UNIT 1 PRINCIPLES OF HEAT AND MASS TRANSFER

Structure

1.0 OBJECTIVES

By the time you have studied this unit, you should be able to:

- define the basic principles and methods of heat transfer;
- explain the role of heat transfer in heat preservation processes;
- identify the type of food for heat processing;
- determine the heat penetration and calculate the process time in a food; and
- identify the factors affecting heat transfer and apply corrective measures to enhance the process of heat transfer.

1.1 INTRODUCTION

Heat transfer is an important operation in the food industry. Whether it is called cooking, baking, drying, sterilizing or freezing, heat transfer is part of processing of almost every food. Heat transfer is a dynamic process in which heat is transferred spontaneously from one body to another cooler body. The rate of heat transfer depends upon the differences in temperature between the bodies, the greater the difference in temperature, the greater will be the rate of heat transfer.

Temperature difference between the source of heat and the receiver of heat is, therefore, the driving force in heat transfer. An increase in the temperature difference increases the driving force and, thus the rate of heat transfer. The heat passing from one body to another travels through some medium, which in general offers resistance to the heat flow. Both these factors, the temperature difference and the resistance to heat flow, affect the rate of heat transfer.

1.2 HEAT TRANSFER SYSTEM

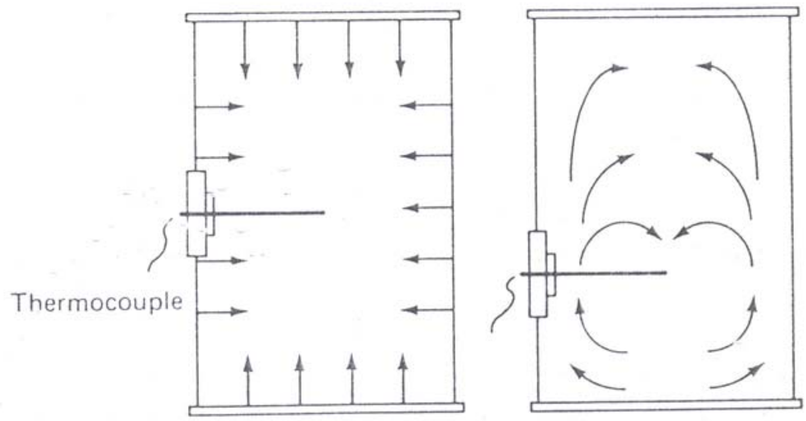
Heat can be transferred from one object to another in three ways: by **conduction,** by **convection** and by **radiation**.

Conduction is the movement of heat by direct transfer of molecular energy within solids. The molecules with greater energy communicating some of this energy to neighbouring molecules with less energy. An example of conduction is the heat transfer through the solid walls of a refrigerated store.

Convection is the transfer of heat by the movement of groups of molecules in a fluid. The groups of molecules may be moved by either density changes or by forced motion of the fluid. An example of convection heating is cooking in a jacketed pan: without a stirrer, density changes cause heat transfer by natural convection; while with a stirrer, the convection is forced.

Radiation is the transfer of heat energy by electromagnetic waves, which transfer heat from one body to another, in the same way as electromagnetic light waves transfer light energy. An example of radiant heat transfer is when a foodstuff is passed below a bank of electric resistance heaters that are red-hot (electric grill).

In general, heat is transferred in solids by conduction and in fluids by conduction and convection (Figure 1.1). Heat transfer by radiation occurs through open space, can often be neglected, and is most significant when temperature differences are substantial. In practice, the three types of heat transfer may occur simultaneously. For calculations it is often best to consider the mechanisms separately, and then to combine them where necessary.



(a) **(b)**

Figure 1.1: Heat transfer in containers by (a) conduction and (b) convection

1.2.1 Conduction

In the case of heat conduction, the equation, heat transfer rate = driving force/resistance, can be applied directly. The driving force is the temperature difference per unit length of heat-transfer path, i.e., temperature gradient. Instead of resistance to heat flow, its reciprocal, **conductance**, is used. This changes the form of the general equation to:

Rate of heat transfer = driving force x conductance, which is:

$$dQ/dt = kA\, dT/dx \qquad (1.1)$$

Where, dQ/dt (JS^{-1})is the rate of heat transfer, the quantity of heat energy transferred per unit of time, A (m^2)is the area of cross-section of the heat flow path, dT/dx ($^0Cm^{-1}$)is the temperature gradient, that is the rate of change of temperature per unit length of path, and k (Jm^{-1} s^{-1} ^0K or Wm^{-1} $^0K^{-1}$)is the thermal conductivity of the medium. Notice the distinction between thermal conductance, which relates to the actual thickness of a given material (k/x) and **thermal conductivity**, which relates only to unit thickness. Eq. (1.1) is known as the **Fourier equation** for heat conduction.

Thermal conductivity does change slightly with temperature, but in many applications it can be regarded as a constant for a given material. Most foodstuffs contain a high proportion of water and as the thermal conductivity of water is about 0.7 J m^{-1} s^{-1}°C^{-1} above 0°C, thermal conductivities of foods are in the range 0.6-0.7 J m^{-1} s^{-1}°C^{-1}. Ice has a substantially higher thermal conductivity than water, about 2.3 J m^{-1} s^{-1}°C^{-1}. The thermal conductivity of frozen foods is, therefore, higher than foods at normal temperatures.

1.2.2 Convection

Convection heat transfer is the transfer of energy by the mass movement of groups of molecules. It is restricted to liquids and gases, as mass molecular movement does not occur at an appreciable speed in solids. It cannot be mathematically predicted as easily as can transfer by conduction or radiation and so its study is largely based on experimental results rather than on theory.

Newton found, experimentally, that the rate of cooling of the surface of a solid, immersed in a colder fluid, was proportional to the difference between the temperature of the surface of the solid and the temperature of the cooling fluid. This is known as **Newton's Law of Cooling**, and it can be expressed by the following equation.

$$q = h_s A(T_a - T_s) \qquad (1.2)$$

Where, h_s is called the surface heat-transfer coefficient, T_a is the temperature of the cooling fluid and T_s is the temperature at the surface of the solid. The surface heat-transfer coefficient can be regarded as the conductance of a hypothetical surface film of the cooling medium of thickness x_f such that

$$h_s = k_f / x_f$$

Where, k_f is the thermal conductivity of the cooling medium. It is useful at this point, however, to appreciate the magnitude of h_s under various common conditions and these are shown in Table 1.1.

Table 1.1: Approximate range of surface heat transfer coefficients

	hs (J m^{-2} s^{-1}°C^{-1})
Boiling liquids	2400-24,000
Condensing liquids	1800-18,000
Still air	6
Moving air (3 m s^{-1})	30
Liquids flowing through pipes	1200-6000

1.2.3 Radiation

Radiation heat transfer is the transfer of heat energy by electromagnetic radiation. Radiation operates independently of the medium through which it occurs and depends upon the relative temperatures, geometric arrangements and surface structures of the materials that are emitting or absorbing heat.

Radiation of wavelength 0.8-400 μm (infrared) is referred to as thermal radiation or heat rays since electro magnetic radiation with this wavelength is most readily absorbed and converted to heat energy. The infrared radiation is used primarily for surface heating as it is transmitted rapidly to the surface. It is used for dehydration of fruits and vegetables, freeze drying, baking, etc.

Radiation can be significant with small temperature differences as, for example, in freeze-drying and in cold stores, but it is generally more important where the temperature differences are greater. Under these circumstances, it is often the most significant mode of heat transfer, for example in bakers' ovens and in radiant driers.

The basic formula for radiant-heat transfer is the **Stefan-Boltzmann Law**

$$q = A\,\sigma \boldsymbol{T}^4 \tag{1.3}$$

Where, ***T*** is the absolute temperature (measured from the absolute zero of temperature at –273°C, and indicated in Bold type) in degrees Kelvin (K) in the SI system, and □ (sigma) is the Stefan-Boltzmann constant = 5.73×10^{-8} J m^{-2} $s^{-1}K^{-4}$ The absolute temperatures are calculated by the formula K = (°C+273).

This law gives the radiation emitted by a perfect radiator (a **black body** as this is called though it could be a red-hot wire in actuality). A black body gives the maximum amount of emitted radiation possible at its particular temperature. Real surfaces at a temperature *T* do not emit as much energy as predicted by Eq. (1.3), but it has been found that many emit a constant fraction of it. For these real bodies, including foods and equipment surfaces, that emit a constant fraction of the radiation from a black body, the equation can be rewritten

$$q = \varepsilon A\,\sigma \boldsymbol{T}^4 \tag{1.4}$$

Where, ε (epsilon) is called the **emissivity** of the particular body and is a number between 0 and 1. Bodies obeying this equation are called **grey bodies**. Emissivities vary with the temperature ***T*** and with the wavelength of the radiation emitted. For many purposes, it is sufficient to assume that for:

* dull black surfaces (lamp-black or burnt toast, for example), emissivity is approximately 1;
* surfaces such as paper/painted metal/wood and most foods, emissivities are about 0.9;
* rough un-polished metal surfaces, emissivities vary from 0.7 to 0.25;
* polished metal surfaces, emissivities are about or below 0.05.

These values apply at the low and moderate temperatures, which are those encountered in food processing. Just as a black body emits radiation, it also absorbs it and according to the same law, Eq. (1.3). Again grey bodies absorb a fraction of the quantity that a black body would absorb, corresponding this time to their **absorptivity** α (alpha). For grey bodies it can be shown that α = ε. The fraction of the incident radiation that is not absorbed is reflected, and thus, there is a further term used, the **reflectivity**, which is equal to (1 – α).

The radiant energy transferred between two surfaces depends upon their temperatures, the geometric arrangement, and their emissivities. For two parallel surfaces, facing each other and neglecting edge effects, each must intercept the total energy emitted by the other, either absorbing or reflecting it. In this case, the net heat transferred from the hotter to the cooler surface is given by:

$$q = AC\sigma\,(\boldsymbol{T}_1^4 - \boldsymbol{T}_2^4) \qquad (1.5)$$

where $1/C = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$, ε_1 is the emissivity of the surface at temperature T_1 and ε_2 is the emissivity of the surface at temperature T_2.

1.2.4 Overall Heat Transfer Coefficients

It is most convenient to use overall heat transfer coefficients in heat transfer calculations as these combine all of the constituent factors into one, and are based on the overall temperature drop. Radiation coefficients, subject to the limitations discussed in the section on radiation, can be incorporated in the overall coefficient. The radiation coefficients should be combined with the convection coefficient to give a total surface coefficient, as they are in series, and so:

$$h_s = (h_r + h_c) \qquad (1.6)$$

The overall coefficient U for a composite system, consisting of surface film, composite wall, surface film, in series, can then be calculated as:

$$1/U = 1/(h_r + h_c)_1 + x_1/k_1 + x_2/k_2 + \ldots + 1/(h_r + h_c)_2 \qquad (1.7)$$

In Eq. (1.7) often one or two terms are much more important than other terms because of their numerical values. In such a case, the important terms, signifying the low thermal conductance are said to be the **controlling terms**.

1.2.5 Heat Transfer from Condensing Vapours

The rate of heat transfer obtained when a vapour is condensing to a liquid is very often important. In particular, it occurs in the food industry in steam-heated vessels where the steam condenses and gives up its heat; and in distillation and evaporation where the vapours produced must be condensed. In condensation, the latent heat of vaporization is given up at constant temperature, the boiling temperature of the liquid. Two generalized equations have been obtained:

1) For condensation on **vertical tubes or plane surfaces**

$$h_v = 0.94\,[(k^3\rho^2 g/\mu) \times (\lambda/L\Delta T)]^{0.25} \qquad (1.8)$$

Where, λ (lambda) is the latent heat of the condensing liquid in J kg^{-1}, L is the height of the plate or tube and the other symbols have their usual meanings.

2) For condensation on a **horizontal tube**

$$h_h = 0.72\,[(k^3\rho^2 g/\mu) \times (\lambda/D\Delta T)]^{0.25} \qquad (1.9)$$

1.2.6 Heat Transfer to Boiling Liquids

When the presence of a heated surface causes a liquid near it to boil, the intense agitation gives rise to high local coefficients of heat transfer. A considerable amount of experimental work has been carried out on this, but generalized correlations are still not very adequate. It has been found that the apparent coefficient varies considerably with the temperature difference between the heating surface and the liquid. For temperature differences greater than about 20°C, values of *h* decrease, apparently because of blanketing of the heating surface by vapours. Over the range of temperature differences from 1 to 20°C, values of *h* for boiling water increase from 1200 to about 60,000 J m^{-2} s^{-1} $°C^{-1}$. For boiling water under atmospheric pressure, the following equation is approximately true:

$$h = 50(\Delta T)^{2.5} \tag{1.10}$$

Where, ΔT is the difference between the surface temperature and the temperature of the boiling liquid and it lies between 2 and 20°C. In many applications the high boiling film coefficients are not of much consequence, as resistance in the heat source controls the overall coefficients.

Check Your Progress Exercise 1

Note: a) Use the space below for your answer.
b) Compare your answers with those given at the end of the unit.

1. List the different methods of heat transfer.

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2. What is the relationship of conduction heat transfer rate with temperature difference? What is the name of the equation used for determining the conduction heat transfer rate?

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3. What is the name of the equation used for expressing the radiative flux from an object? How is it related to temperature and properties of the material?

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4. While estimating the rate of heat transfer between two objects, the temperature of one of the objects is doubled. If convection and radiation are the two modes of heat transfer between the two objects, which mode would increase more and why?

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1.3 TYPE OF FOOD FOR HEAT PROCESSING

There are essentially two types of food when we talk of thermal processing:

1. Acid foods
2. Low acid foods

These two categories of foods differ significantly in their behaviour when thermally processed. The acidity of the food, using the pH scale as a measure of acidity, where 1 = very high acid and 4 = very low acid; the dividing line for **acid foods** and **low-acid foods** is pH 4.6. **Acid foods** can be canned at a temperature of 100°C, while **low-acid foods** must be pressure canned (to a temperature of 115°C). The reason for this is that the toxin-producing, potentially lethal organism, *Clostridium botulinum*, will not grow and produce toxins at a pH below 4.6. Many spoilage microorganisms will not grow between pH 1 and 4.6 either. The most common spoilage microorganisms associated with **acid foods** are yeasts and moulds that can tolerate acid environments.

1. Acid foods

High acid foods contain more natural acids. Many fruits are high acid foods and the presence of these natural acids helps prevent growth of some spoilage microorganisms. If the food product has a high enough acid level, boiling-water temperatures are high enough to destroy spoilage organisms. This is a prevention method for the deadly *Clostridium botulinum* bacteria.

2. Low acid foods

Low acid foods, such as vegetables and meat products, contain very little natural acid. They must be processed at higher temperatures than boiling-water to destroy any *Clostridium botulinum* bacteria. Water boils at 100°C, at sea level, and at a lower temperature at higher elevations. Turning up the temperature under the pot or letting the water boil for a longer time does not raise the temperature of the water above its boiling point. To make water boil at a higher temperature, it has to be put under pressure, such as in a pressure canner. When a food is processed at 1.0 kg/cm^2 pressure, the water boils when it gets to 115°C, rather than at 100°C. This is high enough to kill the bacteria that causes botulism poisoning.

Adjust for Altitude to Ensure Safety

The above values of temperatures have been determined for mean sea level. As we move up the mountains, the atmospheric pressure goes down and water boils at lower temperatures as altitude increases. Lower boiling temperatures are less effective for killing bacteria. You must increase either the process time or canner pressure to make up for lower boiling temperatures.

Because altitude affects pressure and the boiling point of liquid, adjustments must be made when canning foods at altitudes of 300 m above sea level or higher. When using the boiling water bath method, processing time must be increased. Add 5 minutes to processing time for altitudes between 300 m and 1500 m above sea level. When using the pressure canner method, pressure must be increased. If using a dial-gauge pressure canner, process foods at 0.8 bar pressure for altitudes between 600 m and 1200 m and at 0.9 bar pressure for altitudes between 1200 m and 1800 m. If using the weight-gauge pressure canner, use 1.0 bar of pressure.

When you mix low-acid and acid foods, assume that the mixture remains low-acid. Although tomatoes used to be considered an acid food, some are now known to have pH values slightly above 4.6, which means they are low-acid. To safely can them as acid foods in a boiling-water canner, you must add lemon juice or citric acid.

Check Your Progress Exercise 2

Note: a) Use the space below for your answer.
b) Compare your answers with those given at the end of the unit.

1. How are acid and low-acid foods distinguished?

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2. How is a thermal process for an acid food different than that for a low-acid food?

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3. What is the method used to raise the boiling point of water in food processing?

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4. What changes are required for thermal processing of foods at high altitudes?

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1.4 HEAT PENETRATION

Heat penetration studies are required to be conducted for verifying the sterilizing temperature of a load (food) meant for moist heat sterilization. These studies are conducted to ensure that the coolest unit within a pre-defined loading pattern (including minimum and maximum loads) will consistently be exposed to sufficient heat lethality (minimum “F”).

Heat penetration curve can be drawn by plotting the logarithmic difference between either retort temperature and product temperature (heating curve) or product temperature and cooling medium temperature (cooling curve) versus time. The purpose of a heat-penetration study is to determine the heating and cooling behaviour of a product/package combination in a specific retort system for the establishment of safe thermal processes and evaluating process deviations. The study is designed to adequately and accurately examine all critical factors associated with the product, package and process, which affect heating rates. A goal in conducting these studies is to identify the worst-case temperature response expected to occur in commercial production as influenced by the product, package and process.

Several product, process, package and measurement-related factors can contribute to variations in the time-temperature data gathered during a heat-penetration test. Establishment of a process requires expert judgment and sound experimental data for determining which factors are critical and the effect of changing those factors both within and beyond established critical limits.

A typical heat penetration curve is shown in Figure 1.2. A broken heating curve occurs when a food is initially heated by convective heating but then undergoes a rapid transition to conductive heating (for example in foods, which contain high concentration of starch, which undergoes a sol-to-gel transition).

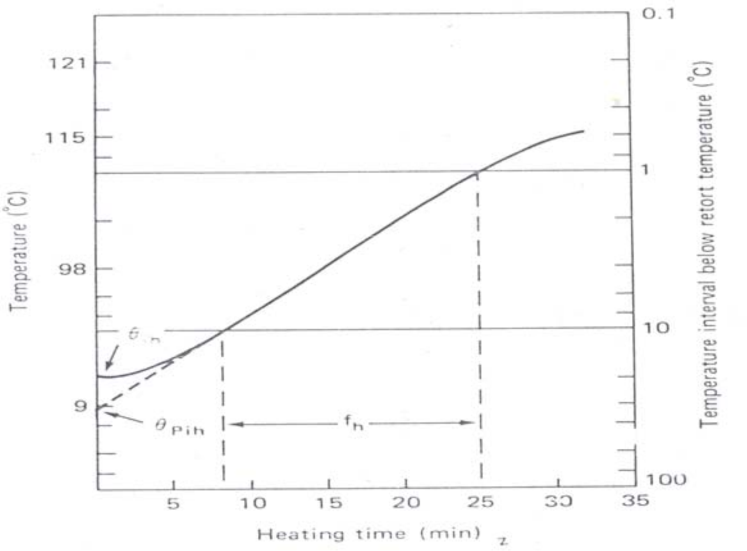

Figure 1.2: Heat penetration curve

There are a number of ways of estimating how effective heat sterilization can be. The thermal death time is the time microbes must be exposed to a particular temperature before they are all dead. Similarly, the thermal death point is the temperature at which all microbes in a sample are killed. Both are very unsatisfactory, since they depend on many factors such as number of microbes present in a sample, analytical conditions and techniques, etc.

1.5 HEAT TRANSFER CHARACTERISTICS OF FOOD

It is necessary to have information on both the heat resistance of microorganisms or enzymes and the rate of heat penetration into the food for determination of process time of a food.

Heat is transferred from steam or pressurized water through the container and into the food. Generally the surface heat transfer coefficient is very high and is not a limiting factor in heat transfer. The following factors influence the rate of heat penetration into a food:

i) Type of product
ii) Size of the container
iii) Agitation of the container
iv) Temperature of the retort
v) Shape of the container. Tall containers promote convection currents in convective heating foods.
vi) Type of container. Heat penetration is faster through metal than through glass or plastics owing to differences in thermal conductivity.

In this section, the objective is to learn as to how the thermal properties of food products affect the heat penetration and the quantity of heat. Two thermal properties of importance are thermal conductivity and thermal diffusivity in determining heat penetration. Specific heat and latent heat are important in determining the quantity of heat required for the process.

I. Thermal conductivity is the property indicating the rate at which heat flows through a food product. A product with high thermal conductivity lets the heat flow easily, whereas a material with low thermal conductivity, also known as an insulator, puts resistance to the flow of heat. Fourier's heat conduction equation could be used to derive the units of thermal conductivity, i.e., W/(m°C). It does change slightly with temperature, but in many applications it can be regarded as a constant for a given material. Most foodstuffs contain a high proportion of water and as the thermal conductivity of water is about 0.7 J m^{-1} s^{-1} $°C^{-1}$ above 0°C, thermal conductivities of foods are in the range of 0.6-0.7 J m^{-1} s^{-1} $°C^{-1}$. Ice has a substantially higher thermal conductivity than water, about 2.3 J m^{-1} s^{-1} $°C^{-1}$. The thermal conductivity of frozen foods is, therefore, higher than foods at normal temperatures.

Typical thermal conductivities

Metals: k = 50-400 W/m°C
Water: k = 0.597 W/m°C
Air: k = 0.0251 W/m°C
Insulating materials: k = 0.035 - 0.173 W/m°C

For foods it is represented as

$$k = 0.25\ m_c + 0.155\ m_p + 0.16\ m_f + 0.135\ m_a + 0.58\ m_m$$

Where m is mass fraction and subscripts c: carbohydrate, p: protein, f: fat, a: ash and m: moisture.

or

$$k = 0.55p/100 + 0.26(100-p)/100\ J\ m^{-1}\ s^{-1}\ °C^{-1}\ \text{above freezing}$$

$$= 2.4p/100 + 0.26(100 - p)/100\ J\ m^{-1}\ s^{-1}\ °C^{-1}\ \text{below freezing.}$$

Where p is the percentage of water in the foodstuff.

II. Thermal diffusivity is the actual ability of a food to conduct heat to adjacent molecules. Thermal diffusivity is a derived property that is the ratio of thermal conductivity and the product of density and specific heat. The units of thermal diffusivity, therefore, work out to be m^2/s. Higher value of thermal diffusivity means faster heat penetration and vice versa.

III. Specific heat: The specific heat is an important quantity that determines the amount of energy that must be supplied or withdrawn from a unit mass of material in order to increase or decrease its temperature by one degree. Knowledge of the specific heat of a material is, therefore, important in the design of processes such as chilling, freezing, warming, sterilization and cooking. Specific heat has the units of kJ/(kg.K) in SI system of units.

$$\text{Specific heat} = 4.19p/100 + 0.84(100 - p)/100\ kJ\ kg^{-1}\ °C^{-1}\ \text{above freezing}$$
$$= 2.1\ p/100 + 0.84(100 - p)/100\ kJ\ kg^{-1}\ °C^{-1}\ \text{below freezing.}$$

p is percentage of water in food stuff

IV. Phase transitions: It is important to determine the temperature at which transitions occur, the enthalpy change associated with a transition, the type of transition involved (exothermic or endothermic), and the quantity of material that undergoes a transition. As an example, we will consider the melting and crystallization of food components. When a material changes its physical state from solid-to-liquid (melting) or from liquid-to-solid (crystallization) it absorbs or gives out heat, respectively. A process that absorbs heat is an endothermic process, whereas a process that evolves heat is an exothermic process. Pure substances usually have very sharp melting or crystallization points and, therefore, all the heat is absorbed or evolved over a narrow range of temperature. Most foods are complex materials and, therefore, do not exhibit sharp transitions from one phase to another. The amount of heat required for the phase change is called the latent heat and has the units of kJ/kg.

$$\text{Latent heat} = 335p/100 \text{ kJ kg}^{-1}$$

This equation and the ones given earlier for thermal conductivity and specific heat represent a considerable over-simplification so they should be used with caution, particularly in the region between −18°C to 0°C. Freezing of foodstuffs occur over a range of temperatures and not at any fixed point.

Some properties of liquids and thermal data for food products are depicted in Tables 1.2 and 1.3, respectively.

Table 1.2: Some properties of liquids

	Thermal conductivity	**Specific heat**	**Density**	**Viscosity**	**Temperature**
	($J\ m^{-1}\ s^{-1}\ °C^{-1}$)	($kJ\ kg^{-1}\ °C^{-1}$)	($kg\ m^{-3}$)	($N\ s\ m^{-2}$)	(°C)
Water	0.57	4.21	1000	1.87×10^{-3}	0
		4.21	987	0.56×10^{-3}	50
	0.68	4.18	958	0.28×10^{-3}	100
Sucrose 20% soln.	0.54	3.8	1070	1.92×10^{-3}	20
				0.59×10^{-3}	80
60% soln.				6.2×10^{-3}	20
				5.4×10^{-3}	80
Sodium chloride 22% soln.	0.54	3.4	1240	2.7×10^{-3}	2
Acetic acid	0.17	2.2	1050	1.2×10^{-3}	20
Ethyl alcohol	0.18	2.3	790	1.2×10^{-3}	20
Glycerine	0.28	2.4	1250	830×10^{-3}	20
Olive oil	0.17	2.0	910	84×10^{-3}	20
Rape-seed oil			900	118×10^{-3}	20
Soya-bean oil			910	40×10^{-3}	30
Tallow			900	18×10^{-3}	65

Milk (whole)	0.56	3.9	1030	2.12×10^{-3}	20
Milk (skim)			1040	1.4×10^{-3}	25
Cream 20% fat			1010	6.2×10^{-3}	3
30% fat			1000	13.8×10^{-3}	3

Table 1.3: Thermal data for some food products

	Freezing point (°C)	Percent water	Specific heat		Latent heat of fusion (kJ kg^{-1})
			Above freezing	Below freezing	
			(kJ kg^{-1}°C^{-1})		
Fruit					
Apples	–2	84	3.60	1.88	280
Bananas	–2	75	3.35	1.76	255
Grapefruit	–2	89	3.81	1.93	293
Peaches	–2	87	3.78	1.93	289
Pineapples	–2	85	3.68	1.88	285
Watermelons	–2	92	4.06	2.01	306
Vegetables					
Asparagus	–1	93	3.93	2.01	310
Beans (green)	–1	89	3.81	1.97	297
Cabbage	–1	92	3.93	1.97	306
Carrots	–1	88	3.60	1.88	293
Corn	–1	76	3.35	1.80	251
Peas	–1	74	3.31	1.76	247
Tomatoes	–1	95	3.98	2.01	310
Water	0	100	4.19	2.05	335

1.6 DEVICES FOR DETERMINATION OF HEAT PENETRATION

There are different types of thermometers available for measuring the temperature in a thermal process and, thereby, permitting the determination of heat penetration.

I. Mercury-in-glass (MIG) thermometer

Each retort system used for the thermal processing is equipped with a MIG thermometer. Aseptic processing systems may have a temperature indicating device other than MIG thermometer as the sole temperature indicator. The MIG thermometer is the reference instrument for all temperature readings, including vent temperature, come-up temperature and process temperature during processing.

It is important that the MIG thermometer be tested/calibrated at the operating temperature of the retort system (i.e., 115°C, 120°C, 125°C etc.) and if possible in the heating medium used in the retort. If the retort is operated at more than one processing temperature or over a wide range of temperatures the MIG thermometer should be checked at all of the temperatures normally used for processing. The MIG thermometers should be tested against a thermometer that can be traced back to a BIS Standard thermometer. The accuracy of the standard thermometer should be checked at least once every 3 years depending upon how it is handled and stored.

II. Temperature recording device

Each retort system is equipped with an accurate temperature-recording device. The recording device provides a continuous record of the temperature in the retort system during thermal processing. Common systems in use are circular or strip charts, which are marked with ink pens, electrical sparks, pressure pins, or which are created by graph plotters at the time temperature readings are received. Electronic temperature monitors and recorders are now available for the purpose and should be utilized for greater accuracy and precision avoiding human errors. A band or ribbon type surface pyrometer is used by processors to monitor container surface temperatures.

III. Temperature sensors

Temperature measurement can be accomplished by essentially five basic methods: (1) liquid-in-glass, (2) resistance thermometry, (3) thermoelectric thermometry, (4) optical/radiation pyrometry, and (5) bi-metal. Investigators are most familiar with the liquid (mercury or alcohol usually) -in-glass and the bi-metal (dial gauge) types. It is possible now that investigators will encounter the use of the optical/radiation pyrometers as well.

i) Resistance thermometry

A resistance thermometer is a temperature-measuring instrument consisting of a sensor (an electrical circuit element whose resistance varies with temperature), a framework on which to support the sensor, a sheath by which the sensor is protected, and wires by which the sensor is connected to a measuring instrument, which is used to indicate the effect of variations in the sensor resistance. Resistance thermometers provide absolute calibration of temperatures in that no reference junctions are involved, and no special extension wires are needed between the sensor and the measuring instrument (as with thermocouples).

The sensors can be of two types: resistance temperature detectors (RTD's) and thermistors. The RTD sensing element is formed of solid conductors (usually in wire form) wound upon an insulating core. The insulating core is usually made of mica or ceramic. The conductors, which are wound in a helical coil to prevent mechanical restraints during thermal expansion, are generally made of platinum; however nickel and copper have been used. Platinum best meets the requirements because being a noble metal, it can be highly refined, it resists contamination, it is mechanically and electrically stable, and the relationship between temperature and resistance is quite linear.

Thermistors (a contraction for "thermally sensitive resistors") are electrical circuit elements formed of solid semi conducting materials such as oxides of nickel, manganese, iron, cobalt, copper, magnesium, titanium, and other metals. The powdered metal is formed under pressure into the desired shape, usually a flat disc. The disc is sintered, leads are attached, and encapsulated in epoxy. The finished thermistor can also be encased in a sheath of plastic, stainless steel, copper or aluminum. Both the RTD and thermistor can be obtained in various configurations.

ii) Thermoelectric thermometry

The thermoelectric thermometer is a temperature measuring instrument consisting of two continuous, dissimilar thermocouple wires extending from a measuring junction to a reference junction with copper connecting wires to a potentiometer. Unlike the resistance types, where power must be supplied to the circuit, the thermocouple circuit generates a measurable low voltage output that is almost directly proportional to the temperature difference between the "hot" junction and the "cold" junction. A unit change in this temperature difference will produce some net change in electromotive force (emf or voltage). Thermoelectric thermometry makes use of the known relationship between a difference in junction temperatures and the resulting emf developed by a thermocouple circuit. The temperature of one junction (reference junction, T1) is held at a constant known value. This is usually accomplished with an ice water (0°C) bath. The temperature of the other junction (measuring junction, T2) is determined by measuring the thermocouple circuit emf and referring to calibration tables for the particular thermocouple materials. The thermocouple junction usually is formed by twisting and fusing the two wires together or they may be butt-welded. The finished element may be used bare or enclosed in a sheath.

Check Your Progress Exercise 3

Note: a) Use the space below for your answer.
b) Compare your answers with those given at the end of the unit.

1. Write the full forms of the following abbreviations:

   a) MIG thermometer
   b) RTD sensor

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2. How is a thermocouple used for temperature measurement?

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3. What is a thermistor? How does it differ from a RTD sensor?

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4. How is temperature in Kelvin scale related to temperature in Celsius scale?

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1.7 DETERMINATION OF COLD POINT IN A FOOD CONTAINER

In a study, determination of the cold spot was made using data collected for heat penetration curves at 5 potential cold spot locations in the jars in 18 canner loads (Table 1.4). Two levels of two procedural variations were used in testing for process calculations. Temperature profiles were compared for two fill weights (450g, 480g) and two fill temperatures (direct-fill, and after a 10 minute wait, which had means of 84.4°C and 80.4°C, respectively). Process calculation was accomplished by using thermocouples in each of six jars in different canner loads of each of the three fill methods (standard, low initial temperature, and high-fill weight). These jars were processed to 90.5°C plus an additional 5 minutes. Processing was done in a boiling water canner using the stovetop burners of a household gas range. Data were recorded using Type T copper-constantan thermocouples.

Cold Spot Location

- The cold spot for this product and jar combination was located at the geometric centre of the jar, Table 1.4.

- The D value is the number of minutes it takes the straight line portion of the heat penetration plot to pass through one logarithmic cycle.
- A larger D represents a slower rate of heat penetration.

Table 1.4: Cold spot determination of cranberry salsa in pint jars

Thermocouple height in pint jar	Average D value n = 18	Range	Standard deviation
Centre	54.86[1]	48.5-73.4	5.3
½" Below Center	53.89	48.6-64.7	3.9
1" Below Center	51.94	45.8-64.9	4.8
1½" Below Center	48.98	43.0-60.8	4.7
2" Below Center	47.00	41.4-58.0	4.5

[1]Location of cold spot, as determined by largest individual D value (worst-case scenario)

Heat penetration measures the rate at which a product heats during a thermal process. A temperature sensor or thermocouple measures temperature changes in the slowest heating region of the product or container and temperature is monitored on a recording device. The time/temperature data, and heat resistant data for the target microorganism, are used to calculate the scheduled process.

1.8 CALCULATION OF PROCESS TIME

The time/temperature relationship required for desired reduction of microbial population is based on thermal resistance characteristics of the microorganisms. The translation of this information into a form for use by the operator of a commercial system requires integration with the heating and cooling characteristics of the food product within the container. The methods to be presented lead to the establishment of a processing system operator time to ensure that the impact of the thermal process is equivalent to the desired time/temperature for a given microbial population.

One of the first concepts to be understood when establishing process times is **lethality**. The term lethality can be defined as the integrated influence of time and temperature on a microbial population. Lethality is expressed as time at a reference temperature.

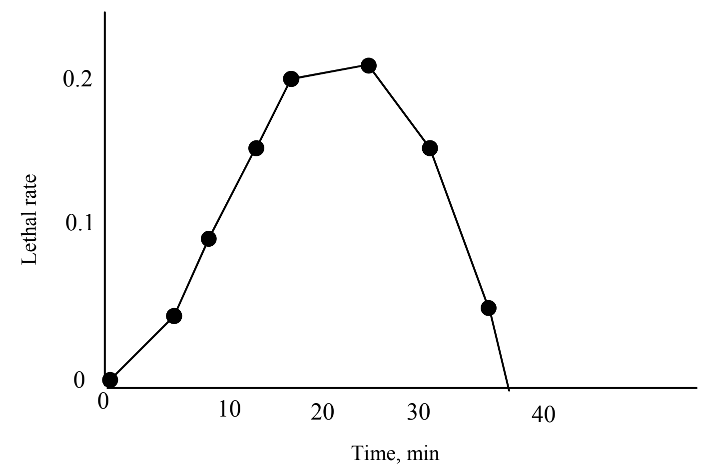

Figure 1.4: Lethal rate curve for typical process in retort

The lethal rate increases gradually with time as the temperature of the product increases. As the product temperature begins to plateau at a magnitude near the heating medium temperature, the lethal rate also plateaus and eventually decreases as the product temperature decreases during cooling. Lethality is expressed in time units for the process accomplished at the heating medium temperature.

The time/temperature relationship representing the process is compared to the process requirement needed to achieve product safety or an established spoilage rate. For example, if the process under consideration is being used to ensure the elimination of *Clostridium botulinum* as a health risk, the lethality for the process must be equal to or greater than the thermal death time for the microbial population.

The D-value or Decimal Reduction Time may be used as a measure. This is defined as the time taken under specified conditions and at a particular temperature to kill 90 per cent of the microbes in a sample. Only 10 per cent or 1/10 of the original number of microbes survive the decimal reduction time: hence its name. D-values can be determined from survivor curves when the log of population is plotted against time.

$$D_{\text{reference temperature}} = \text{Time}/(\text{Log}_a - \text{Log}_b)$$

Where a = the initial population, and b = the survivors after a time interval. F value is a mathematically calculated number that describes the total lethal effect of the process at the slowest heating point in a food container. It is the equivalent, in minutes at a given temperature, of all heat considered with respect to its capacity to destroy spores or vegetative cells of a particular microorganism.

The effectiveness of a canning process is determined from a combination of experimentation and calculation. Processing parameters are expressed in terms of a series of symbols of which D, z, and F are key. When bacterial spores are heated to a lethal temperature as during retorting of canned foods, the death of most species approximates a first order chemical reaction that can be described by a straight line on a semi-logarithmic graph paper. Figure 1.4 shows a hypothetical result from heating a species of spore at 115°C (240°F).
In Figure 1.5, one minute is required to reduce the survivors from 10,000 to 1,000 or a 90 per cent reduction (one log reduction). Similarly, one minute is required to reduce the survivors from 1,000 to 100 per gram of food and so on until only 0.01 of a spore is present in 1 gram of food-which really means that there remains only one living spore for each 100 grams of food. This time to reduce the survivors by 90% is the Decimal reduction (D) value or in Figure 1, D_{115} = 1 min. The subscript after the D indicates temperature at which the D value was determined. Many factors affect the D value, such as the species of spore, and the kind of food the spore is suspended in.

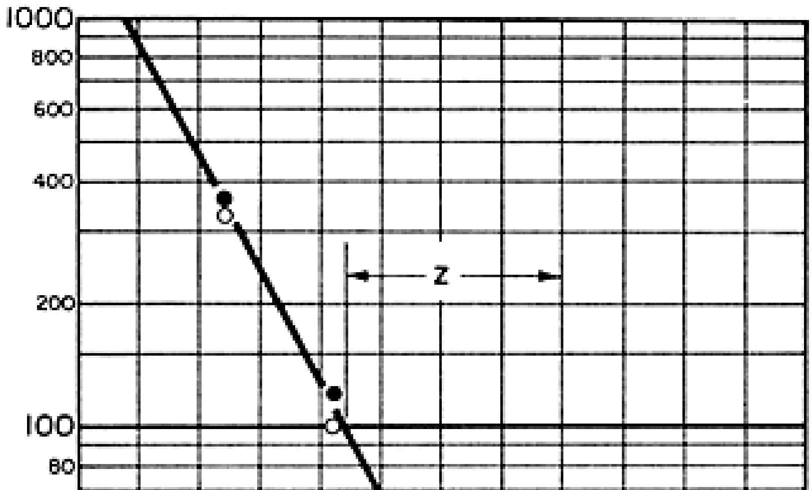

Figure 1.5: Thermal death time curve for *Clostridium botulinum*

Check Your Progress Exercise 4

Note: a) Use the space below for your answer.
b) Compare your answers with those given at the end of the unit.

1. What is Decimal Reduction Time (D)? How is it determined?

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2. What is F value and how is it related to D value?

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3. Name the microorganism that is considered in the determination of thermal processing.

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4. What is meant by lethality in food processing? How is it related to various process parameters?

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1.9 FACTORS AFFECTING HEAT PENETRATION

There are many factors, which affect the heat transfer into the food. Generally the surface heat transfer coefficient is very high and is not a limiting factor in heat transfer. The following factors are important which influences the rate of heat penetration into a food:

1. **Type of product:** Liquid or particulate food (for example peas in brine), where natural convection current is established, heat faster than solid food (for example meat pastes and corned beef), where heat is transferred by conduction. The low thermal conductivity of food is a major limitation to heat transfer in conduction heating.

2. **Size of the container:** Heat penetration to the centre is faster in small containers than in large containers.

3. **Agitation of the container:** End-over-end agitation (Figure 1.6) and, to a lesser extent, axial agitation increases the effectiveness of natural convection curie: and thereby increases the rate of heat penetration in viscous or semi-solid foods (for example beans in tomato sauce).

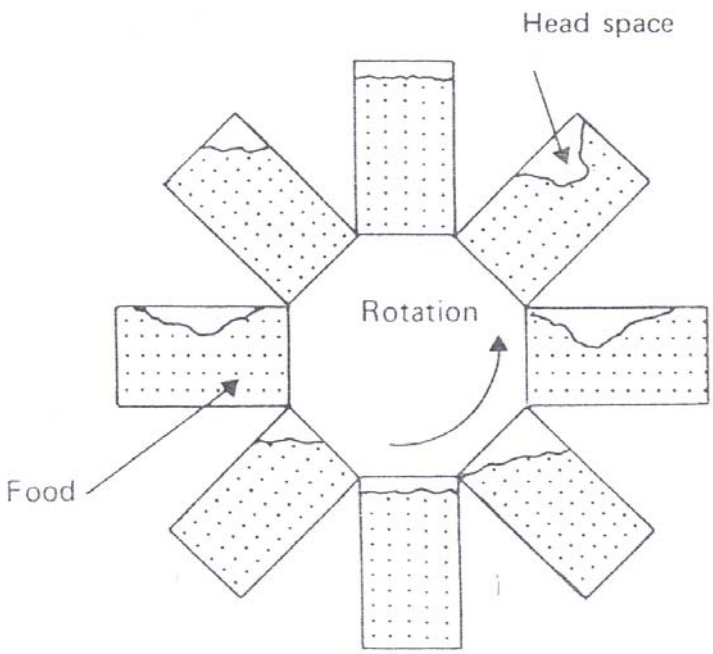

Figure 1.6: End-over-end agitation of containers

4. **Temperature of the retort:** A higher temperature difference between the food and the heating medium causes faster heat penetration.

5. **Shape of the container:** Tall containers promote convection currents in convective heating foods.

6. **Type of container:** Heat penetration is faster through metal than through glass or plastics owing to differences in thermal conductivity.

1.10 LET US SUM UP

We have in this unit learnt the basic concept of heat transfer. Heat is transferred by conduction, convection or radiation modes in a given situation. The methods of temperature measurement include mercury-in-glass (MIG) thermometers, resistance temperature detectors, thermistors, thermocouples and radiation pyrometers. Temperature measurements permit us to evaluate heat penetration rates in the thermal processes so as to determine the process durations to achieve acceptable sterilization levels. These levels differ for acid and less acid foods. If the pH level is below 4.6 the food is classified as an acid food. However, if the pH is equal to or more than 4.6, the foods are low-acid and the process temperatures would have to be more than 100°C. Temperatures more than 100°C are achievable through raising process pressure above that of the ambient. It is important to identify the cold spot in the sterilization process because the heat penetration to that spot will control the overall effectiveness of the process. Decimal reduction time at a given reference temperature is used to fix the process time. Usually, 12 logarithmic cycles are allowed for the microbial population reduction and, thus, the process time F is equal to 12 D. The factors responsible for affecting the temperature distribution and heat penetration rate need to be given due consideration for finalizing the process durations.

1.11 KEY WORDS

Conduction	:	Exchange of molecular energy directly exchanged, from the hotter to the cooler regions.
Convection	:	Transfer of heat by the movement of groups of molecules in a fluid.
Radiation	:	Transfer of heat energy by electromagnetic waves.
Black body	:	It is a body which absorbs all incident light on it.
Grey body	:	Body which partially absorbs and partially reflects incident light falling on it.
Fourier equation	:	It is the general equation guiding conduction heat transfer.
Newton's law of cooling	:	It is the guiding principle behind convective heat transfer.
Radiation pyrometers	:	Measures temperature of a distant / hot object without coming into contact with it.
Decimal reduction time	:	Time required for reducing the microbial population to one tenth of its initial number.
Microbial lethality	:	Time temperature combination to kill all microorganisms including its spores.

1.12 ANSWERS TO CHECK YOUR PROGRESS EXERCISES

Check Your Progress Exercise 1

Your answers should include the following points:

1. The different methods of heat transfer are: Conduction, Convection and Radiation.

2. The rate of conduction heat transfer increases as the temperature gradient increases.

   The equation, $dQ/dt = kA\, dT/dx$ is known as **Fourier equation** of heat conduction.

3. The basic formula for radiant-heat transfer is the **Stefan-Boltzmann Law,** $q = \in \sigma \boldsymbol{T}^4$.

   As indicated in the equation, the radiative heat flux q, is proportional to the fourth power of temperature. That means for any increase in temperature the flux increases much faster. The emissivity of the object, $\in$, indicates its capacity in relation to a black body to emit thermal radiation. The value of $\in$ is in the range of 0-1; a black body has $\in = 1$ and a perfectly reflective body has $\in = 0$. The σ is Stefan-Boltzmann constant.

4. If the temperature of one of the objects is doubled, it means the temperature difference between the two objects has increased. Since convection is directly proportional to the temperature difference, it will increase in proportion to the temperature difference. On the other hand the radiation heat transfer is proportional to the difference in the fourth power of the temperatures of the two objects, the radiation heat transfer will increase much more steeply. You can therefore, appreciate that the radiation heat transfer increases much faster than the conduction or convection when the temperature difference between two objects increases.

Check Your Progress Exercise 2

Your answers should include the following points:

1. The acid and low-acid foods are distinguished on the basis of pH. The foods with pH less than 4.6 are called acid and the foods with pH more than 4.6 are called low-acid foods.

2. The thermal process for an acid food consists of treating it in a 100°C boiling water bath, whereas the low-acid food must be pressure treated to a temperature of 115°C or higher to kill the spoilage causing microorganisms.

3. To make water boil at a temperature higher than 100°C in food processing, it has to be put under pressure, such as in a pressure canner. When a food

is processed at 1.0 kg/cm^2 pressure, the water boils when it gets to 115°C, rather than at 100°C.

4. At higher altitudes the atmospheric pressure goes down and water boils at lower temperatures. Thus, to make the thermal processing effective, either the process time or canner pressure must be increased to make up for lower boiling temperatures. That means pressure treatment may be required even for acid foods.

Check Your Progress Exercise 3

Your answers should include the following points:

1. a) Mercury-in-Glass (MIG) Thermometer
   b) Resistance temperature detector sensors

2. A thermocouple is made by joining two dissimilar metals. When one of the junctions is at a different temperature than the surrounding temperature, then a small voltage is developed which can then be measured across the two leads at the other junction. When provision is made in the circuit to take care of the reference point such as the freezing point of water, then the resultant voltage is calibrated in terms of temperature difference between the reference point and the temperature of the junction.

3. A thermistor is normally a thermally sensitive material whose electrical resistance changes with temperature. This change in resistance is calibrated in terms of temperature. It differs from a resistance temperature detection (RTD) sensor in terms of its sensitivity. As a result a thermistor is able to sense very small changes in temperature as compared to a RTD sensor.

4. K = (°C + 273), where K and C are units of temperature in Kelvin scale and Celsius scale.

Check Your Progress Exercise 4

Your answers should include the following points:

1. The Decimal Reduction Time or D-value is defined as the time taken to kill 90% of the microbes in a sample under specified conditions and at a particular temperature. D-values are determined from survivor curves when the log of population is plotted against time.

   $$D_{\text{reference temperature}} = \text{Time}/(\text{Log}_a - \text{Log}_b)$$

   Where a = the initial population, and b = the surviving population after a time interval.

2. The F value for a process is the number of minutes required to kill a known population of microorganisms in a given food under specified conditions. This F value is usually set at 12 D values and the resultant microbial population is extremely low such as one microbe in 10,000 cans (say).

3. *Clostridium botulinum* is the reference microorganism, which is used in determining the different parameters related to thermal processing.
4. Lethality is defined as the integrated influence of time and temperature on a microbial population. It is expressed in time units for the process accomplished at the heating medium temperature. For e.g., a thermal process may require 65 min at 115°C of steam temperature for a given food product to achieve full lethality.

1.13 SOME USEFUL BOOKS

1. Henderson, S.M. and Perry, R.L. (1976) Agricultural Process Engineering. AVI Publishing Co. West Port, Connecticut.

2. McCabe, W.L., Smith, J.C. and Harriott, P. (1993) Unit Operations of Chemical Engineering. McGraw Hill, New York.

3. Nielsen, S.S. (1998) Introduction to Food Analysis. Aspen Publications Inc., Maryland.