the dielectric loss factor (\(\varepsilon''\)). The dielectric constant is a measure of the ability of a material to store electromagnetic energy, whereas the dielectric loss factor is a measure of the ability of a material to convert electromagnetic energy to heat (Metaxas & Meredith, 1983). Dielectric properties can be defined in terms of a complex permittivity (\(\varepsilon\)) as:

\[
\varepsilon = \varepsilon_0 (\varepsilon' - j\varepsilon''),
\]

(2.22)

where \(j^2 = -1\) and \(\varepsilon_0\) is the permittivity of free space \((8.86 \times 10^{-12} \, \text{F/m})\). Loss tangent (\(\tan \delta\)), a parameter used to describe how well a product absorbs microwave energy, is the ratio of the dielectric loss factor (\(\varepsilon''\)) to the dielectric constant (\(\varepsilon'\)). A product with a higher loss tangent will heat faster in a microwave field compared to a product with a lower loss tangent. Dielectric properties of food products depend on the frequency of the microwaves, temperature, composition, and density of the materials (Nelson & Datta, 2001).

The power absorption for volumetric heating using microwave is given as (Coronel et al., 2008):

\[
P = 2\pi f \varepsilon_0 \varepsilon'' E^2
\]

(2.23)

where \(P\) is power absorbed \((\text{W/m}^3)\) per unit volume, \(f\) is the microwave frequency \((\text{Hz})\), and \(E\) is the electric field strength \((\text{V/m})\). Power penetration depth \((\delta_p)\), often used in microwave heating applications, is the distance within the product at which power drops to \(e^{-1}\) of its value at the surface of the material and is given by the following equation (Nelson & Datta, 2001):

\[
\delta_p = \frac{\lambda}{2\pi \sqrt{2\varepsilon' \left[1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2 - 1\right]}}.
\]

(2.24)

where \(\lambda\) is the wavelength of the microwave in free space. Power penetration depth is used to calculate the tube diameter for a continuous flow microwave heating system. For volumetric heating systems such as ohmic heating and microwave heating, the heat transfer model should include the appropriate volumetric heating term.

### 2.10 Future trends

The principles associated with thermal processing have not changed over the years. However, there have been constant improvements in the technologies used for sustainable food preservation, equipment used for processing (heating and cooling), sensors used for process monitoring, mathematical models developed to characterize the heating within the product, techniques used to improve product quality, protocols developed for handling process deviations, and methodologies used for process validation. We can thus anticipate continued changes in these areas. Some of the expected changes are elaborated in this section.

Microwave, radiofrequency, and ohmic heating technologies are rapid volumetric heating technologies that are gaining popularity in the food industry for thermal processing of hard-to-heat foods (viscous and particulate foods). It is expected that their use will become more prevalent in the next decade. With rapid heating becoming a reality, the lack of a rapid cooling technology is currently an impediment in improving product quality. Thus, it is expected that techniques to rapidly cool products will be developed in the near future. That will also lead to sustainable use of existing energy sources. Another sustainable practice gaining traction in recent years is heat and water recovery of heat transfer equipment. An electronic sensor to monitor the time-temperature history at the cold spot of a particulate product during a continuous retorting operation and an aseptic process will be a reality, the lack of a rapid cooling technology is currently an impediment in improving product quality. Thus, it is expected that techniques to rapidly cool products will be developed in the near future. That will also lead to sustainable use of existing energy sources. Another sustainable practice gaining traction in recent years is heat and water recovery of heat transfer equipment. An electronic sensor to monitor the time-temperature history at the cold spot of a particulate product during a continuous retorting operation and an aseptic process will be a reality.
as enzymatic TTIs, biological indicator units, micro-electronic sensors, and nanosensors) can be expected in the decades to follow. All of these will aid in the development of new processes with improved safety and efficiency and new products with improved quality and functionality.

References


