UNIT 1 UNIT OPERATIONS

Structure

1.0 OBJECTIVES

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

- comprehend the use and utility of food engineering in the food processing sector;
- know various systems of units and dimensions of quantities used in food engineering; and
- understand the principles of thermal processing and effective utilization of freezing, evaporation and dehydration in food processing and preservation.

1.1 INTRODUCTION

Most food processing operations are designed to extend the shelf-life of the product by reducing or eliminating microbial activity. This general objective implies that the processing operation meets the minimum requirement of ensuring any human health safety concerns associated with microbial activity. It must be acknowledged that most, if not all, food processing operations will influence the physical and sensory characteristics of the product. It is now a common practice within the food industry to utilize processing operations as an approach to enhance the physical and sensory characteristics of food products for better consumer acceptance.

The aims of the food processing are fourfold:

1. To extend the period during which a food remains wholesome (the shelf life) by preservation techniques which inhibit microbiological or biochemical changes and thus allow greater time for distribution and home storage;

2. To increase variety in the diet by providing a range of attractive flavours, colours, aromas and textures in food (collectively known as *eating, sensory* or *organoleptic quality);* a related aim is to change the form of the food to allow further processing (for example the pulping of fruits);

3. To provide the nutrients required for health (termed as *nutritional quality*);

4. To generate income for the entrepreneur or manufacturing company.

All the food processing activities involve a combination of procedures to achieve the intended changes to the raw materials. These procedures are conventionally categorized as *unit operations,* each of which has a specific, identifiable and predictable effect on a food item. A number of unit operations, same or different in nature form a process. The combination and sequence of operations, same or different in nature determines the nature of the final product.

In this unit, we will take up some basic concepts and unit operations that are important in food engineering.

1.2 DIMENSIONS

In food processing, we will talk of several parameters/quantities that make sense of when their dimensions and units are known. A dimension defines a physical entity, which can be observed and / or measured, quantitatively. For example, time, length, area, volume, mass, force, temperature, and energy are all considered dimensions. A unit expresses the quantitative value of a dimension. For example, length may be measured as metres, centimetres, or millimetres. According to the selected unit, the magnitude would be different.

Primary dimensions, such as length, time, temperature, mass, and force, express a physical entity. Secondary dimensions involve a combination of primary dimensions (e.g., volume is length cubed; velocity is distance divided by time).

It is necessary for equations to be dimensionally consistent. Thus, if the dimension of the left-hand side of an equation is “length,” it is necessary that the dimension of the right-hand side is also “length” otherwise the equation is inconsistent. In solving numerical problems, it is always useful to write units for each of the dimensional quantities within the equations. This practice is helpful to avoid mistakes in calculations.

1.3 ENGINEERING UNITS

Physical quantities are measured using a wide variety of unit systems. The most common systems are the Imperial (English) system; the centimeter, gram, second (CGS) system; and the meter, kilogram, second (MKS) system. The use of these systems, along with a myriad of symbols to designate units, has often caused considerable confusion. International organizations have attempted to standardize unit systems, symbols and the quantities to avoid confusion. As a result of international agreements, the "System International" or the SI system has emerged. The SI system consists of seven basic units, two supplementary units, and a series of derived units.

1.3.1 Base Units

The SI system is based on a choice of seven well-defined units, which by convention are regarded as dimensionally independent. The seven base units are as given in Table 1.1

Table 1.1: SI base units

Measurable attribute of phenomenon or matter	Name	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	Ampere	A
Thermodynamic temperature	Kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

1.3.2 Derived Units

Derived units are algebraic combinations of base units expressed by means of multiplication and division. Often, for simplicity, derived units carry special names and symbols that may be used to obtain other derived units. Some commonly used derived units are summarized in Table 1.2.

Table 1.2(a): Derived units expressed in terms of base units

Quantity	SI Units	
	Name	Symbol
Derived units expressed in terms of Base Units		
Area	square metre	m^2
Volume	cubic metre	m^3
Acceleration	metre per second squared	m/s^2
Density	kilogram per cubic metre	kg/m^3
Magnetic field strength	Ampere per metre	A/m
Concentration (of amount of substance)	mole per cubic metre	mol/m^3
Specific volume	cubic metre per kilogram	m^3/kg

Table 1.2(b): Derived units with specific names

Quantity	SI Units			
	Name	Symbol	Expression in terms of other units	Expression in terms of SI base units
Derived units with specific names				
Frequency	hertz	Hz		cycles.s^{-1}
Force	newton	N		m.kg.s^{-2}
Pressure	pascal	Pa	N/m²	m^{-1}.kg.s^{-2}
Energy	joule	J	N/m	m².kg.s^{-2}
Power	watt	W	J/s	m².kg.s^{-3}
Capacitance	farad	F	C/V	m^{-2}.kg^{-1}.s^{-4}.A²
Conductance	siemens	S	A/V	m^{-2}.kg^{-1}.s^{-3}.A²

Table 1.2(c): Derived units expressed by means of special names

Quantity	SI Units		
	Name	Symbol	Expression in terms of SI base units
Derived units expressed by means of special names			
Dynamic viscosity	pascal second	Pa.s	m^{-1}.kg.s^{-1}
Moment of force	newton metre	N.m	m².kg.s^{-2}
Surface tension	newton per metre	N/m	kg.s^{-2}
Heat capacity, entropy	joule per kelvin	J/K	m².kg.s^{-2}.K^{-1}
Specific heat capacity	joule per kilogram kelvin	J/(kg.K)	m².s^{-2}.K^{-1}
Specific energy	joule per kilogram	J/kg	m².s^{-2}
Thermal conductivity	watt per metre kelvin	W/(m.K)	m.kg.s^{-3}.K^{-1}

1.3.3 Supplementary Units

This class of units contains two purely geometric units, which may be regarded either as base or derived units. Both of them are given in Table 1.3.

Table 1.3: SI supplementary units

Quantity	SI Units	
	Name	Symbol
Plane angle	radian	rad
Solid angle	steridian	sr

1.4 SYSTEM AND PROPERTIES

1.4.1 System

A careful description of the system is vital in engineering analysis. A region prescribed in space or a finite quantity of matter is called a system and that is enclosed by an envelope, which is stated to be the boundary of the system. The boundary of a system can be real, such as walls of a tank, or it can be an imaginary surface that encloses the system. For example, in Figure 1.1, the boundary in system A is along the walls of a storage tank; thus it does not include the pipe and the valve. However, in system B, the boundary envelops the tank, valve and the pipe. The composition of the system is described by the components present inside the system boundary.

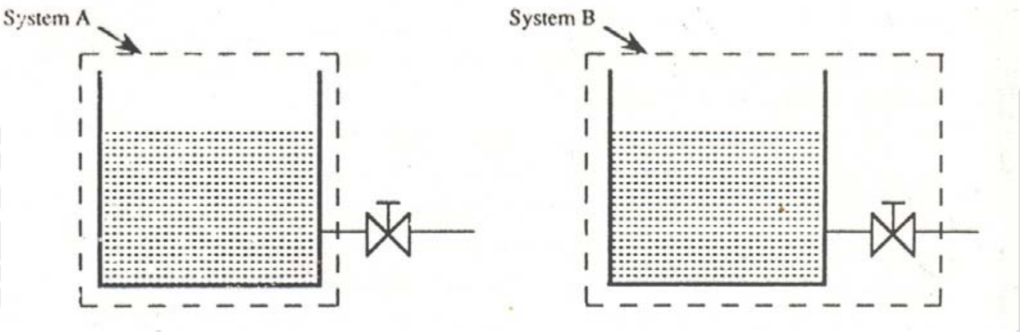

Figure 1.1: Examples of systems and their boundaries

Both closed and open systems are often encountered. In closed systems, the boundary of the system is impervious to any flow of matter. In an open system, heat and/or matter can flow into or out of the system. For example, a system boundary that contains only a small section of the wall is impervious to the flow of matter, and may be considered a close system. On the other hand, system B in Figure 1.1 is an open system since both heat and liquid can flow through the system.

1.4.2 Properties

Properties are those observable characteristics, such as pressure and temperature, which define the equilibrium state of a thermodynamic system. Properties do not depend on how the state of a system is attained: they are only functions of the state of a system. Thus, properties are independent of the process by which a system attained a certain state.

Intensive Properties

Intensive properties do not depend on the size of a system, such as temperature, pressure and density.

Extensive Properties

An extensive property depends on the size of the system: for example, mass, length, volume, energy. This definition implies that an extensive property of a system is a sum of respective partial property values of the components of a system. These properties, one of which may be mass are required to uniquely give an extensive property of a single component system.

The ratio of two extensive properties of a homogenous system is an intensive property. For example the ratio of two extensive properties mass and volume is density, which is an intensive property.

The state of a system is defined by independent properties. Once the properties become fixed, when the state of the system is defined, they are called dependent properties.

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. What is a dimensionally consistent equation?

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2. Enlist different systems of measurement and state the most acceptable one among them.

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3. Write the SI units of the following:

Quantity	Unit	Quantity	Unit
Length		Frequency	
Thermodynamic temperature		Pressure	
Amount of substance		Power	
Area		Moment of force	
Density		Specific energy	
Concentration		Thermal conductivity	

4. Differentiate between the following

   i) Open & closed systems

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ii) Intensive & extensive properties

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1.5 THERMAL PROCESSING

Since many of the processes utilized to preserve food products depend on the addition of thermal energy, it is important to understand the principles associated with food preservation through the addition of thermal energy. The design of a thermal process to achieve food preservation involves two principles: (a) the use of elevated temperatures to increase the rate of reduction in the microbial population present in the raw food material and (b) the transfer of thermal energy into the food product required to achieve the desired elevated temperatures.

The information in this section will address the typical parameters used to quantify the influence of elevated temperatures on reduction of microbial populations. Details will be presented in subsequent sections.

1.5.1 Influence of Elevated Temperatures on Microbial Populations

When microbial population in a food is exposed to an elevated temperature, changes in individual microbial cells within the population and a reduction in the viability of the microorganisms result in a reduction of the population with time of exposure when quantified by standard microbiological procedures. A typical pattern of microbial population change as a function of time when the population is exposed to an elevated temperature is illustrated in Figure 1.2. The reduction in population occurs in a logarithmic manner with increasing time at a given constant elevated temperature.

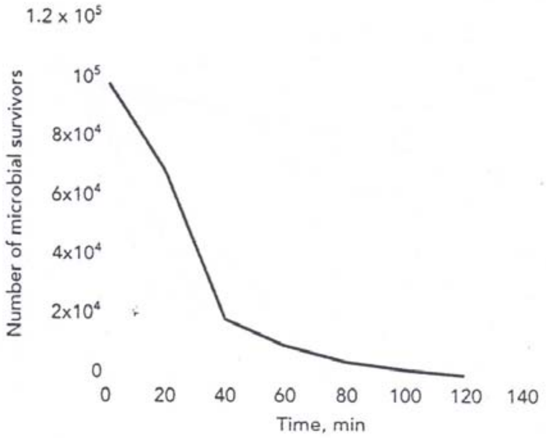

Figure 1.2: Changes in microbial population as a function of time at a constant elevated temperature

Decimal Reduction Time

The decimal reduction time (D Value) is defined as the time necessary for 90% reduction in the microbial population. When the microbial population is plotted against corresponding heating time on semi log coordinates, the D value is the time required for a one log cycle reduction in the number of microorganisms (Figure 1.3). The initial microbial population has no influence on the D value since the magnitude is directly related to the slope of the straight line. Exposure of the microbial population to higher temperatures results in a decrease in the D value. In fact, a plot of decimal reduction time as a function of temperature on semi log coordinates results in a linear relationship (Figure 1.4). This curve is known as thermal resistance curve.

Based on the definition, the following equation can be used:

$$\log N_0 - \log N = {}^{t}\!/_{D} \qquad (1.1)$$

or,
$$ {}^{N}\!/_{N_0} = 10^{-t/D} \qquad (1.2)$$

where N_0 is the initial number of microorganisms (t=o), N is the number of microorganisms surviving after heating for time 't' at a temperature and D is decimal reduction time for the microorganism under conditions of heating.

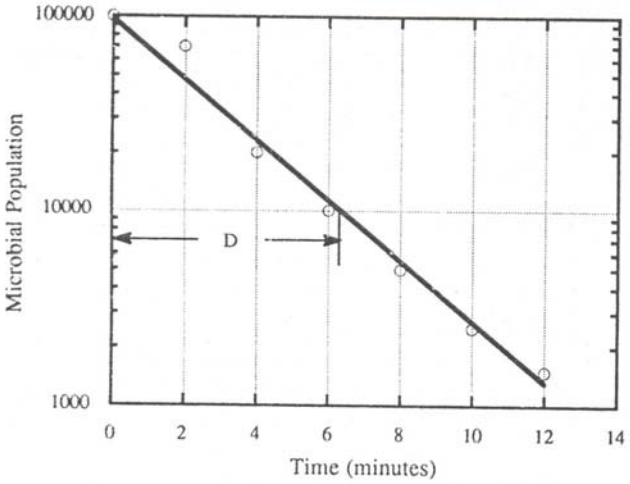

Figure 1.3: Semi-logarithmic plot of microbial population versus heating time at an elevated temperature

Thermal Resistance Constant

The temperature increase required to cause a one log cycle reduction in the decimal reduction time is defined as the thermal resistance constant (z). The thermal resistance constant, or z-value, is a second quantitative parameter normally used to quantify the thermal process required for a given microbial population. A large z-value suggests that a given increase in temperature of exposure for the microbial population results in a small change in decimal reduction time. In most situations, this observation would indicate that the microbial population contains vegetative cells or microbial spores; the spores exhibit greater heat resistance or higher z-value than vegetative populations which are characterized by a lower z-value. It is important to note that the complete characterization of the impact of elevated temperature on microbial population requires reference to both the decimal reduction time (D) and the thermal resistance constant (*z*). The *z*-value as shown in Figure 1.4 can be expressed by the following equation:

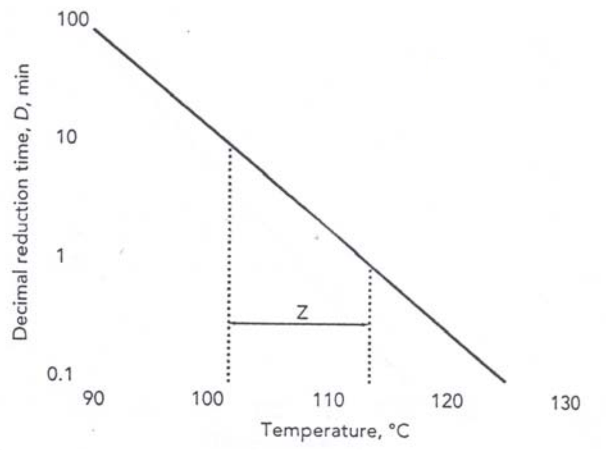

Figure 1.4: Thermal resistance curve of microbial population

$$z = \frac{T_2 - T_1}{\log D_{T_1} - \log D_{T_2}} \tag{1.3}$$

where D_{T_1} and D_{T_2} are decimal reduction times for micro-organisms at temperatures T_1 and T_2, respectively and 'z' is thermal resistant constant.

Thermal Death Time

The third quantitative parameter found frequently in thermal processing is the thermal death time, or F-value, which finds use in the actual thermal process. Thermal death time is defined as the time required for achieving a *stated reduction* in the microbial population at a given temperature. The key part of the definition is the stated reduction, which may be the reduction in the population of microbial pathogens required to establish product safety. Alternatively, the stated reduction may be the reduction in the population of a vegetative microorganism causing product spoilage, and the stated reduction is that required to achieve the desired product shelf-life.

A thermal death time curve would appear to be very similar to a thermal resistance curve (Figure 1.4), but would cover the entire range of times required to achieve the desired or stated reduction in microbial population. A typical thermal death time curve is presented in Figure 1.5. Note that the curve describes the entire reduction in microbial population from time zero until the population has been reduced to a defined level of microbial survivors. This point has been defined as the thermal death time, or F-value.

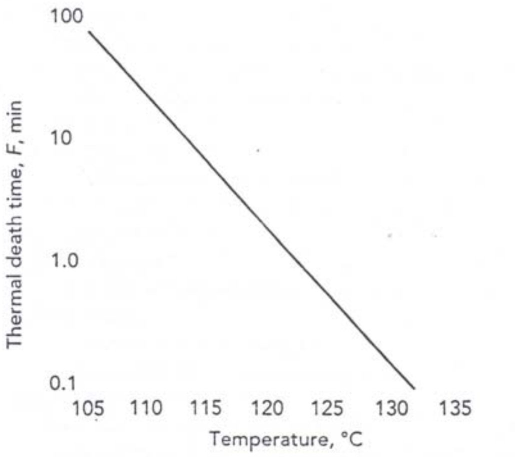

Figure 1.5: Thermal death time curve

The similarity in the thermal resistance and the thermal death time curve is evident from Figures 1.4 and 1.5. Each log cycle reduction in the microbial population on the thermal resistance curve represents a decimal reduction time, or D-value. It follows that F-values may be expressed as multiples of D-values. The most common of these relationships is F = 12D for *Clostridium botulinum* in *com*mercial sterilization of low acid foods. It must be emphasized that any given F-value will apply to a single elevated temperature. In other words, different elevated temperatures result in different F-values or times required achieving the same stated level of reduction in microbial population.

Inter-relationships

The relationships between microbial populations and time, as well as the impact of temperature, are very similar to the relationships used to describe kinetic parameters in first-order chemical reactions. The reaction rate constant *(k)* is used to describe the change in concentration of a reactant as a function of time. In microbial populations, the D-value is utilized to describe the same relationship. It follows that the relationship between the reaction rate constant *(k)* and the decimal reduction time (D) is given by Eq. (1.4):

$$k = \frac{2.303}{D} \tag{1.4}$$

The influence of temperature on reaction rate is described by Q_{10} or the activation energy constant (E). It follows that a relationship between Q_{10} and thermal resistance constant (z) must exist. It is relatively easy to demonstrate that this relationship is as shown in Eq. (1.5):

$$Q_{10} = 10^{\frac{10}{z}} \tag{1.5}$$

The relationship between the activation energy constant (E) and the thermal resistance constant (z) is more complex. It must be noted that the activation energy constant (E) is obtained from an Arrhenius plot: the natural logarithm of the reaction rate constant *(k)* versus the inverse of absolute temperature. Nevertheless, the relationship has been derived and presented in Singh and Heldman (1993) as Eq. (1.6):

$$E = \frac{2.303 R T_A^2}{z} = \frac{19.15 T_A^2}{z} \tag{1.6}$$

where R is the universal gas constant and $T_{A,}$ represents the mid-point between two absolute temperatures used to define the z-value in the relationship. The relationship between the activation energy constant and the thermal resistance constant applies over limited ranges of temperature where the experimental data utilized to quantify the z-value were measured.

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. Define thermal death time & decimal reduction time.

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2. Compute the first order rate constant corresponding to the decimal reduction time of 4.1 minutes.

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3. Estimate Q_{10} for a z value of 11°C.

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4. Estimate the activation energy of a microorganism having a thermal resistance constant of 11°C at 100°C?

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1.6 REFRIGERATION

Refrigeration system allows transfer of heat from the cooling chamber to a location where the heat can be discarded. The transfer of heat is accomplished by using a refrigerant, which like water changes state – from liquid to vapour. The primary purpose of refrigerating foods is to extend shelf-life by slowing down degradatory reactions and limiting microbial growth. Through reduction in rates of chemical, biochemical and microbial kinetics (rates of lipid oxidation, non enzymatic browning, sugar conversion, enzymatic browning, and respiration reactions), low temperature storage can extend the shelf-life of fresh and processed foods. Typically, refrigerated storage means holding food in a temperature range of –1 to 8°C.

Other factors besides low temperature may influence shelf-life of refrigerated foods. For fresh foods, these include the type of food and variety, the condition of the food at harvest (mechanical damage, microbial contamination, and degree of maturity), and the relative humidity of storage atmosphere. For processed foods, factors affecting shelf life include type of food, degree of microbial or enzyme destruction during processing, hygienic factors during processing and packaging, and the nature of the package (barrier properties).

1.6.1 Components of a Refrigeration System

The major components of a simple mechanical vapour compression refrigeration system are shown in Figure 1.6. As the refrigerant flows through these components its phase changes from liquid to gas and then back to liquid. At location D, just prior to the entrance of the expansion valve, the refrigerant is in a saturated liquid state. After passing through the expansion valve, the refrigerant experiences a drop in pressure accompanied by a drop in temperature. Due to the drop in pressure, some of the liquid refrigerant changes to gas. The liquid gas leaving the expansion valve is termed 'flash gas'.

The liquid/gas mixture enters the evaporator coils at location E. In the evaporator, the refrigerant completely vaporizes to gas by accepting heat from the media surrounding the evaporator coils. The saturated vapour may also get superheated due to gain of additional heat from the surroundings.

The saturated or superheated vapours enter the compressor, where the refrigerant is compressed to a high pressure. This high pressure must be below the critical pressure of the refrigerant and high enough to allow condensation of the refrigerant at a temperature slightly higher than that of commonly available heat sinks, such as ambient air or water. Inside the compressor, the compression process of the vapours occurs at constant entropy (called an isentropic process). As the pressure of the refrigerant increases, the temperature increases, and the refrigerant become superheated.

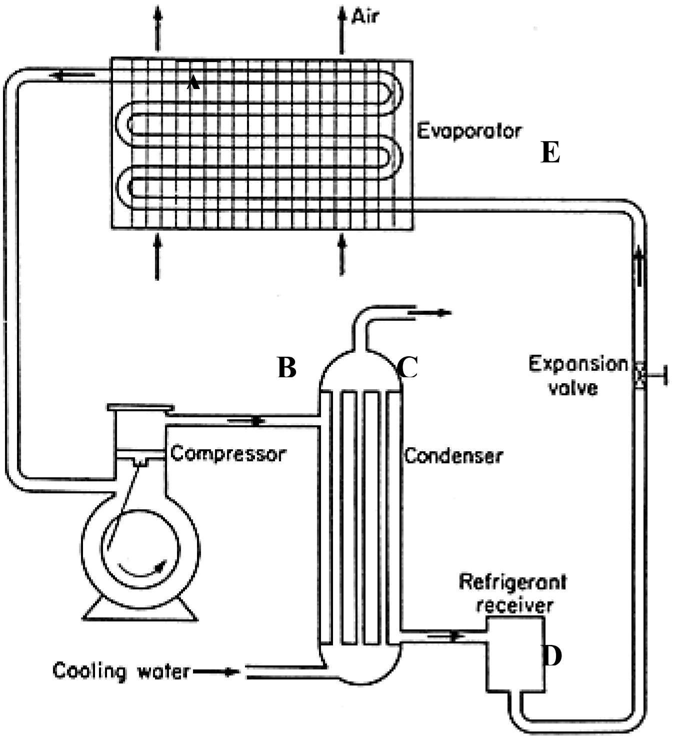

Figure 1.6: Mechanical refrigeration circuit

The superheated vapours are then conveyed to the condenser. Using either an air cooled or water cooled condenser, the refrigerant discharges heat to the surrounding media. The refrigerant condenses back to the liquid state in the condenser (saturated liquid). The temperature of the refrigerant may decrease below that of its condensation temperature (sub cooled) due to additional heat discharged to the surrounding media. The saturated or sub cooled liquid then enters the expansion valve and the cycle continues.

The process can also be followed on the pressure-enthalpy chart shown in Figure 1.7.

1.6.2 Some Useful Mathematical Expressions

Cooling Load

The cooling load is the rate of heat energy removal from a given space (or object) in order to lower the temperature of that space (or object) to a desired level. A typical unit of cooling load used in commercial practice is ‘ton of refrigeration’. One ton of refrigeration is equivalent to the amount of heat required to melt one ton of ice in one day at 0^0 C {(1000 kg x 336 kJ/kg)/24 hr} = (336000 kJ / 86400 s) = 3.888 kW. Thus a mechanical refrigeration system that has a capacity to absorb heat from the refrigerated space at the rate of 3.888 kW is rated as one ton of refrigeration.

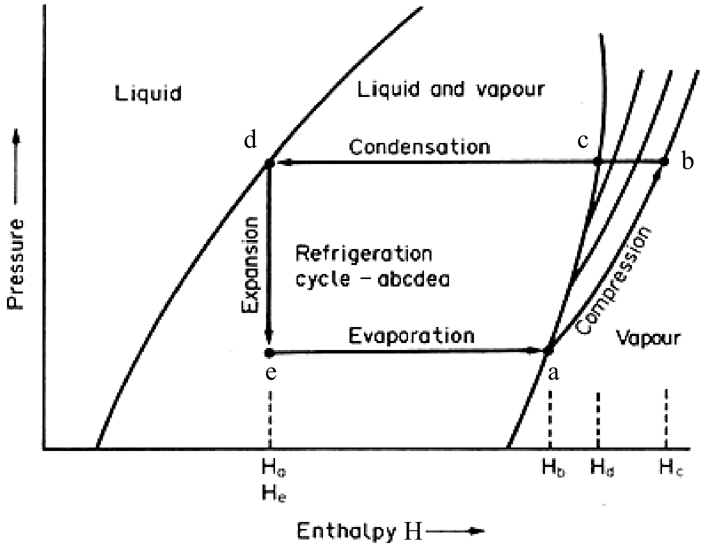

Figure 1.7: Pressure/enthalpy chart

The factors which contribute to the cooling load include the sensible heat, heat of respiration (in case of fresh produce); heat infiltration through walls, floor and ceiling; heat gain through doors; heat given by lights, people and use of fork lifts for material handling; etc.

Coefficient of Performance

The coefficient of performance (C.O.P.) is defined as a ratio between the heat absorbed by the refrigerant as it flows through the evaporator to the heat equivalence of the energy supplied to the compressor. In other words, it is the ratio of the useful refrigeration effect obtained from the system to the work expended on it to produce that effect.

$$C.O.P. = \frac{H_a - H_e}{H_b - H_a} \qquad (1.7)$$

where H_a is heat content of vapour learning evaporator, H_b is heat content of vapour learning compressor, H_d or H_e is heat content of liquid entering evaporator.

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. Describe the principle behind shelf-life extension through refrigeration.

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2. Enlist the various components of a vapour compression refrigeration system along with their functions.

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3. Define cooling load and C.O.P.

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1.7 FOOD FREEZING

Food freezing is a preservation process that depends on the reduction of product temperatures to levels well below the temperature at which ice crystals begin to form within the food. By reducing the temperature of the product to –10°C to –20°C, the normal reactions that cause deterioration of foods are reduced to negligible or minimal rates. These temperature levels eliminate microbial growth as a concern in shelf-life of the food product. As would be expected, the shelf-life of a frozen food is a function of temperature, with lower temperatures leading to longer shelf-life.

The limitations of freezing as a food preservation process include both quality concerns and energy requirements. The formation of ice crystals within the structure of most food products creates changes in the structure that are at times irreversible and most often cause negative changes in the quality characteristics of the product. The refrigeration requirements associated with the food-freezing process, as well as maintaining the low temperatures associated with frozen food storage and distribution are factors that must be considered while evaluating the costs of this preservation process. The value of the shelf-life extension achieved by food freezing must be balanced against the added costs associated with energy requirements for the production and storage of the frozen foods.

1.7.1 Theory

In theory, the freezing process is the removal of the thermal energy from the food product to the extent required to reduce the temperature below the freezing temperature of water. The thermal energy removed, as a part of freezing is primarily latent heat of fusion required to convert water to ice within the product.

If the temperature is monitored at the thermal center of food (the point that cools most slowly) as heat is removed, a characteristic curve is obtained (Figure 1.8).

The six portion of the curve are as follows:

AS The food is cooled to below its freezing point θ_f which, with the exception of pure water, is always below 0°C. At point S the water remains liquid although the temperature is below the freezing point. This phenomenon is known as sub-cooling and may be as much as 10°C below the freezing point

SB The temperature rises rapidly to the freezing point as ice crystals begin to form and latent heat of crystallization is released.

BC Heat is removed from the food at the same rate as before. Latent heat is removed and ice forms, but the temperature remains almost constant. The freezing point is depressed by the increase in solute concentration in the unfrozen liquor, and the temperature therefore falls slightly. It is during this stage that the major part of the ice is formed.

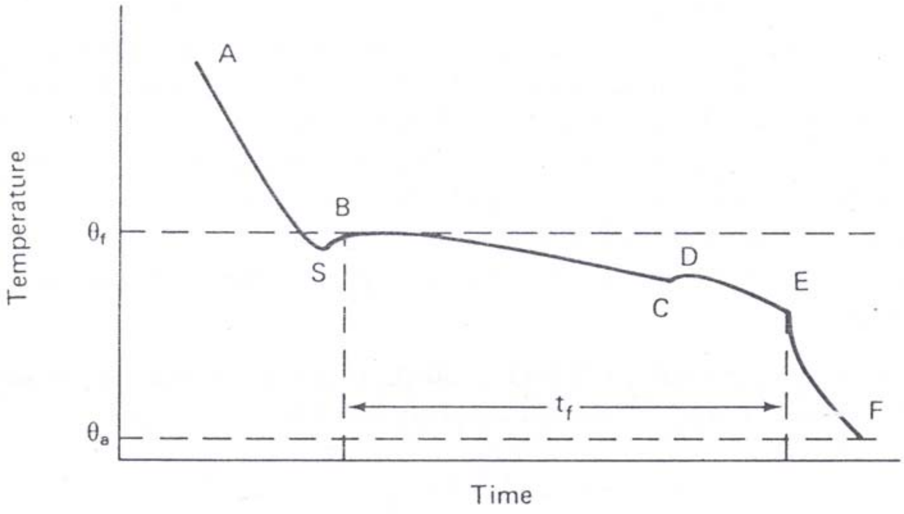

Figure 1.8: Time temperature relationships during freezing

CD One of the solutes becomes supersaturated and crystallizes out. The latent heat of crystallization is released and the temperature rises to the eutectic temperature for that solute

DE Crystallization of water and solutes continues. The total time t_f taken (the freezing plateau) is determined by the rate at which heat is removed.

EF The temperature of the ice-water mixture falls to the temperature of the freezer. A proportion of the water remains unfrozen at the temperature used in commercial freezing; the amount depends on the type and composition of the food and the temperature of freezing.

Ice Crystal Formation

The freezing point of a food is the temperature at which a minute crystal of ice exists in equilibrium with the surrounding water. However, before an ice crystal can form, a nucleus of water molecules must be present. Nucleation therefore precedes ice crystal formation. The rate of ice crystal growth during freezing is controlled by the rate of heat transfer for the majority of the freezing plateau. The rate of mass transfer does not control the rate of crystal growth except towards the end of the freezing period when solutes become more concentrated. The time taken for the temperature of the food to pass through the critical zone (Figure 1.9) therefore, determines the number and the size of the ice crystals.

Solute Concentration

The increase in solute concentration during freezing causes changes in pH, viscosity and redox potential of the unfrozen liquor. As the temperature falls individual solutes reach saturation point and crystallizes out. The temperature at which a crystal of an individual solute exists in equilibrium with the unfrozen liquor and ice is its eutectic temperature. However, it is difficult to identify individual eutectic temperatures in the complex mixture of solutes in foods, and the term final eutectic temperature is used. This is the lowest temperature of the solutes in the food. Maximum ice crystal formation is not possible until this temperature is reached. Commercial foods are not frozen to such low temperatures and unfrozen water is therefore always present.

Volume Changes

The volume of ice at 0^0 C is 9% greater than that of pure water, and an expansion of foods after freezing would therefore be expected. However, the degree of expansion varies considerably owing to the moisture content (higher moisture content produce greater changes in volume), cell arrangement, the concentration of solutes (high concentrations reduce the freezing point) and the freezer temperature (this determines the amount of unfrozen water and hence the degree of expansion). Temperatures below 0^0 C cause shrinkage in the volume of ice formed during freezing process.

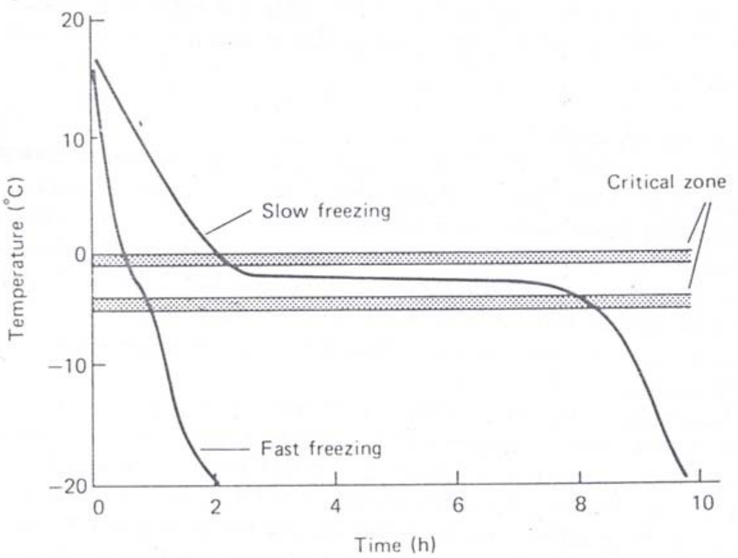

Figure 1.9: Temperature changes of food through the critical zone during freezing

1.7.2 Freezing Systems

The freezing process can be accomplished using either indirect or direct contact systems. Most often, the type of system used will depend on the product characteristics, before and after freezing is completed.

Indirect Contact Systems

In numerous food products freezing systems the product and the refrigerant are separated by a barrier throughout the freezing process. This is called an indirect contact system (Figure 1.10). Although many systems use a non-permeable barrier between product and refrigerant, indirect freezing systems include any system without direct contact, including those where the package material becomes the barrier. These include plate freezer, air blast freezer and freezer for liquid foods.

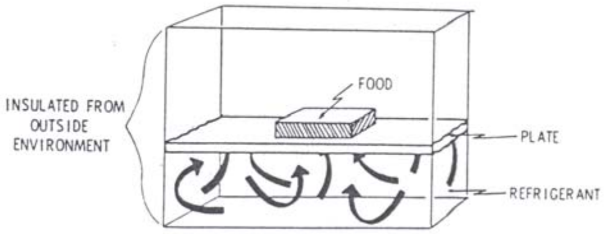

Figure 1.10: Schematic diagram of indirect contact freezing

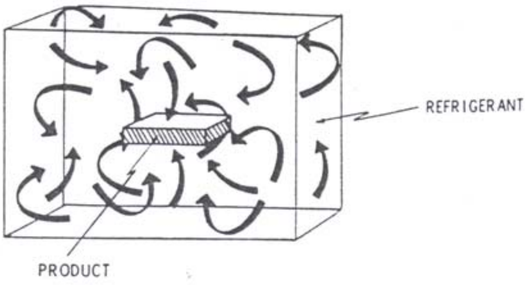

Figure 1.11: Schematic diagram of direct contact freezing

Direct Contact Systems

Direct contact freezing systems operate with direct contact between the refrigerant and the product (Figure 1.11). In most situations these systems operate more efficiently since there is no barrier to heat transfer between the refrigerant and the product. All direct contact freezing systems are designed to achieve rapid freezing, and the term individual quick freezing (IQF) applies. This includes fluidized bed freezing immersion freezing and cryogenic freezing.

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. Define food freezing.

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2. Define eutectic point.

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3. Enlist the factors affecting volume changes during freezing.

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4. Differentiate between indirect and direct contact freezing systems.

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1.8 EVAPORATION

Evaporation is an important unit operation commonly employed to remove water from dilute liquid foods to obtain concentrated liquid products (for e.g. manufacture of tomato puree from juice). Removal of water from foods provides microbiological stability and assists in reducing packaging, transportation and storage costs. Evaporation is also a necessary step before drying and crystallization process. Evaporation differs from dehydration, since the final product of evaporation process remains in liquid state.

The evaporator in which the vapour produced are discarded without further utilizing its inherent heat is called a single effect evaporator, whereas the evaporator in which the inherent heat of the vapour is reused again as heating medium is called a multiple effect evaporator.

The evaporation process is largely dependent on the principle of heat transfer and the factors, which hamper heat transfer, are the major impediments for the process. Some of these factors are: (1) Boiling point rise, (2) Heat sensitivity of the liquid, (3) Fouling & foaming properties of the food, etc.

1.8.1 Boiling Point Elevation

Boiling point elevation of a solution (liquid food) is defined as the increase in boiling point over that of pure water, at a given pressure. A simple method to estimate boiling point elevation is the use of Duhring's rule. The Duhring's rule states that a linear relationship exists between the boiling point temperature of a solution and the boiling point temperature of water at the same pressure. Duhring lines for sodium chloride – water system are shown in Figure 1.12.

1.8.2 Types of Evaporators

Several types of evaporators are used in the food industry. In the following paragraphs we would discuss some of the most commonly used evaporators.

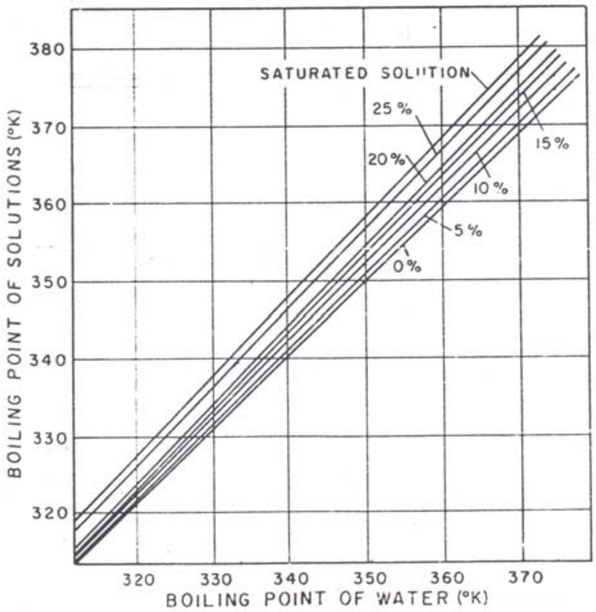
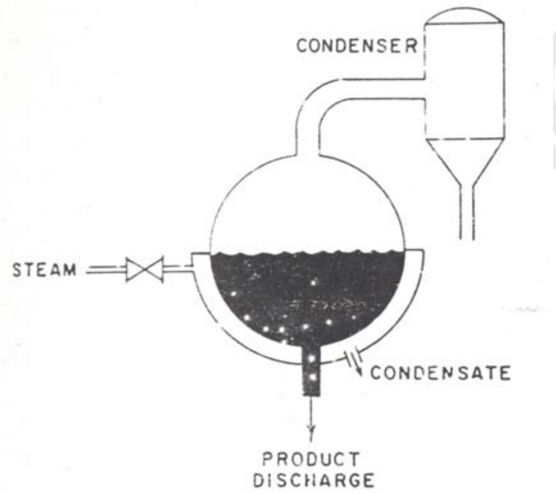


Figure 1.12: Duhring lines for sodium chloride – water system

Batch Type Pan Evaporator

One of the simplest and perhaps oldest types of evaporators used in food industry is the batch-type pan evaporator (Figure 1.13). The product is heated in a steam jacketed spherical vessel. The heating vessel is either open to atmosphere or connected to a condenser and vacuum system.

Heating of the product occurs mainly due to natural convection, resulting in smaller convective heat transfer coefficients. The poor heat transfer coefficients substantially increase the residence time of the product and reduce the processing capacities of these evaporators.



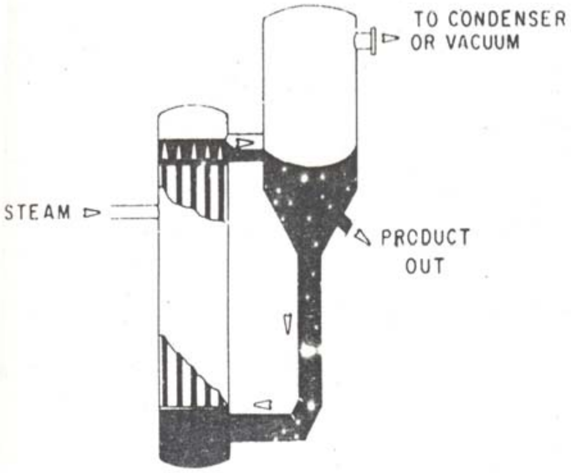


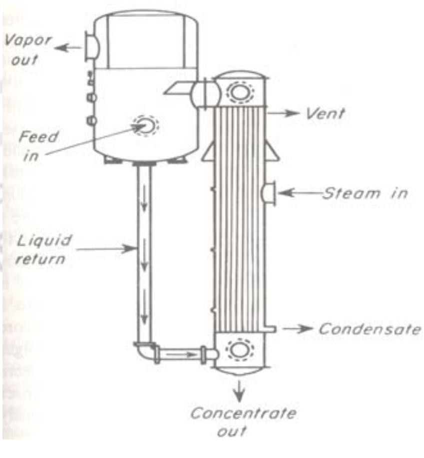
Figure 1.13: Batch type pan evaporator **Figure 1.14: Natural circulation evaporator**

Natural Circulation Evaporators

In natural circulation evaporators (Figure 1.14), short vertical tubes are arranged inside a steam chest. The whole calendria (tubes and steam chest) is located at the bottom of the vessel. The product when heated rises through these tubes by natural circulation while steam condenses outside the tubes. Evaporation takes place inside the tubes and the product is concentrated. The concentrated liquid falls back to the base of the vessel through a central annular section.

Rising Film Evaporator

In a rising film evaporator (Figure 1.15), a low viscosity liquid food is allowed to boil inside 10-15 m long vertical tubes. The tubes are heated from outside with steam. The liquid rises inside these tubes by vapours formed near the bottom of the heating tubes. The upward movement of vapour causes a thin liquid film to move rapidly upward. A temperature differential of at least 14°C between the product and the heating medium is necessary to obtain a well-developed film. High convective heat-transfer coefficients achieved in these evaporators mostly makes the operation once through. However, liquid can be recirculated to obtain the required solid concentration.



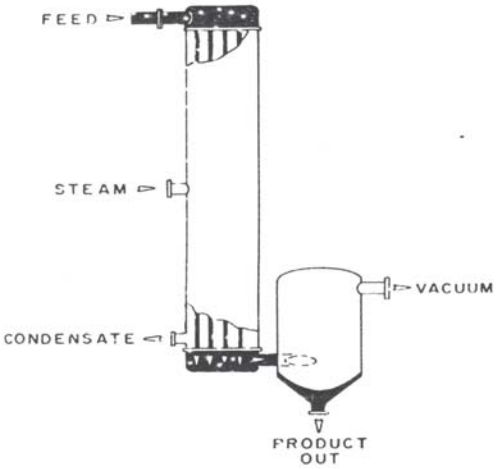


Figure 1.15: Rising film evaporator **Fig 1.16: Falling film evaporator**

Falling Film Evaporator

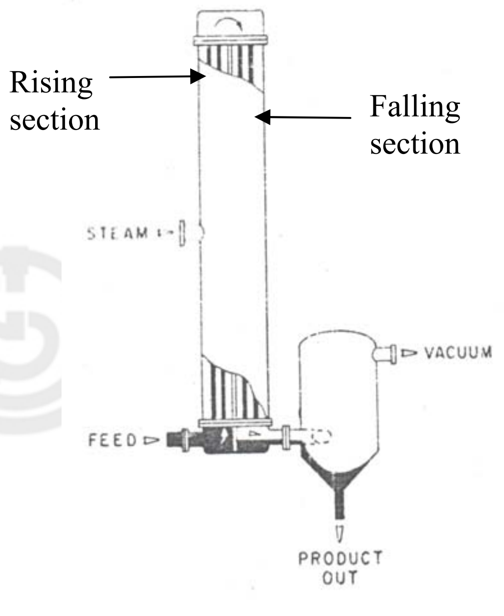
In contrast to the rising film evaporator, the falling film evaporator has a thin liquid film moving downward under gravity on the inside of the vertical tubes (Figure 1.16). The distribution of liquid in a uniform film flowing downward is accomplished by the use of specially designed distributors or spray nozzles. The falling film evaporator can handle more viscous liquids than the rising film type. These evaporators are best suited for highly heat sensitive products. Typical residence time in a falling film evaporator is 20-30 seconds, compared with residence time of 3-4 minutes in a rising film evaporator.

Rising / Falling Film Evaporator

In the rising / falling film evaporator, the product is concentrated by circulation through a rising film section followed by a falling film section of the evaporator. As shown in Figure 1.17, the product is first partially concentrated as it ascends through a rising tube section, followed by the pre-concentrated product descending through a falling film section; there it attains its final concentration.

Forced Circulation Evaporators

The forced circulation evaporator involves a non contact heat exchanger where liquid food is circulated at high rates (Figure 1.18). A hydrostatic head, above the top of the tubes, eliminates any boiling of the liquid. Inside the separator, absolute pressure is kept slightly lower than that in the tube bundle. Thus, the liquid entering the separator flashes to form a vapour. The temperature difference across the heating surface in the heat exchanger is usually 3-5°C. Axial flow pumps are generally used to maintain high circulation rates with linear velocities of 2-6 m/s, compared with a linear velocity of 0.3 – 1 m/s in natural convection evaporators. Both capital and operating costs of these evaporators are very low in comparison to other types of evaporators.



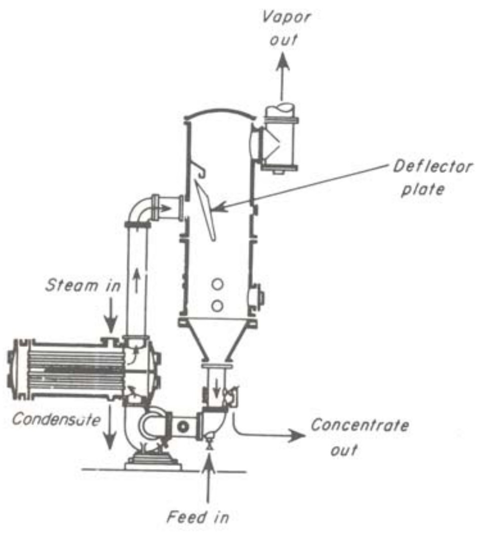


Figure 1.17: Rising / Falling film evaporator

Figure 1.18: Forced circulation evaporator

Agitated Thin Film Evaporator

For very viscous fluid foods, feed is spread on the inside of the cylindrical heating surface by wiper blades, as shown in Figure 1.19. Due to high agitation, considerably higher heat transfer rates are obtained. The cylindrical configuration results in low heat transfer area per unit volume of the product. High pressure steam may be used as the heating medium to obtain high wall temperatures for reasonable evaporation rates. The major disadvantages are the high capital and maintenance costs and low processing capacity.

In addition to the tubular shape, plate evaporators are also used in the industry. Plate evaporators use the principles of rising / falling film, falling film, wiped film and forced circulation evaporators.

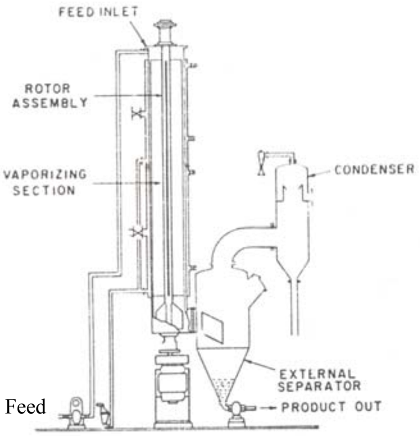


Figure 1.19: Agitated thin film evaporator

Check Your Progress Exercise 5

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

1. Differentiate between evaporation and dehydration.

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2. Define boiling point elevation.

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3. Write short notes on the following.

   a) Batch type pan evaporator
   b) Rising film evaporator
   c) Forced circulation evaporator
   d) Agitated thin film evaporator

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1.9 DEHYDRATION

Drying is one of the oldest methods of preserving food. Primitive societies practiced the drying of meat and fish in the sun long before recorded history. Today the drying of foods is still important as a method of preservation. Dried foods can be stored for long periods without any deterioration in quality. The principal reasons for this are that the microorganisms, which cause food spoilage and decay, are unable to grow and multiply in the absence of sufficient water and many of the enzymes which promote undesired changes in the food cannot function without water.

Preservation is the principal reason for drying, but drying can also occur in conjunction with other processing. For example, in the baking of bread, application of heat expands gases, changes the structure of the protein and starch molecules and dries the loaf.

Drying of foods implies the removal of water from the foodstuff. In most cases, drying is accomplished by vaporizing the water that is contained in the food, and to do this the latent heat of vaporization must be supplied. There are, thus, two important process-controlling factors that enter into the unit operation of drying:

a) Transfer of heat to provide the necessary latent heat of vaporization,

b) Movement of water or water vapour through the food material and then away from it to effect separation of water from foodstuff.

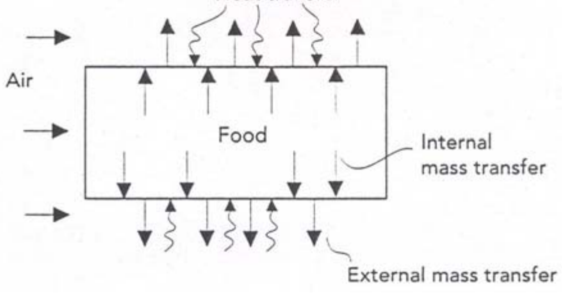

Figure 1.20: Principle of drying of food

1.9.1 Basic Drying Theory

Pure water can exist in three states, solid, liquid and vapour. The state in which it is at any time depends on the temperature and pressure conditions and it is possible to illustrate this on a phase diagram, as in Figure 1.21.

If we choose any condition of temperature and pressure and find the corresponding point on the diagram, this point will lie, in general, in one of the three-labelled regions, solid, liquid, or gas. This will give the state of the water under the chosen conditions.

Under certain conditions, two states may exist side by side, and such conditions are found only along the lines of the diagram. Under one condition, all three states may exist together; this condition arises at what is called the triple point, indicated by point O on the diagram. For water it occurs at 0.0098°C and 0.64 kPa (4.8 mm of mercury) pressure.

If heat is applied to water in any state at constant pressure, the temperature rises and the condition moves horizontally across the diagram, and as it crosses the boundaries a change of state will occur. For example, starting from condition A on the diagram adding heat warms the ice, then melts it, then warms the water and finally evaporates the water to condition A'. Starting from condition B, situated below the triple point, when heat is added, the ice warms and then sublimes without passing through any liquid state.

Liquid and vapour coexist in equilibrium only under the conditions along the line OP. This line is called the vapour-pressure line. The vapour pressure is the measure of the tendency of molecules to escape as a gas from the liquid.

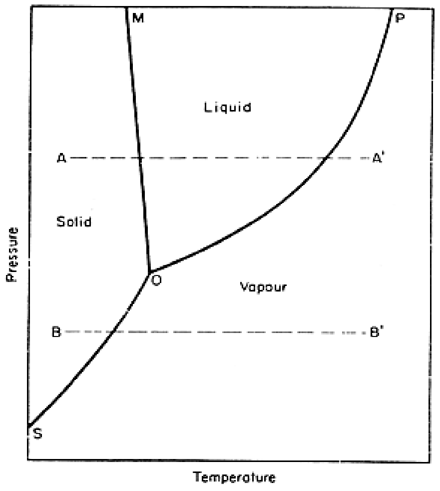

Figure 1.21: Phase diagram for water

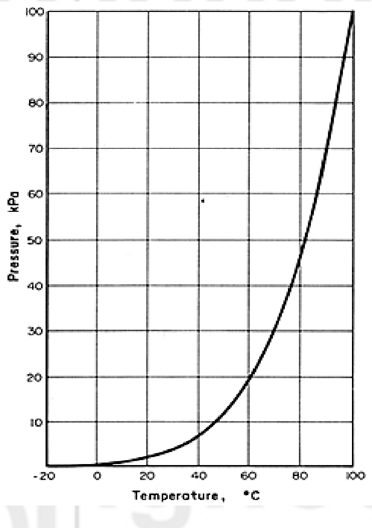

Fig 1.22: Vapour pressure/temperature curve for water

Boiling occurs when the vapour pressure of the water is equal to the total pressure on the water surface. The boiling point at atmospheric pressure is of course 100°C. At pressures above or below atmospheric, water boils at the corresponding temperatures above or below 100°C as shown in Figure 1.22 for temperatures below 100°C.

Recently, state diagrams have been employed to depict conditions of water in foods and its use has improved our knowledge of drying technology. The state diagram shown in figure 1.23 for simple system of solute and solvent, is a phase diagram based on components of the food product supplemented by the glass transition curve. The glass transition curve represents a meta stable transition where viscosity is effectively so high that the product does not ‘flow’ over time scale of importance to food stability. Below this curve on the state diagram, the food is stable to diffusion related processes (such as moisture migration) for extremely longer times.

Heat Transfer in Drying

The rates of drying are generally determined by the rates at which heat energy can be transferred to the water or to the ice in order to provide the latent heats, though under some circumstances the rate of mass transfer (removal of the water) can be limiting. All three of the mechanisms by which heat is transferred - conduction, radiation and convection - may enter into drying. The relative importance of the mechanisms varies from one drying process to another and very often one mode of heat transfer predominates to such an extent that it governs the overall process.

As an example, in air drying the rate of heat transfer is given by:

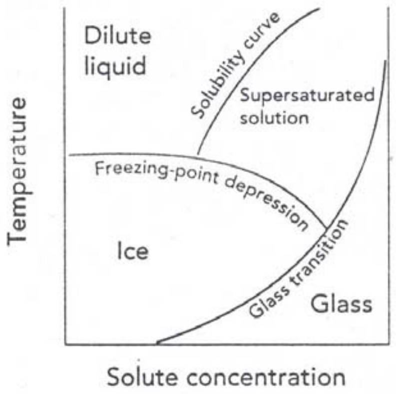

Figure 1.23: State diagram for a simple binary mixture

$$q = UA\,(T_a - T_s) \tag{1.8}$$

where q is the heat transfer rate in J s^{-1}, U is the overall heat-transfer coefficient in J s^{-1} m^{-2} k^{-1}, A is the area through which heat flow is taking place, T_a is the air temperature and T_s is the temperature of the surface which is getting dried.

In cases where substantial quantities of heat are transferred by radiation, it should be remembered that the surface temperature of the food might be higher than the air temperature. Estimates of surface temperature can be made using the relationships developed for radiant heat transfer although the actual effect of combined radiation and evaporative cooling is complex. Convection coefficients also can be estimated using the standard equations.

As drying proceeds, the character of the heat transfer situation changes. Dry material begins to occupy the surface layers and conduction must take place through these dry surface layers that are poor heat conductors. Therefore, the heat is transferred to the drying region progressively more slowly.

Mass Transfer in Drying

In heat transfer, heat energy is transferred under the driving force provided by a temperature difference, and the rate of heat transfer is proportional to the potential (temperature) difference and to the properties of the transfer system characterized by the heat-transfer coefficient. In the same way, mass is transferred under the potential gradient force provided by a partial pressure or concentration difference. The rate of mass transfer is proportional to the potential (pressure or concentration) gradient and to the properties of the transfer system characterized by a mass-transfer coefficient.

Writing the relationship symbolically, analogous to heat transfer (Eq. 1.8), we have

$$w = k_G A(H_a - H_s) \qquad (1.9)$$

where w is the mass being transferred kg s^{-1}, A is the area through which the transfer is taking place, k_G is the mass-transfer coefficient in this case in units kg m^{-2} s^{-1} , and the quantity within brackets i.e., $(H_a - H_s)$ is the humidity difference in kg kg^{-1}(kg of moisture per kg of air).

Unfortunately the application of mass-transfer equation is not as straightforward as heat transfer, one reason being because the movement pattern of moisture changes as drying proceeds. Initially, the mass (moisture) is transferred from the surface of the material and later, to an increasing extent, from deeper within the food to the surface and thence to the air. So the first stage is to determine the relationships between the moist surface and the ambient air and then to consider the diffusion through the food. In studying the surface/air relationships, it is necessary to consider mass and heat transfer simultaneously. Air for drying is usually heated and it is also a major heat-transfer medium. Therefore, it is necessary to look carefully into the relationships between air and the moisture it contains.

Factors Influencing Drying

There are many factors that influence the rate of drying. These are related to either: (1) the process conditions present during drying, as determined by dryer type and operating conditions, or (2) the nature of the food product placed inside the dryer. The process conditions include dry look temperature, air velocity, wet bulb depression, pressure etc. whereas those of food product include surface area, constituent orientation, cellular structure, type and concentration of solutes.

Drying Methods

The methods involved in industrial drying of foods include: (1) Cabinet drying, (2) Tunnel drying, (3) Spray drying, (4) Vacuum drying, (5) Foam mat drying, (6) Freeze drying, (7) Fluidized bed drying, (8) Microwave drying, (9) Drum drying etc. The principles of different drying methods and the equipments used will be dealt in detail in subsequent blocks.

Check Your Progress Exercise 6

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

1. Enumerate the principle of drying and its controlling factors?

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2. Define triple point of water.

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3. Triple point of pure water occurs at _______°C temperature and _________ kPa pressure.

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4. Define vapour-pressure line.

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5. Define glass transition curve.

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6. What is the driving force for heat and mass transfer during drying of foods?

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7. Enlist the factors that influence drying.

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1.10 LET US SUM UP

We have learnt that there are magnitudes of various quantities and properties, which do not make sense unless, qualified with appropriate units. Although there are different systems of units such as MKS, CGS, FPS and SI, it is the SI system of units that is internationally accepted. A system for the purpose of analysis may be either a closed or an open system. Thermal processing of food is required to ensure that the population of harmful micro-organisms is reduced to acceptable level and then not allowed to grow for an intended period of time. The concepts of Decimal reduction time, thermal resistance constant and thermal death time have been presented. Then, the processes of evaporation, refrigeration and dehydration as they relate to food processing have been introduced. Simple relationships for estimating the extents of these unit operations have been presented.

1.11 KEY WORDS

Dimensions	:	A dimension defines a physical entity, which can be observed and / or measured, quantitatively.
Units	:	A unit expresses the quantitative value of a dimension.
Open system	:	The composition of the system is described by the components present inside and outside the system boundary.
Close system	:	The composition of the system is described by the components present inside the system boundary.
Intensive Properties	:	Properties that does not depend on the size of a system.
Extensive Property	:	Depends on the size of the system: for example, mass, length, volume, energy. This definition implies that an extensive property of a system is a sum of respective partial property values of the components of a system.
Decimal reduction time	:	The decimal reduction time (D) is defined as the time necessary for 90% reduction in the microbial populationly heating at a constant temperature.
Thermal resistance constant	:	It is defined as the temperature increase required to cause a one log cycle reduction in the decimal reduction time.
Thermal death time	:	Thermal death time is defined as the time required for achieving a *stated reduction* in the microbial population at a given temperature.
Evaporator	:	Completely vaporizes the refrigerant by heating it.

Compressor : Compresses the refrigerant at constant entropy.

Condenser : Condenses the refrigerant after going the heat to the surrounding medium

Expansion valve: It is the point of differentiation between the high pressure and low pressure sides of the refrigeration cycle.

Cooling load : The cooling load is the rate of heat energy removal from a given space (or object) in order to lower the temperature of that space (or object) to a desired level.

Coefficient of performance : The coefficient of performance (C.O.P.) is defined as a ratio between the heat absorbed by the refrigerant as it flows through the evaporator to the heat equivalence of the energy supplied to the compressor.

Eutectic temperature : The temperature at which a crystal of an individual solute exists in equilibrium with the unfrozen liquor and ice is its eutectic temperature.

Boiling point elevation : Boiling point elevation of a solution (liquid food) is defined as the increase in boiling point over that of pure water, at a given pressure.

Triple point : Triple point of water is defined as a condition in which pure water can exist in all the three states i.e., solid, liquid and vapour.

1.12 ANSWERS TO CHECK YOUR PROGRESS EXERCISES

Check Your Progress Exercise 1

1. A dimensionally consistent equation is the one, which is balanced on both of its sides in terms of the dimensions, i.e. the LHS & RHS are dimensionally equal.
2. The different measuring systems are FPS, CGS, MKS and SI. The most acceptable and standard among them is the SI system.
3.

Quantity	Unit	Quantity	Unit
Length	m	Frequency	s^{-1}
Thermodynamic temperature	K	Pressure	$m^{-1}.kg.s^{-2}$
Amount of substance	Mol	Power	$m^2.kg.s^{-3}$
Area	m^2	Moment of Force	$m^2.kg.s^{-2}$
Density	Kg m^{-3}	Specific Energy	$m^2.s^{-2}$
Concentration	Mol m^{-3}	Thermal conductivity	$m.kg.s^{-3}.K^{-1}$

4. i) Open system is one which allows flow of heat and/or matter into or out of the system along its boundary whereas closed system is one in which the boundary is impervious to any flow of matter.

   ii) Intensive properties are those, which do not depend on the size of the system whereas extensive properties are those, which are dependent on the size of the system.

Check Your Progress Exercise 2

1. Thermal death time is defined as the time required to achieve a *stated reduction* in the microbial population at a given temperature, whereas, the decimal reduction time D is defined as the time necessary for 90% reduction in the microbial population.

2. $$k = \frac{2.303}{D} = \frac{2.303}{4.1} = 0.56/\min..$$

3. $$Q_{10} = 10^{10/z} = 10^{10/11} = 8.1$$

4. $$E_A = \frac{19.15}{z} T_A^2 = \frac{19.15}{11} (383)^2 = 2.55 X 10^5\, kJ/kg$$

Check Your Progress Exercise 3

1. Refrigeration involves the principle of transfer of heat from the cooling chamber or object to a location where the heat can be discarded with the use of a refrigerant, which like water changes state – from liquid to vapour.

2. a) Evaporator: It completely vaporizes the refrigerant by accepting heat from the media surrounding the coils.

   b) Compressor: It compresses the refrigerant to a high pressure so as to condense it at a temperature slightly higher than the heat sink.

   c) Condenser: Condenses the refrigerant to saturated / sub-cooled liquid by discharging heat to the surrounding media.

   d) Expansion valve: It is essentially a metering device that controls the flow of refrigerant into the evaporator. It separates the high pressure region from the low pressure region.

3. Cooling load is defined as the rate of heat energy removal from a given space (or object) in order to lower the temperature of that space (or object) to a desired level whereas C.O.P. is defined as the heat absorbed by the refrigerant as it flows through the evaporator to the heat equivalence of the energy supplied to the compressor.

Check Your Progress Exercise 4

1. Food freezing is defined as a preservation process that depends on the reduction of product temperatures to levels well below the temperature at which ice crystals begin to form within the food.

2. Eutectic temperature is defined as the temperature at which a crystal of an individual solute exists in equilibrium with the unfrozen liquor and ice.

3. The factors affecting volume changes during freezing are: (1) moisture content, (2) cell arrangement, (3) concentration of solutes and (4) freezer temperature.
4. In indirect contact freezing systems the product and the refrigerant are separated by a barrier throughout the freezing process whereas in direct contact freezing systems there is no such barrier between the refrigerant and the product.

Check Your Progress Exercise 5

1. Evaporation is a unit operation commonly used to remove water from dilute liquid foods to obtain concentrated liquid products whereas dehydration is used to remove water and obtain dry solid product i.e evaporation involves partial removal of water from the food products whereas drying involves complete removal of moisture from the foods.
2. Boiling point elevation of a solution (liquid food) is defined as the increase in boiling point over that of pure water, at a given pressure.

Check Your Progress Exercise 6

1. Drying of foods implies the removal of water from the foodstuff, which is accomplished by supplying the latent heat of vaporization.

   The two important process-controlling factors that enter into the unit operation of drying are:

   a) Transfer of heat to provide the necessary latent heat of vaporization,
   b) Movement of water/water vapour through the food material and then away from it to effect separation of water from foodstuff.
2. Triple point of water is defined as a condition in which pure water can exist in all the three states i.e., solid, liquid and vapour.
3. 0.0098°C and 0.64 kPa.
4. Vapour-pressure line is defined as a line along which liquid and vapour coexist in equilibrium.
5. The glass transition curve represents a metastable transition where viscosity is effectively so high that the product does not ‘flow’ over time scale of importance to food stability.
6. The driving force for heat transfer is temperature gradient whereas that of mass transfer is pressure or concentration.
7. The factors that influence the rate of drying are (1) the process conditions present during drying, as determined by dryer type and operating conditions (temperature, air velocity, relative humidity, pressure etc.), or (2) the nature of the food product placed inside the dryer (surface area, constituent orientation, cellular structure, type and concentration of solutes).

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