CHAPTER 2

HEAT TRANSFER PRINCIPLES

Food preservation remains to be one of the important food processing industries. Early approaches to food preservation applied the methods of preservation naturally available, such as sun drying, salting, and fermentation, which were used to provide food in periods when fresh foods were not available. As civilization developed, demand for large quantities of better quality processed food also increased. This led to the development of a large food preservation industry aimed at supplying food of high quality in an economical way. Thermal sterilization of foods is the most significant part of this industry (Karel et al., 1975). Other methods of sterilization such as a pulsed electric field (Barbosa-Canovas et al., 1998; Barbosa-Canovas and Zhang, 2000; Jia et al., 1999; Martin et al., 1997; Qin et al., 1994, 1998; Sepulveda-Ahumada et al., 2000; Vega-Mercado et al., 1997, 1999; Zhang et al., 1995), ultrahigh hydrostatic pressure (Barbosa-Canovas et al., 1997a; Furukawa and Hayakawa, 2000; Paloua et al., 1999; Sancho et al., 1999), and ultraviolet (UV) treatment (Farid et al., 2000) have been widely studied. However, with the exception of high-pressure processing, these technologies have not yet reached commercialization stage.

2.1. INTRODUCTION TO THERMAL STERILIZATION

Two different methods of conventional thermal processing are known: aseptic processing, in which the food product is sterilized prior to packaging, and canning in which the product is packed and then sterilized (Barbosa-Canovas et al., 1997b). Food after being canned has to undergo thermal treatment to deactivate most organisms (i.e. sterilization). In 1981, the food industry in the United States alone processed more than 16.3 billion kg of food products in approximately 37 billion containers (Kumar et al., 1990).

Thermal sterilization is one of the most effective means of preserving a large part of our food supply. The objective of sterilization is to extend the shelf life of food products and make the food safe for human consumption by destroying harmful microorganisms. A sterilizer is a unit in which food is heated at high temperature and then held at that temperature for a period sufficient to kill the microorganisms of concern from the foodproduct. A sterile product is one in which no viable microorganisms are present. A viable organism is one that is able to reproduce when exposed to conditions that are optimum for its growth. Temperature slightly higher than the maximum for bacterial growth results in the death of vegetative bacterial cells, whereas bacterial spores can survive at much higher temperatures. Since bacterial spores are far more heat resistant than vegetative cells, they are of primary concern in most sterilization processes. Saturated steam is the most commonly used and highly desirable heating medium for commercial sterilization of canned foods. Conventional canning consists of the following operations:

1. Preparing the food (cleaning, cutting, grading, blanching, etc.)
2. Filling the container
3. Sealing the container

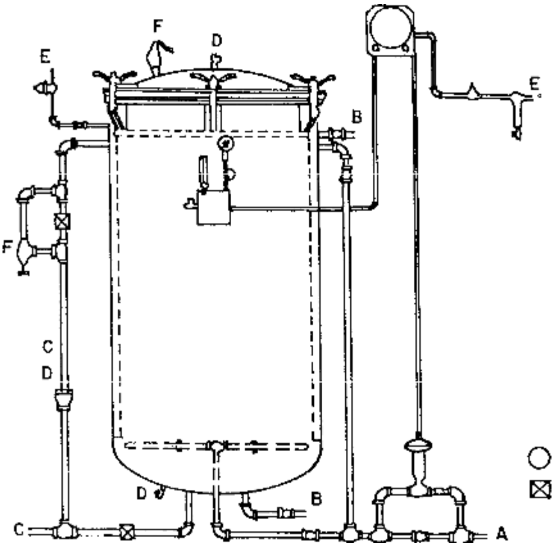

Figure 2.1. Vertical retort (Rahman, 1999).

4. Placing the container in a batch or continuous retort where it is heated for a time sufficient for commercial sterility
5. Cooling of the container, which is usually done using a cold shower

The still retort is the oldest type of equipment used for thermal processing. It is still used in large canning plants for metal- and glass-packed products. The sterilization method using a still retort consists of loading the containers, which are placed into baskets immediately after seaming and then into an appropriately designed iron vessel (retort), closing the vessel, and heating the containers with steam. A controller regulates the temperature, and the duration of heating is determined by the rate of heat transfer into the containers. Introduction of steam into the retort should be done with care since it is necessary to displace all of the air in the retort. The presence of air during thermal sterilization processing can result in under-processing since steam–air mixtures result in lower heat transfer rates (Karel et al., 1975).

Still retorts are usually arranged either vertically (Figure 2.1) or horizontally (Figure 2.2). The metal shell pressure vessel is fitted with a steam inlet (A), a water inlet (B), outlet ports for venting

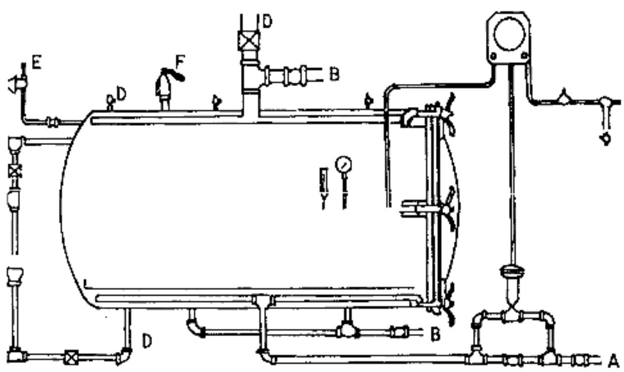

Figure 2.2. Horizontal retort (Rahman, 1999).

air during retort come-up and for draining (D), outlet ports for venting the retort at the end of the cycle (C), and a safety and pressure relief valve (F). A pocket for instruments, a thermometer, a temperature-recording probe, and a pressure gauge is located on the side of the vessel.

The operating cycle of this type of a retort involves bringing the retort up to a temperature of around 121°C. Steam is then allowed to pass through the vessel so that all air in the retort and between the cans is removed (venting) before the retort is finally brought up to the operating pressure and processing temperature (Rahman, 1999). At the end of the processing time, the steam is turned off, and a mixture of cooling water and air is introduced into the retort to cool the cans. The purpose of the air is to maintain the pressure in the retort, following the condensation of the residual steam after the initial introduction of cooling water. The containers may deform because of the pressure difference between inside and outside of the container if this pressure is not maintained.

The recent focus on thermal sterilization of foods is to improve the rates of heating, in order to increase production rates and minimize damage to product quality.

2.2. HEAT TRANSFER

In the sterilization of canned food, the heat transfer mechanism through liquid food in cans is classified as convection-heated, conduction-heated, or combined convection- and conduction-heated mechanism (Herson and Hulland, 1980). *Conduction* is the movement of heat by direct transfer of molecular energy within solids. *Free convection* is the transfer of heat in fluid by groups of molecules or fluid bulk that moves as a result of differences in the density of the fluid. In most applications these two types of heat transfer occur simultaneously, but one type may be more important than the other. *Steady-state* heat transfer takes place when there is no change in temperature with time. However, in most food processing applications, the temperature of the food or of the heating or cooling medium is constantly changing, and *unsteady-state* heat transfer is found more commonly. Calculations of heat transfer under these conditions are complicated but are simplified by making a number of assumptions (Fellows, 1996). *Forced convection* heat transfer will not be discussed in this chapter since it is not applicable to a number of objectives stated in this book. The subject of forced convection heat transfer is well described in most heat transfer textbooks. Also, the analysis of heat transfer presented in this chapter does not cover heat transfer with phase change such as freezing or evaporation. In retorting, steam condensation occurs at the surface of the cans or pouches. However, the condensation heat transfer coefficient is large enough to allow the assumption that the surface temperature is the same as the condensing steam temperature. The calculation of evaporation and condensation heat transfer coefficients is well described in most textbooks of heat transfer (Holman, 1992; Incropera and DeWitt, 1996). Radiation heat transfer does not play an important role in heat transfer in retorting since the heating temperature does not exceed 121°C and hence will not be considered in the analysis presented in this book.

The thermal conductivities of a variety of food materials are available in the literature. A notable feature of food products is their low value of thermal conductivity compared to metals. In metals, electrons transmit most of the heat energy, whereas in foods, where water is the main constituent, the free electron concentration is low, and the transfer mechanism involves primarily vibration of atoms and molecules (Karel et al., 1975). Moreover the thermal conductivity of liquid food is close to that of water.

2.2.1. Unsteady-State Heat Conduction

In food processing, there are many situations where temperature is a function of time. The most notable examples of unsteady-state heat transfer are heating and cooling of particulate materials, such as cooling and heating of products in containers (canning). If the heated or cooled materials are solid, then heat will transfer by conduction only. The calculations of unsteady-state heat transfer are usually complicated and involve solving the Fourier equation, written in terms of the partial differential equation in three dimensions (Karel et al., 1975). In unsteady-state heat transfer, the temperature within a food during processing depends on the time and position. The temperature changes are influenced by

1. the initial temperatures of the heated body
2. the temperature of the heating medium
3. the surface heat transfer coefficient (heat transfer coefficient at all interfaces as well as where convection is involved)
4. the thermal conductivity, specific heat, and density of the food and their variation with temperature and composition
5. thickness of the heated body

The basic equation for unsteady-state heat conduction in one-space dimension (x) is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \frac{\partial^2 T}{\partial x^2} \tag{2.1}$$

where $\partial T/\partial t$ is the change of temperature with time, ρ is the density (kg m^{-3}), C_p is the specific heat capacity (J kg^{-1}K^{-1}), and k is the thermal conductivity (W m^{-1}K^{-1}).

When a solid piece of food is heated or cooled by a fluid, the resistance to heat transfer is mainly controlled by the surface heat transfer coefficient (h) and the thermal conductivity of the food (k). These two factors are related by the *Biot number* (*Bi*):

$$Bi = \frac{h\delta}{k} \tag{2.2}$$

where δ is the characteristic dimension or heat transfer path length in the solid (m). At small *Bi* values (>0.2), the surface film is the main resistance to heat flow; in this case, the assumption of a negligible internal (conductive) heat transfer resistance in the solid food is valid (Barbosa-Canovas et al., 1997b). However, in most applications the thermal conductivity of the food limits the rate of heat transfer ($Bi > 1$). The calculations in these cases are complex, and a series of charts is available to solve the unsteady-state equations for simple-shaped foods, as described in the following section.

2.2.1.1. Convection Boundary Conditions

In most practical situations, a transient heat conduction problem is connected with a convection boundary condition at the surface of the solid. Naturally, the boundary conditions for the differential equation must be modified to take into account this convective heat transfer at the surface (Holman and White, 1992). The most important cases are plates whose thickness is smaller than their other dimensions, cylinders whose diameter is smaller than their length, and spheres. Results for these geometries have been presented in a graphical form known as *Heisler charts* (Heisler, 1947; Holman, 1992). In all cases the convection temperature is designated as T_∞ and the center temperature for plate ($x = 0$) or cylinder and sphere ($r = 0$) as T_0. At time zero, each solid is assumed to have a uniform temperature T_i. Temperatures in the solids are given in Heisler charts as a function of time and spatial position. The calculations for the Heisler charts are performed by truncating the infinite series solutions for the problems into a few terms. This restricts the applicability of the charts to values of the Fourier number (Fo) greater than 0.2.

Heisler charts may be used to obtain the temperature distribution in the infinite plate, the long cylinder, or the sphere. When a wall whose height and depth dimensions are not large compared with the thickness or a cylinder whose length is not large compared with its diameter is encountered, additional space coordinates are necessary to specify the temperature, and the above charts no longer apply. In this case we have to seek another solution (Holman and White, 1992). Fortunately, it is possible to combine the solution for the one-dimensional system in a very straightforward way to obtain solutions for the multidimensional problems. There are many other practical heating and cooling problems of interest. The solutions for a large number of cases are presented in graphical form by Schneider (1955).

The charts described above are very useful for calculating temperatures in certain regular-shaped solids under transient heat flow conditions. Unfortunately, many geometric shapes of practical interest do not fall into these categories, and we are also frequently faced with problems in which the boundary conditions vary with time. These transient boundary conditions as well as the geometric shape of the body do not allow analytical solutions. In these cases the problems are best handled by numerical techniques such as those used and presented in detail in this book for the cases of thermal sterilization in cans and pouches.

2.2.2. Free Convection

When a fluid's temperature changes, the resulting changes in density establish natural convection currents, which occur as a result of bulk movement of the fluid, such as the movement of liquid inside a can during sterilization. Obviously, heat transfer by conduction occurs simultaneously but is generally negligible compared to convection heat transfer (Karl et al., 1975). The rate of convection heat transfer is governed by Newton's law of cooling. This law states that the rate of heat transfer by convection is directly proportional to the heat transfer area and the temperature difference between the fluid and heating/cooling surface:

$$Q = h_s a\,(T_{bu} - T_s) \tag{2.3}$$

where Q is the rate of heat transfer (W), a is the surface area (m^2), T_s is the surface temperature, T_{bu} is the bulk fluid temperature, and h_s is the surface or film heat transfer coefficient (W m^{-2} K^{-1}). The surface heat transfer coefficient is inversely related to heat flow resistance, caused by the boundary film near the surface, and is therefore equivalent to the term $k/\Delta x$ in the conduction equation. The heat transfer coefficient is a function of the physical properties of the liquid food used in thermal processing, such as the density, viscosity, specific heat, and thermal expansion coefficient. It is also related to the gravity, which causes circulation due to the changes in density; the temperature difference; and the length or diameter of the container under investigation. The formulae, which relate these factors, are expressed as dimensionless numbers as shown below:

$$\text{Nusselt number Nu} = \frac{h d_v}{k} \tag{2.4}$$

$$\text{Prandtl number Pr} = \frac{C_p \mu}{k} \tag{2.5}$$

$$\text{Grashof number Gr} = \frac{d_v^3 \rho^2 g \beta \Delta T}{\mu^2} \tag{2.6}$$

where h is the heat transfer coefficient at the solid liquid interface (W m^{-2} K^{-1}); d_v is the characteristic dimension (m), which may be the height or diameter of the can, as will be discussed later; k is the thermal conductivity of the fluid (W m^{-1}K^{-1}); ρ is the density (kg m^{-3}); C_p is the specific heat capacity (J $kg^{-1}K^{-1}$); μ is the viscosity (N s m^{-2}); g is the acceleration due to gravity (m s^{-2}); β is the thermal expansion coefficient (K^{-1}); and ΔT is the temperature difference (°C).

There are large numbers of empirical correlations available in literatures describing the relationship between Nu, Gr, and Pr for many cases (Holman, 1992; Incropera and DeWitt, 1996; Mills, 1995). These cases include fluid heated or cooled by vertical and horizontal solid cylinders, inclined surfaces, etc. These correlations are approximate and purely empirical and can be used only for the geometries for which they have been developed. Such empirical correlations are not available in literatures for liquid heated in cylinders or pouches. The only approach left to account for the free convection of liquid in these geometries is to solve the Navier–Stokes equations of continuity, momentum, and energy conservation in a cylinder and pouch space, as described in the following chapters of this book.

NOMENCLATURE

a	area, m^2
Bi	Biot number, $Bi = \frac{h\delta}{k}$, dimensionless
C_P	specific heat of liquid food, J $kg^{-1}K^{-1}$
d_v	vertical dimension, m
Gr	Grashof number, $Gr = \frac{d_v^3 \rho^2 g \beta \Delta T}{\mu^2}$, dimensionless
g	acceleration due to gravity, m s^{-2}
h	heat transfer coefficient, W $m^{-2}K^{-1}$
k	thermal conductivity, W m^{-1} K^{-1}
Nu	Nusselt number, $Nu = \frac{h_c d_v}{k}$, dimensionless
Pr	Prandtl number, $Pr = \frac{C_p \mu}{k}$, dimensionless
F_o	Fourier number
Q	rate of heat transfer, J s^{-1}
t	time, s
T	temperature, °C
β	thermal expansion coefficient, K^{-1}
μ	viscosity, Pas
ρ	density, kg m^{-3}
δ	diameter, m

Subscripts

bu	bulk
s	surface
x, y, z	coordinates

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