

# Food Engineering



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# *Food Engineering*

*Course Developers*

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**Lesson 1.****Rheological Properties of Foods****1.1. INTRODUCTION**

Rheology is the science of flow and deformation of matter and describes the interrelation between force, deformation and time. It is the study of the manner in which materials respond to applied stress or strain. The term comes from Greek 'rheos' meaning to flow. The science of rheology is only about 76 years of age. It was founded by two scientists meeting in the late '20s and finding out having the same need for describing fluid flow properties. The scientists were Professor Marcus Reiner and Professor Eugene Bingham.

Sensory evaluation as a scientific discipline represents a very unique technique that harnesses human behavioral instincts of perception, learning, cognition, psychophysics and psychometric for the evaluation of foods. The textural properties of a food are that group of physical characteristics that are sensed by the feeling of touch, are related to the deformation, disintegration and flow of food under application of force. Textural characteristics are an important factor in the overall quality of many food products. Unless these quality attributes meet the standards which the consumer expects, the product will be rejected regardless of its nutritional value.

**1.2. PSYCHORHEOLOGY**

Psychorheology of foods is the scientific study of man's perception of texture of foods. It may be divided into two major areas (i) Qualitative psychorheology work concerns the attributes of texture to which man responds, the structure of his mental lexicon of texture descriptors and the cluster of similar meaning texture descriptors. (ii) Quantitative work may consider mathematical relations between pairs of texture descriptors, or functions relating one or several subjective textural properties. The major thrust of quantitative psychorheology has been to ascertain the class of functions relating mechanical to subjective properties and through experimentations to quantify the parameters of those functions. Now it is well established that the psychorheological models are important in texture studies.

**1.3. IMPORTANCE OF RHEOLOGY**

Study of rheological properties is important in food science due to its utility in food processing operations and sensory characteristics. It gives information about the microstructure of a food. Rheology properties are manifestation of the rate and nature of the deformation that occurs when a material is stressed. These parameters can be used to predict how the fluid will behave in a process and in determining the energy requirement for transporting the fluid from one point to another in processing plant. Rheological parameters are also useful in defining the quality attribute of food products.

### 1.3.1. Rheology is very important in the following area in the food industry

- (i) Mixing-Two or more material are blended manually or mechanically.
- (ii) Flow Control-Flowability of material varies from very thin to highly viscous.
- (iii) Dispensing- Material comes out easily or with difficulty.
- (iv) Settling/ Floating – Material with different specific gravity either settle or float depending on viscosity of the material.
- (v) Pumping- Liquids or semi-solids are forced through the pipe
- (vi) Coating- Spreading of one material as thin layer over other.
- (vii) Cleaning – Soil removal from the surface of the equipments and pipeline.
- (viii) Control of processing parameters- velocity, magnitude of pressure drop, piping design, pumping requirement for fluid transport system, power requirement of agitation, power requirement of mixing and blending, amount of heat generated during extrusion etc.
- (ix) Influence on unit operations – Heat transfer, Mass transfer, mixing, grinding, sedimentation, separation, filtration, evaporation and drying etc.
- (x) Study of rheology helps to select proper method of harvesting and sorting of raw materials
- (xi) Study of rheology helps to select proper ingredients to manufacture processed foods.
- (xii) Study of rheology helps to select proper technology/equipment to manufacture processed foods with desirable sensory and rheological properties.
- (xiii) Study of rheology helps in newer product development (e.g. dietetic ice cream, paneer, low fat mozzarella cheese etc.)
- (xiv) Study of rheology helps in designing processing equipment, packaging machines, transportation system etc.
- (xv) Study of rheology helps to improve sensory quality of the products
- (xvi) Study of rheology helps in marketing the products.

### 1.3.2. Importance of Rheological Studies in Dairy Industry

Rheological studies of dairy products are important at a juncture when the need for modernizing the manufacturing and marketing of Traditional Indian Dairy Products (TIDP) is being emphasized in India. It helps to evaluate ingredient for potential contribution to creaminess in fat-free dairy products. Rheological studies also helps to evaluate quality of cheese and applicability of cheese for various applications like suitability for pizza topping. Further, the Bureau of Indian Standards (BIS) is actively considering the views of describing the food products based on their structure and rheology. Most fluid foods including dairy fluids like cream, ice cream mix, stirred yoghurt and liquid infant foods shows complex flow behaviour at different stages of processing and it requires study of its flow behaviour for better control over the processing parameters. Viscoelastic characteristics of foods are of great importance to the manufacturer, the trade and the consumers as these properties affect

'eating quality', usage properties such as ease of cutting, spreading and melting characteristic as well as handling and packaging characteristics. Recent developments in rheological instruments hold out a definite scope for generating valuable informations on the basic rheological parameters of these products. In the context of Indian dairy industry, texture and rheology of certain solid and semi-solid dairy products such as paneer, khoa, chhana and milk sweets have been recognized to play an important role in their acceptance which has a great bearing on the success of their production in modern dairy plants.

#### **1.4. SENSORY TECHNIQUES FOR EVALUATING MECHANICAL TEXTURE CHARACTERISTICS**

(i) Hardness: Place sample between molar teeth and bite down evenly, evaluating the force required to compress the food.

(ii) Cohesiveness: Place sample between molar teeth, compress and evaluate the amount of deformation before rupture.

(iii) Viscosity: Place spoon with sample directly in front of mouth and draw liquid from spoon over tongue by slurping, evaluating the force required to draw liquid over tongue at a steady rate.

(iv) Springiness: Place sample either between molar teeth (if it is solid) or between the tongue and the palate (if it is a semi-solid) and compress partially, remove force and evaluate the degree and quickness of recovery.

(v) Adhesiveness: Place sample on tongue, press it against the palate and evaluate the force required to remove it with the tongue.

(vi) Fracturability: Place sample between molar teeth and bite down evenly until the food crumbles, cracks or shatters, evaluating the force with which the food moved away from the teeth.

(vii) Chewiness: Place sample in the mouth and masticate at one chew per second at a force equal to that required to penetrate a gum drop in 0.5 seconds, evaluating the number of chews required to reduce the sample to a state ready for swallowing.

(viii) Gumminess: Place sample in the mouth and manipulate with the tongue against the palate, evaluating the amount of manipulation necessary before the food disintegrates.

Sensory texture profile is defined as the organoleptic analysis of the texture complex of a food in terms of its mechanical, geometrical, fat and moisture characteristics, the degree of each present, and the order in which they appear from first bite through complete mastication. The data on these parameters is generally collected using either interval or ratio scales.

**Table-1.1: Definition of textural characteristics**

Properties	Physical	Sensory
Primary		
<b>Hardness</b>	Force necessary to attain a given deformation	Force required to compress a substance between teeth
<b>Cohesiveness</b>	Extent to which a material can be deformed before rupture	Degree to which a substance is compressed between the teeth before it breaks
<b>Springiness</b>	Rate at which a material returns to its original condition	Degree to which a product returns to its original size
Secondary		
<b>Fracturability/Brittleness</b>	Force with which a material fractures	Force with which a sample crumbles
<b>Chewiness</b>	Energy required to masticate a food to a state ready for swallowing	Time required to masticate the sample to a state ready for swallowing
<b>Gumminess</b>	Energy required to disintegrate a semisolid food to a state ready for swallowing	Denseness that persists throughout mastication.



## Lesson -2

### Rheology of Processed Foods

#### 2.1. INTRODUCTION:

Rheology of process food is very important in the dairy products as it controls the body and texture of typical dairy products like cream, plastic cream, processed cheeses, traditional Indian dairy products (peda, burfi, halwasan, thabadi, sandesh, chhana podo etc.). Control of rheological properties is very much required in the development of new functional and health dairy products like low fat and low sugar ice cream, fat mimic products to avoid defects related to body and texture. Study of rheology is also important in the other food processing industries, like meat industries, fruits and vegetables processing, snack foods, bakery and confectionaries.

#### 2.2. EXAMPLES OF APPLICATION OF RHEOLOGICAL STUDY IN THE FOOD INDUSTRY

· Meat products : To evaluate type of breed; its growth rate (tenderness); to evaluate effect of pickling, chilling, aging, preservation, etc. on rheological property of meat; for measurement of toughness and compactness of meat and meat products; establishment of quality grade for marketing and export.

Fruits and vegetables : To evaluate variety of crop; for predicting the effect of storage and ripening period on process; prediction of storage and ripening period; in prediction of stage of harvesting and stage of maturing; used for sorting; measurement of\ textural variation, gives us an idea about growing practice; method of harvesting.

Jams and jellies : helps to decide variety of blending ingredients, esp. pectin; deciding jelling quality of pectin as well as integrity of gel structure, helps in deciding ingredients.

Snack foods : To evaluate formula for dough making and paste, particularly for extrusion; for measurement and adjustment of solids content; for measurement of textural properties like crispiness, hardness, softness and other properties to decide packaging and packing material; helps in predicting shelf-life of product under given storage conditions and history of product (method of harvesting, storage conditions, pre-treatments and processing unit operations).

Confectioneries : To evaluate the quality of raw material; to optimize the processing parameters; to decide the ingredient varieties to be used; for measuring properties like thickness of coating, chewiness, elasticity, brittleness and shelf life of product.

Paste : (Tomato paste, spreads, relishes, puddings, gels, jams, jellies, etc.) – used to evaluate consistency of mixture used for measured viscometric parameters at different stages of processing; deciding the pectin retention and prediction of consistency of final products.

Bakery : To evaluate dough consistency; to estimate floor time and rise time; effect of additives; prediction of shelf life.

Dairy products : To evaluate the effect of ingredients i.e. creaming in fat-free dairy products, fat mimic products by using micro-fluidization of whey protein concentrate, desired quality of mozzarella.

## 2.3. TEXTURE AND STRUCTURE OF HEAT AND ACID COAGULATED INDIGENOUS MILK PRODUCTS

Characterization of various food products on the basis of their rheology and microstructure forms the backbone of the scientific approach to product process development and of quality assurance in modern industrial practices. The current trends round the globe favour such studies to facilitate product description/specification for promoting process control and for international trade. Furthermore, the interest of researchers and manufacturers in the texture and structure of various milk products has been growing, as it is recognized that there are definite correlation between the structure and other physical properties of the products. The physical manifestation of food materials is due to its chemical make-up and a micro structural study may yield the true insight into their textual attributes. Evaluation of geometrical properties of foods are important for their characterization; these properties refer to the arrangement of constituents of food including the size, shape and orientation of the particles. Electron microscopy is useful to study surface topology and to develop correlation between the structure of various food material and then physico –chemical properties .

At a juncture when the need for modernizing the manufacturing and marketing of traditional milk products is being emphasized in India, such rheological and electron microscopic studies would be sine qua non to obtain much needed information for product/process development. Further, the Bureau of Indian Standards (BIS) is actively considering the views of defining/describing the food products based on their structure. It is worthwhile to mention here that BIS has already made a headway in this direction in respect of some of the food products such as roasted chicory and coffee powder. In the past few years, some work has been directed to study the rheology of selected indigenous dairy products such as paneer, khoa, rasogolla and sandesh. However, the area encompassing the micro structural studies has not received much scientific inputs so far in our country. Since rheology is determined by micro structure studies, study of rheological parameters would help us later to establish the relationship between microstructure and rheological properties. Keeping this in view, an attempt is made in this lecture to put forth the textural and structural aspects of some of the heat and acid coagulated indigenous milk products such as paneer, chhana and rasogolla.

### 2.3.1. Textural Properties of Paneer

Paneer is widely used in all vegetable dishes as well as for preparation of special foods, which requires to have rheological properties. The control of processing parameters during manufacture of paneer like temperature, pressure of press, control of pH, chilling and freezing during storage etc. are critical parameters, which requires study of its effect on the textural properties of paneer. The data on the objective textural properties of raw and fried and cooked paneers made from cow and buffalo milks has been shown in Table 2.1 It is evident from the table that primary parameters such as hardness and springiness differed significantly between cow and buffalo milk paneers. Cohesiveness, on the other hand, did not differ much between these two paneers. Since secondary parameters such as gumminess and chewiness are dependent on primary parameters, buffalo milk paneer revealed considerably higher vales for gumminess and chewiness compared to those recorded for cow milk paneer.

**Table- 2.1: Instron texture profile analysis of paneer made from cow and buffalo milks**

Attributes	Cow milk panner		Buffalo milk panner	
	Raw	Fried & cooked	Raw	Fried & cooked
Hardness, mN	25.59	8.66	40.72	9.31
Cohesiveness	0.67	0.70	0.64	0.70
Springiness, mm	7.50	9.38	7.70	9.59
Gumminess, mN	17.04	6.12	25.19	6.46
Chewiness, mN. Mm	131.27	54.27	206.36	63.32

Frying in oil and cooking- in salt water remarkably reduced the hardness, gumminess and chewiness and increased the cohesiveness and springiness of both the paneer.

### 2.3.1.1. Microstructure of Paneer

Scanning electron microscopy (SEM) reveals that in the raw state, both cow, and buffalo paneers possessed uniformly aggregated protein particles and fat globules are evenly distributed in the protein net work. Transmission Electron microscopy: (TEM) confirmed the existence of granular structure in paneer and also exhibited the internal structure of the protein particles. Raw cow milk paneer has uniformly packed small protein particles and resembled cottage cheese, while in raw buffalo milk paneer protein particles were more densely packed and fused. Core-and-lining structure, which is characteristic of curds obtained by coagulation of hot milk at pH 5.5 is well developed in both the paneers. The development of core-and-lining structure is influenced by the temperature and pH of coagulation.

Frying of paneer in oil severely changed its structure, resulting into compaction suppressing the smooth granularity of the protein matrix in cow milk paneer. The granularity totally vanished in the buffalo milk paneer. The compaction is more clearly evident in TEM ultragraphs. The compaction also caused the fat globules to acquire sharp and pointed outlines unlike their globular shape in raw paneer. Cooking of fried paneer in salt water restored both the granular structure and core-and- lining structure of the protein bodies. This restoration was more in case of cow milk paneer as compared to buffalo milk paneer.

### 2.3.2. Textural Properties of Chhana

Instron textural attributes of chhana made from cow and buffalo milks are given in table 2.2. It is evident that all the textural values were less for cow milk chhana compared to that of buffalo milk chhana. The secondary parameters such as gumminess and chewiness for buffalo milk chhana were more than two times to those values for cow milk chhana. However there was not much difference between cow milk and buffalo milk chhana as for as the adhesiveness was concerned.

**Table-2.2: Instron Texture Profile Properties of Chhana**

Attributes	Cow milk chhana	Buffalo milk chhana
Hardness, mN	11.60	19.50
Cohesiveness	0.59	0.67
Springiness, mm	3.60	5.00
Gumminess, mN	6.48	13.06
Chewiness, mN. mm	24.64	65.32
Adhesiveness mN	0.35	0.38

### 2.3.2.1. Microstructure of Chhana

SEM of a defatted cow milk chhana reveals conglomerated and compact protein material (casein and whey protein complexes with numerous small uniformly distributed pores of irregular shape. The protein particles coalesced and fused densely during coagulation and lost their natural identity of subunit' sizes as seen in milk. The coalesced, smooth protein bodies were joined with thick bridges. SEM of defatted buffalo milk chhana also shows a similar compact, coalesced protein net work with numerous globular and irregular voids throughout the matrix, but slightly more uneven as compared to cow milk chhana. The globular void spaces indicate that the casein-whey protein complexes are closely interspersed with numerous fat globules due to the usage of whole milk. Cow and buffalo milk chhana has been shown to contain fat globules embedded in coalesced casein micelles with some whey-filled spaces at the edge. The agglomerated large protein particles form continuous thick strands joined together forming somewhat uneven matrix with numerous void spaces in between. The fat globules are strongly cemented in these thick protein strands. The overall structure is more or less similar to that of cream cheese, in which the fat globules are found cemented together with the coalesced protein particles as seen in chhana.

### 2.3.3. Textural Properties of Rasogolla

Instron textural attributes of rasogolla are shown in Table 2.3. It is clear from the table that cow milk rasogolla has significantly lower hardness, springiness, gumminess and chewiness than that of buffalo milk rasogolla. The hardness of buffalo milk rasogolla is 2-3 times higher than that of cow milk rasogolla. Springiness of buffalo milk rasogolla (6.4 mm) is markedly higher than that of cow milk rasogolla (4.8 mm). Cohesiveness varied from 0.61 (cow milk rasogolla) - 0.70 (buffalo milk rasogolla). As the consequence of higher hardness and springiness in buffalo milk rasogolla, their gumminess and chewiness values also increased remarkably than that of cow milk rasogollas. No adhesive force, however, has been recorded for either of the rasogollas.

**Table- 2.3: Instron texture profile properties of rasogolla**

Attributes	Cow milk rasogolla	Buffalo milk rasogolla
Hardness, mN	5.85	16.82
Cohesiveness	0.61	0.70
Springiness, mm	4.80	6.40
Gumminess, mN	3.57	12.17
Chewiness, mN. mm	17.15	77.88

#### 2.3.3.1. Microstructure of Rasogolla

Cooking of chhana in sugar syrup (for 15 min.) severely altered the structure of both the fat and the protein phases. The microstructure of rasogolla exhibits a distinctly different protein net work from, chhana at low magnification, a ragged and cracked protein matrix can be seen obscured with fat and several void spaces interspersed throughout. Higher magnification revealed that the fat globules are shrunken and ruptured, finally coalescing to a large mass and losing their natural identity as globular with a smooth surface as is found in chhana.

A defatted rasogolla sample showed a ragged porous, loose protein matrix with a folded thread-like structure. The clumped protein particles formed a corrugated edge around the void space. Higher magnification showed that the folded protein particles were interlinked with thick protein bridges forming a core type structure with numerous voids.

Similarly, the fat globule structure in buffalo milk rasogolla revealed drastic shrinkage of the fat globule membrane and globules partly detached from the protein bodies. The defatted protein matrix in buffalo milk rasogolla was more compact and ragged with lesser voids as compared to cow milk rasogolla.

### 2.3.5. Interrelationships between texture and microstructure of Chhana and Rasogolla

The denser protein network present in chhana reduced the mean free path of the coalesced casein micelles which reduced the capacity of the fat and protein phases to move in relation to each other. Where as in rasogolla the large voids between the coalesced protein gave the free access of the protein bodies to move freely during the instron testing, resulting its lower hardness but higher springiness. This higher springiness in rasogollas may be attributed to its loose, porous and ragged protein matrix.



## Lesson 3

### Rheological Methods

#### 3.1. INTRODUCTION

Generally rheological properties are judged by sensory panel, it has its advantages and disadvantages depending on the person selected for judging the products. To have unbiased scores as well as reproducibility of the values of rheological attributes, it is necessary to go for instrumental measurement. There are many instrumental methods are developed based on fundamental principle as well as experimental data. There are certain mathematical models developed by different scientist based on empirical methods, which are widely used for measurement of rheological properties of most of the food products.

#### 3.2 TESTS FOR MEASUREMENT OF RHEOLOGICAL PROPERTIES

Instrumental methods for measurement of rheological properties are classified into two broad categories as follow:

Fundamental tests which measure the properties that are inherent to the material and do not depend on geometry and shape of the sample, conditions of loading or type of apparatus used, e.g. relaxation time, Poisson's ratio, shear modulus and bulk modulus;

Empirical tests (because data are based on comparison with sensory) or imitative tests (because these imitate the chewing in mouth). e.g. properties like puncture force, extrusion energy, cutting force required, pressing/compression force required for juice extraction, etc. – where mass of sample, geometry and speed of test will decide the magnitude of parameter estimated.

Generally fundamental tests are applied on solid foods and these are further classified into quasi-static and dynamic tests

The tests conducted under conditions of static/quasi-static loading are known as quasi-static tests while those conducted under dynamic loading conditions are called dynamic tests.

The use of Instron in determining the modulus of elasticity under compression is an example of quasi-static test while if the determination is done using a vibrating device of certain frequency (generally 200 Hertz), then the test is dynamic. You can say that rate of loading can be used to determine whether test is dynamic/quasistatic.

#### 3.3. Quasi-Static Testing of Solid Food Products

Two types of behaviour can be studied – elastic behaviour of solid and another is pure viscous flow in case of liquids. Pure elastic behaviour is defined such that when force is applied to the material, it will instantaneously and finitely deform and when the force is released, the material will instantaneously come to the original form. Such materials are called 'Hooken solids' i.e. which follow Hook's law. The amount of deformation is proportional to the magnitude of the force. Rheological representation of this type of solids is a spring. The material of this nature can be given a rheological constant modulus of elasticity is ratio of stress/strain, where stress = force/area, and

strain=deformation due to force applied/original dimension. There are 3 types of moduli depending on type of force applied.

If force is applied perpendicular to area defined by stress and it is calculated as – modulus of elasticity(E)

If modulus is calculated by applying force parallel to area defined by stress i.e. a shearing stress, then it is called a shear modulus or modulus of rigidity(G or n) and

If force is applied from all directions (isotropic force) then change in volume over original volume is obtained that can be calculated by bulk modulus(B or K)

Creep : In an experiment if a constant stress is applied to sample and corresponding strain is followed as a function of time and results are expressed in terms of a parameter of compliance ( $J=\text{strain}/\text{stress}$ ). The change in the strain of material can be measured, when stress is removed it known as creep curve. In short we can say that creep curve shows strain as a function of time at constant stress. Visco-elastic materials can often be characterized by a modulus and relaxation time, which can be determined by an analysis of strain curve with time.

Relaxation curve (stress relaxation) – It is the curve obtained when stress is applied as a function of time at a constant strain. That means that instead of applying constant force and measuring the change in strain with time, it is also possible to apply a constant strain and measure change in stress with time. This type of experiment is called relaxation stress and the curve is known as relaxation curve. These relaxation and creep experiments are known as Transient experiments in which a constant force is applied to the material and resulting strain is measured as a function of time and vice-versa.



## Lesson-4

### Measurement of Rheological Parameters

#### 4.1. INTRODUCTION

The instrumental methods that have been used to evaluate the rheological properties of food may be empirical one or fundamental ones. Empirical methods include imitative ones, the Texture Profile Analysis (TPA) method employing the Texturometer as described by Friedman. The TPA has also been performed by many workers using Instron Universal Testing Machine. In these methods, mostly food samples are compressed between two plates using an Instron testing machine or a comparable apparatus and the force is recorded as a function of the compression. Until now no standardization of these tests has been made and many different executions of that have been described. Examples of differences are: shape and size of the test piece, treatments of the plates to increase or decrease the friction between the plates and the test piece, compression rate and temperature. One or more of the following parameters are usually derived from these tests:

- Force (or stress) at a given compression
- Force at the first maximum in the force-compression curve (often designated as fracture force)
- Initial slope (or modulus) of the force-compression curve
- Compression at the first maximum in the force-compression curve (often designated as fracture compression)
- Work done until a given compression
- Height recovered after deformation
- Adhesive force during ascending motion after compression

#### 4.2 TEXTURAL PROFILE FROM INSTRON

The textural characteristics of the food samples can be interpreted from their respective force-distance compression curve obtained. A generalized texture profile curve obtained from the Instron Universal Testing Machine is shown in Fig:4.1 and the following textural parameters can be interpreted from the Instron Curve:

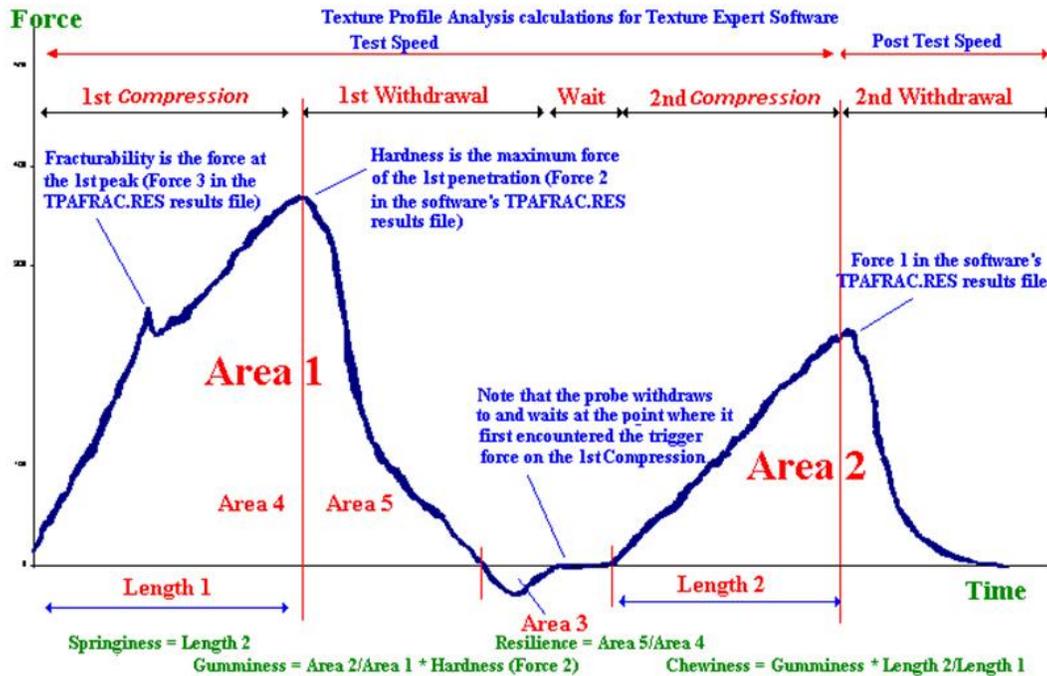


Fig-4.1: Generalized textural profile curve obtained from Instron|universal testing machine

(i) Hardness (Kgf): The force necessary to attain a given deformation, i.e. the highest point of peak in the first bite curve (Fig-4.1).

$$\text{Hardness} = H1, \text{ Kgf}$$

(ii) Brittleness (Kgf): Force with which the sample crumbles, cracks or shatters

$$\text{Brittleness (or Fracturability)} = H2, \text{ Kgf}$$

(iii) Adhesiveness: It is the work necessary to overcome the attractive forces between the surfaces of the sample and the other materials with which sample comes in contact. It is negative force area for the first bite curve (Fig-1)

$$\text{Adhesiveness} = A3$$

(iv) Cohesiveness: The extent to which a material can be deformed before it ruptures

$$\text{Cohesiveness} = A2/A1$$

A1 = Area under the first bite curve before reversal of compression

A2 = Area under the second bite curve before reversal of compression

(v) Springiness (mm): The height of sample recovers between the first and second compression, on removal of the deformation force

$$\text{Springiness} = S, \text{ mm}$$

(vi) Gumminess (Kgf): It is the energy required to masticate a sample to a state ready for swallowing a product of hardness and cohesiveness

Gumminess = Hardness x Cohesiveness x 100

(vii) Chewiness (kg-mm): It is the energy required to masticate a sample to a state ready for swallowing. It is a product of hardness, cohesiveness and springiness.

Chewiness = Hardness x Cohesiveness x Springiness

**Table- 4.1: Definition of textural characteristics**

Properties	Physical	Sensory
<b>Primary</b>		
Hardness	Force necessary to attain a give deformation	Force required to compress a substance between teeth
Cohesiveness	Extent to which a material can be deformed before rupture	Degree to which a substance is compressed between the teeth before it breaks
Springiness	Rate at which a material returns to its original condition	Degree to which a product returns to its original size
<b>Secondary</b>		
Fracturability	Force with which a material fractures	Force with which a sample crumbles
Chewiness	Energy required to masticate a food to a state ready for swallowing	Time required to masticate the sample to a state ready for swallowing
Gumminess	Energy required to disintegrate a semisolid food to a state ready for swallowing	Denseness that persists throughout mastication.



## Lesson 5.

### Rheological Properties of Fluid Foods

#### 5.1. INTRODUCTION

It is necessary to study properties of fluid food products for designing and lay-outing of transport system (piping and pumping layout). For the fluid food products, the design of transport system mainly depends on the type and description of flow characteristics of the product. Some of the properties are interdependent and some are dependent on the fluid food composition and therefore it is necessary to measure dependant properties and we can predict its rheological properties.

Most important dependant fluid food property is viscosity i.e. resistance against flow, generally indicated by  $\mu$  i.e. dynamic viscosity /  $\eta$  kinematic viscosity ( $\eta = \mu / \rho$ ). In food industry  $\mu$  is broadly used to describe a single parameter known as 'consistency'. But this approach may lead to confusion in many cases due to non-Newtonian behaviour of many fluid food products. The rheological classification of food is given in Fig-5.1. The stress and rate of shear diagram indicate varieties of food products classified under different categories, which is considered to be non-Newtonian as shown in the figure 5.2.

#### 5.2. CLASSIFICATION

The fluids can be classified into following categories depending on the response to the applied shear force.

##### 5.2.1. Newtonian Fluids:

Newtonian fluids are fluids which exhibit a linear increase in the shear stress with the rate of shear. These fluids exhibit a linear relationship between the shear stress and the rate of shear. The slope ' $\mu$ ' is constant therefore, the viscosity of a Newtonian fluid is independent of the rate of shear. These fluids exhibit a pure viscous flow i.e. the product begins to flow with the slightest force and the rate of flow is proportional to the magnitude of force applied. The examples of Newtonian fluids are milk, clear fruit juices, sucrose solution, most types of honey, corn syrup etc. The equation for characterizing Newtonian fluid is

$$T = \mu (-dv/dx) \text{ ---- (Eq-1)}$$

Where, T = shear stress,  $\mu$  = dynamic viscosity ( $\eta = \mu/\rho$ ),  $-dv/dx$  = velocity gradient

##### 5.2.2. Non-Newtonian Fluids:

A non-Newtonian fluid is broadly defined as one for which the relationship between shear stress and shear rate is not a constant. When the shear rate is varied, the shear stress doesn't vary in the same proportion. These fluids exhibit either shear thinning or shear thickening behaviour and some exhibit a yield stress. The two most commonly used equations for characterizing non-Newtonian fluids are the power law model (Eq-2) and Herschel-Bulkley model (Eq-3) for fluids.

$$T = K (\dot{\gamma})^n \text{ -----(Eq-2)}$$

$$T = T_0 + K (\dot{\gamma})^n \text{-----(Eq-3)}$$

Where, T = shear stress, K = consistency constant,  $\dot{\gamma}$  = shear rate, n = flow behaviour index,

$T_0$  = yield stress

There are several types of non-Newtonian flow behaviour, characterized by the way a fluid viscosity changes in response to variation in shear rate (Fig-5.2). The most common non-Newtonian fluids are:

(A) Time-independent flow of non-Newtonian foods:

The fluid foods whose viscosity is not influenced by the shearing time at a constant shear rate show two distinct patterns of stress – shear rate relationship i.e shear-thinning and shear-thickening.

(i) Pseudoplastic/shear-thinning fluids: - This type of fluids will display a decreasing consistency with an increasing shear rate. Probably the most common of the non-Newtonian fluids, pseudo-plastic include emulsions and dispersions of many types. This type of flow behaviour is some times called shear-thinning. The shear stress ('T' or ' $\sigma$ ') versus shear rate ( $\dot{\gamma}$ ) curve is convex toward the stress axis. The shear thinning behaviour of a fluid or semi-solid food is expressed by the power law model or de Waele's model:

$$T = K (\dot{\gamma})^{n} \text{---- (Eq-4)}$$

Where, T = shear stress, K = consistency constant (Pa s)<sup>n</sup>,  $\dot{\gamma}$  = shear rate, n = flow behaviour index ( 'n' has a positive value between zero and unity)

Protein concentrates, skim milk concentrate, milk ultrafiltration retentates, concentrated fruit juices such as unpectinized apple juice (50-65° Brix), orange juice (50-65° Brix) etc., melted chocolates, thawed frozen egg, fruit and vegetable purees and gum solutions are the examples of pseudo-plastic fluid food products.

(ii) Dilatant/shear-thickening flow behaviour:- This type of fluid will display an increasing viscosity with increase in shear rate. Dilatancy is frequently observed in fluids containing high level of deflocculated solids, such as candy compounds, cooked corn starch paste, certain types of honey etc. Dilatancy is also referred to as shear-thickening flow behaviour. The stress shear rate curve is concave toward the stress axis and the value of 'n' in the power law (Eq-4) is negative.

(B) Time-dependent flow of non-Newtonian foods:

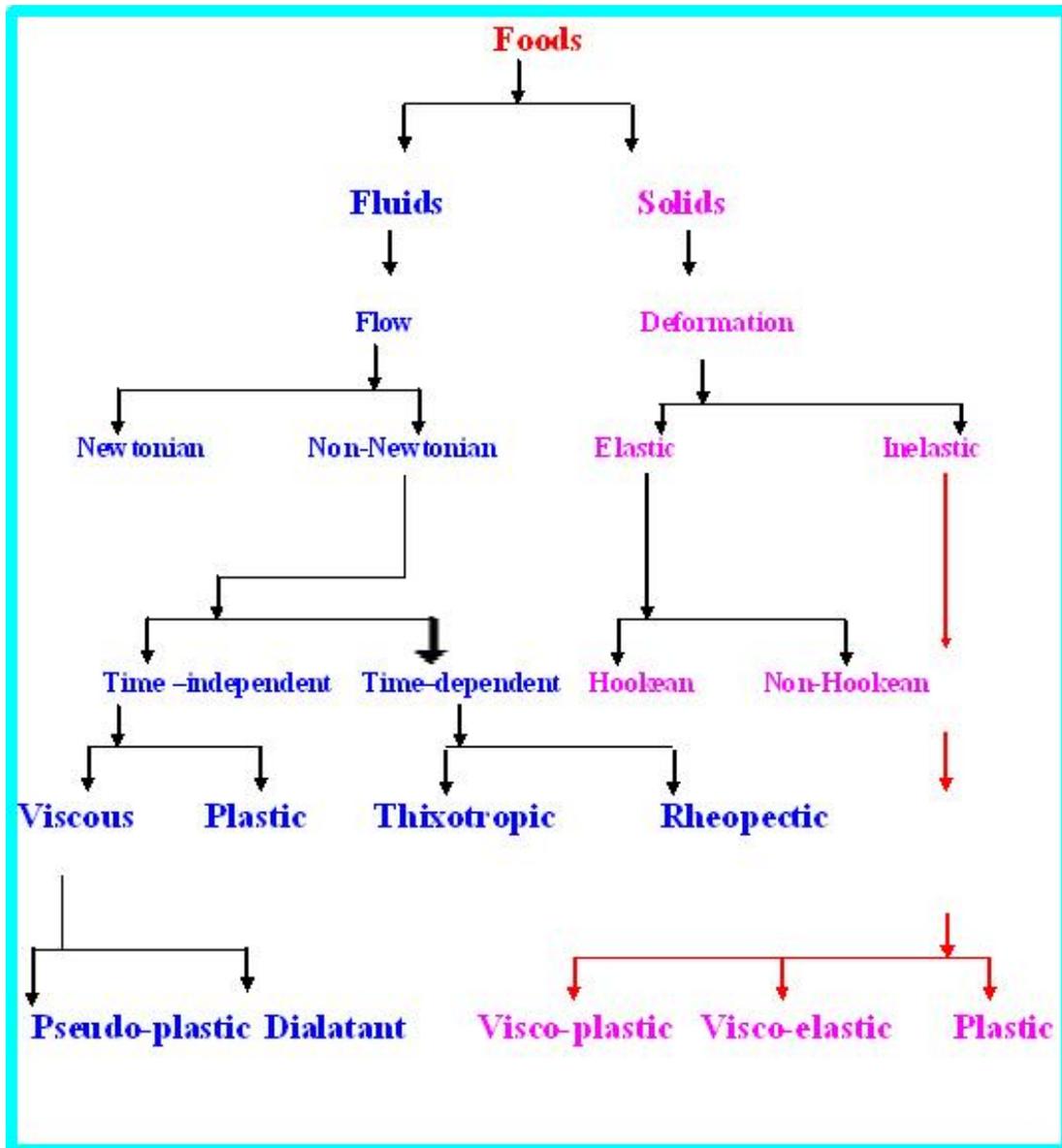
Certain non-Newtonian fluids show a time-dependent stress-shear relationship which can be one of the following types:

(i) Thixotropy: - When at a constant shear rate, the stress decreases over a period of time due to structure breakdown until eventually it reaches a steady value, the product is said to be thixotropic. Aged condensed milk, cream and ice cream mix, egg white etc. reveal thixotropy.

(ii) Rheopectic: - This essentially the opposite of thixotropic behaviour, in which the fluids viscosity increases with time as it is sheared at a constant rate. Rheopectic fluids are rarely encountered. Both thixotropic and rheopectic may occur in combination with any of the previously discussed flow behaviour, or only at certain shear rates.

(iii) Plastic: - This type of fluid will behave as a solid under static conditions. A certain amount of force must be applied to the fluid before any flow is induced, this force is called yield value. Tomato ketchup is a good example of

this type fluid, its yield value will often make it refuse to pour from the bottle until the bottle is shaken or struck, allowing the catchup to flow freely. Once the yield value is exceeded and flow begins, plastic fluids may display Newtonian, pseudoplastic, or dilatant flow characteristics.



**Fig 5.1 Rheological classification of foods**

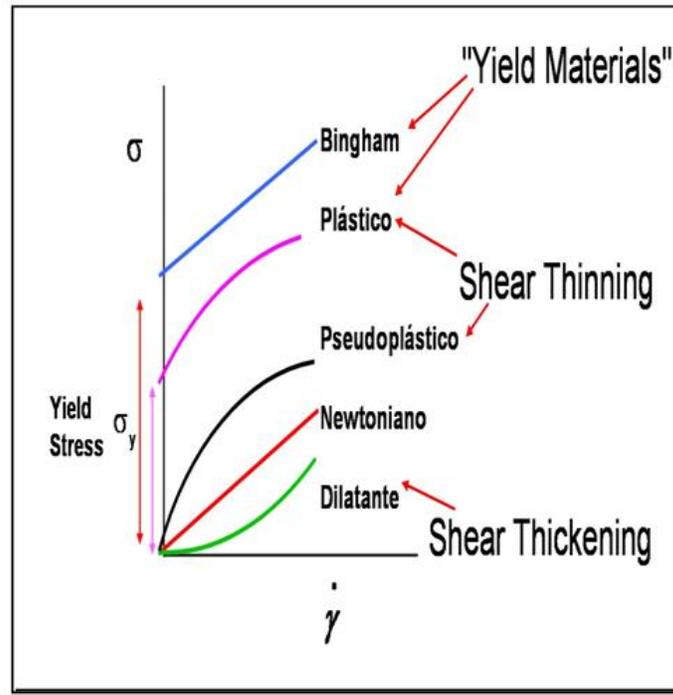


Fig-5.2: Stress-shear rate relationship in different rheological classes of fluids

### 5.3. IMPORTANT PROPERTIES OF FLUID FOODS

- Bounce: The resilience rate at which the sample returns to its original shape after partial compression.
- Chewiness: It is the number of chews (@1 chew/sec.) needed to masticate the sample to a state ready for swallowing.
- Coarseness: Degree to which mass feels coarse in the mouth.
- Cohesiveness: Degree to which the sample deforms before rupturing during biting.
- Denseness: It is a compactness of cross-section of the sample after complete biting.
- Dryness: Degree to which the sample feels dry in the mouth.
- Fracturability: Force with which the sample shatters/breaks. It encompasses crispiness, crumbliness, crunchiness and brittleness.
- Graininess: Degree to which a sample contains small grainy particles.
- Gumminess: Energy required to disintegrate a semisolid food to a state ready to swallow.
- Hardness: Force required to deform the product to a given distortion. Generally the distortion is between tongue and palate.
- Heaviness: Weight of product perceived when first placed on the tongue.
- Moisture absorption (related to sensory): Amount of saliva absorbed by the product in the mouth.

- Moisture released: Amount of wetness and juiciness from the product.
- Mouth coating: Type and degree of coating in the mouth after mastication.
- Roughness: It is the degree of abrasiveness of product surface which is perceived by the tongue.
- Slipperiness: It is the degree to which the product slides over the tongue.
- Smoothness: It represents the absence of any particle, lumps, etc. in the product.
- Springiness/sponginess: Degree to which the product returns to its original position i.e. shape and size after partial compression (without failure). Here compression is between the palette and teeth.
- Uniformity: Degree to which the sample is even throughout.
- Uniformity of bite : Evenness of force applied on the product while biting.
- Uniformity of chew : The degree to which the chewy characteristics of the product are even throughout the mastication
- Viscosity : Force required to draw a liquid from spoon over to the tongue.
- Wetness : Amount of moisture perceived on the product surface.



## Lesson 6.

## Rheological Properties of Granular Foods and Powders

## 6.1. INTRODUCTION

Dry food products make up a considerable portion of the total amount of food products available. Like fluid food products they are handled in various ways in different parts of processing plant. The design of handling system for dried products requires knowledge of the flow properties of the product being handled and transported or conveyed. The manner in which granular foods or powder may flow into or out of container is of particular concern in processing plants. In addition to the density and particle size parameters, there are specific parameters which describe the flow properties of these types of food products. Two common parameters used for this purpose are the angle of repose and the angle of slide. Both of these parameters lack theoretical considerations but do serve as a means of comparing different food powders. The angle of slide is a rather simply defined parameter in which the powder is placed on a horizontal plate and the angle of the plate is changed until the powder slides from the plate. The angle from the horizontal which is required for the powder to lose its position on the plate is measured and this angle will be a function of the type of surface on which the powder is placed.

Dry food products are handled in various ways in different parts of processing plants. The design of handling system for dry products requires knowledge of the properties of the product being handled.

## 6.2. DENSITY

Density is one of the basic properties of any material but in the case of granular food products, various types of densities have been defined:

6.2.1. **Bulk Density** ( $\rho_B$ ): It is defined by following expression:

$$\rho_B = m / V \text{ ----- 1}$$

Two types of bulk densities have been designated for dried products.

1) *Loose bulk density* ( $\rho_L$ ): - measured after placing the product in constant volume container without vibration.

2) *Packed bulk density* ( $\rho_P$ ): is measured after the sample is placed in constant volume container which is vibrated until the volume seems to be constant. The bulk density value will be dependent on particle size characteristics and any factor which effects them.

Two additional properties of granular products, which relate to density, are *void* and *porosity*.

**6.2.2. Void (v):** It may be defined as a ratio of volume of space between particle and the entire volume.

$$v = \rho_B [1/\rho_B - 1/\rho_P] \text{ ----- } 2$$

$$v = 1 - \rho_B / \rho_P$$

Void can be computed after measurement of bulk density,  $\rho_B$  and apparent particle density,  $\rho_P$ .

**6.2.3. Porosity ( $\psi$ ):** can be defined as the ratio of the air volume within the particles to the particles volumes and can be computed by

$$\psi = 1 - \rho_B / \rho_T \text{ ----- } 3$$

where  $\rho_T$  – true density of air free solids that make up the products.

Normally this can be calculated from knowledge of the density of various chemical components, which make up the product solids.

#### 6.2.4. Particle shape

All particles are not exactly of spherical shape, how far it is deviated from spherical shape is expressed by the term sphericity. The term sphericity  $\Phi_S$  which is independent of particle size is used to express shape of the particle.

$$\Phi_S = 6 V_p / D_p S_p$$

Where  $D_p$  equivalent diameter of particle

$S_p$  surface area of one particle

$V_p$  volume of one particle

For a regular particle  $\Phi_S = 1$

For many crushed material  $\Phi_S = 0.6$  to  $0.7$

#### 6.2.5. Particle Size and Size Distributions

A very important property of granular foods and powders is particle size and size distribution. One of the important factors to consider when discussing the mean diameter of a particle is the type of diameter being utilized. Mugele and Evans (1951) developed a generalized expression, which can be used to define all types of mean diameters.

This expression is

$$d = \frac{\sum(dq N)}{\sum(d^p N)}$$

$$\sum(d^q N)$$

where

Symbol	Name of Mean Diameter	p	q	Order
dL	Linear arithmetic	0	1	1
dS	Surface	0	2	2
dV	Volume	0	3	3
dM	Mass	0	3	3
dSD	Surface diameter	1	2	3
dVD	Volume diameter	1	3	4
dVS	Volume surface	2	3	5
dMS	Mass surface	3	4	7

For eg . Arithmetic or number diameter is

$$DL = \frac{\sum d N}{N}$$

Which is obtained when p = 0 and q = 1. Another commonly used notation is volume surface diameter usually called sauter mean diameter.

$$DVS = \frac{\sum d^3 N}{\sum d^2 N}$$

Example: Compute the arithmetic, surface diameter and volume - surface mean diameter for particles in a dry food product with the following distribution of sizes.

**Numbers sizes (microns)**

- 1 40
- 4 30
- 25 20
- 20 15
- 10 10
- 4 5

Solution:

$$\begin{aligned}
 \text{Arithmetic mean diameter } dL &= \frac{\sum (d_1 N)}{\sum (d_0 N)} \\
 &= \frac{40 \times 1 + 30 \times 4 + 20 \times 25 + 15 \times 20 + 10 \times 10 + 5 \times 4}{1 + 4 + 25 + 20 + 10 + 4} \\
 &= 16.9 \mu
 \end{aligned}$$

Surface diameter,  $d_{SD} = \frac{\sum (d^2 N)}{\sum (d_1 N)}$

$$= 40 \times 1 + 30 \times 2 \times 4 + 20 \times 2 \times 25 + 15 \times 2 \times 20 + 10 \times 2 \times 10 + 5 \times 2 \times 4$$

$$40 \times 1 + 30 \times 4 + 20 \times 25 + 15 \times 20 + 10 \times 10 + 5 \times 4$$

$$= 19.26 \mu$$

Volume surface diameter:  $d_{VS} = \frac{\sum (d^3 N)}{\sum (d^2 N)}$

$\sum (d^2 N)$

$$= 40 \times 1 + 30 \times 3 \times 4 + 20 \times 3 \times 25 + 15 \times 3 \times 20 + 10 \times 3 \times 10 + 5 \times 3 \times 4$$

$$40 \times 1 + 30 \times 2 \times 4 + 20 \times 2 \times 25 + 15 \times 2 \times 20 + 10 \times 2 \times 10 + 5 \times 2 \times 4$$

$$= 21.6 \mu$$



## Lesson 7.

## Properties of Solid Foods

## 7.1. INTRODUCTION

Solid foods are generally characterized in terms of stress - strain relationship. The stress may be of tensile, compressive, tangential (shear) or torsional (acting on a transverse cross section). The classification of solid foods is even more hazy than that of fluid foods. There are two major groups : elastic and non elastic. visco - elastic foods, mostly of semi - solid and solid nature, form an important group of non - elastic foods.

## 7.2. ELASTIC SOLIDS

## 7.2. 1. Hookean or linear elasticity

Elasticity is defined as the tendency of the product to recover upon unloading the shape and dimensions it had before loading. If there is no permanent deformation after unloading, the elasticity is said to be complete elasticity. Ideal or Hookean elasticity is characterized by a linear relationship between force (or stress) and deformation (or strain) starting at the origin (Fig. 7.1a) The body instantaneously returns to its initial form with no residual strain upon unloading.

Further, the Linear relationship is retraced when the sample is unloaded. The ratio of tensile stress to strain for these so-called Hookean bodies is termed Young's modulus (E) or elongation modulus. The ratio between shear stress to shear strain in an ideal linear elastic solid is called shear modulus (G) or rigidity.

## 7.2.2. Non - Hookean or non - linear elasticity

In reality, most elastic solids exhibit a non-linear or non-Hookean elasticity, in which case the stress is not proportional to strain, and the linear dependence of stress on strain exists only at the lowest strain 'levels. In general, at higher strain levels the loading-and-unloading cycle yields two separate traces describing a hysteresis loop (Fig. 7.1b). Since the stress-strain relationship is curvilinear, the modulus of elasticity is frequently given as the tangent modulus, which is the slope of the stress-strain curve at any specified stress or strain.

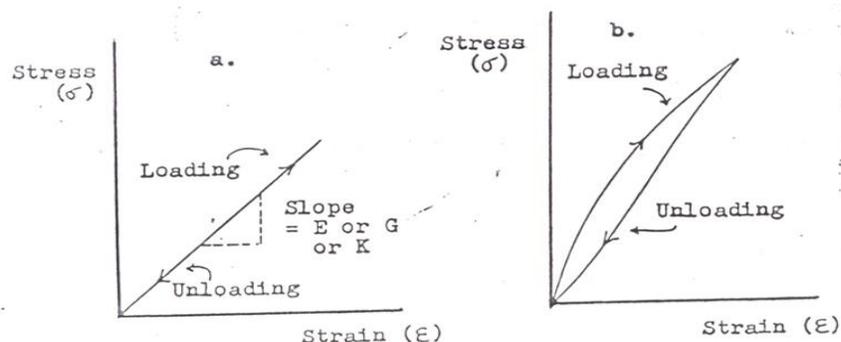


Fig-7.1: Linear (a) and Non-linear (b) elasticity: Stress-strain relationship

### 7.3. NON-ELASTIC SOLIDS

A material may show elasticity, linear or non-linear, if the applied stresses and corresponding strains are small. However, for large deformations most solids are non-elastic. Non-elastic products may exhibit failure when stress exceeds the strength of the body.

Failure

Failure may be seen as fracture or rupture.

(i) Fracture : Cracking of hard materials such as hard cheese at low temperature ultimately resulting in two or more separate pieces is termed fracture. Elastic fracture is fracture without or with a very limited amount of flow (only in the region just around the crack) of the material, as in unripe fruit flesh, tubers etc., whereas plastic fracture is fracture accompanied by flow of material as may be seen in certain soft or semi-hard cheeses.

(ii) Rupture : This term refers to tearing (in pieces) of soft materials. Rupture point is sometimes defined as a point on the stress-strain or force-deformation curve at which the axially loaded specimen ruptures. The failure in rupturing materials such as certain cheese gels, cooked egg white etc. is characterized by a multitude of failure planes.

### 7.4. PLASTIC SOLIDS

Certain non-elastic products may show yield value and tend to flow when the stress exceeds this point. Plasticity is found more frequently in semi-solid and soft products such as butter, spreads etc. rather than hard solids.

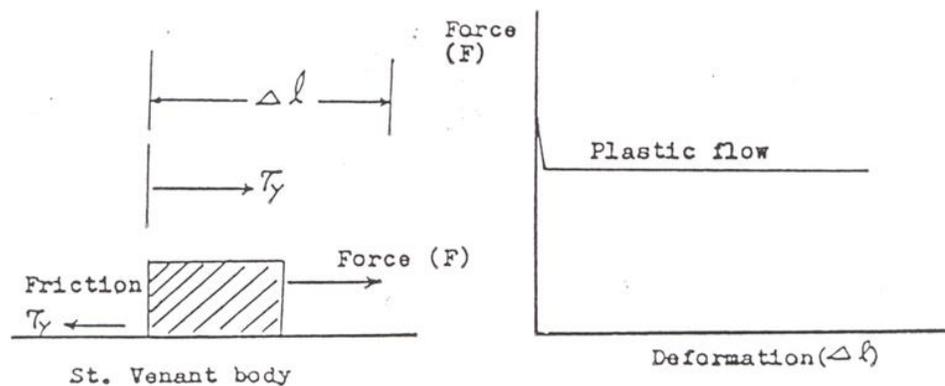


Fig-7.2: Ideal plastic behaviour

### 7.5. VISCOELASTIC FOODS

Failure resulting in rupture, fracture or plastic flow usually involves relatively large stresses and large deformation in solid foods. On the other hand, small deformation in most solids and semi-solid products may reveal what is known as viscoelasticity. Certain, shear-thinning fluids such as age thickened sweetened condensed milk also exhibits viscoelasticity.

The reaction of a viscoelastic body to stress (or strain) consists partly of a viscous component and partly an elastic one. Since stress and strain are time-dependent, the response of the material is rate dependent.

Attempts have been made to classify food products on the basis of their rheological behaviour. However, the rheological phenomena in various foods are so complex that it is not simple to categorize them into distinct groups or classes. Yet the classification of foods based on the stress-strain rate relationship for fluid and semi-solid products, and stress-strain relationship for solids would greatly facilitate comprehending the rheological behaviour of various dairy and food products and relating it to their processing, handling and texture attributes.

## 7.5. RHEOLOGICAL PROPERTIES OF SOLID DAIRY PRODUCTS

Solid dairy products such as butter and cheese are valued for their textural characteristics. Admittedly, the texture of other products, solid, semi-solid or fluid, is an equally important determinant of their overall sensory acceptance, but probably because of their solid nature and its variability. Several empirical methods have been developed in attempts to best describe the product's rheology in relation to their textural properties. Considerable efforts have also been devoted to obtain information on the fundamental rheological properties of cheese and butter. However, owing to the complexities of the product texture, progress made in this regard is rather limited. Nevertheless, recent developments in rheological instruments hold out a definite scope for generating valuable information on the basic rheological parameters of these products. In the context of Indian dairy industry, texture and rheology of certain solid and semi-solid products such as paneer, khoa, chhana and milk sweets have been recognized to play an important role-in their acceptance which, in turn has a great bearing on the success of their production in modern dairy plants.

### 7.5.1. Rheology of Cheese

Ever since the early report pertaining to the Davis's plastometer devised to measure deformations in cheese, butter etc. under compression several different rheometers have been developed. These include Devis's apparatus for measuring the crushing strength of cheese, a spherical compression device of Scott Blair and Coppen (employing a 3.8 cm sphere for compression of cylindrical cheese samples), Caffyn's ball compressor and sectilometer ( a write cutting apparatus), and several penetrometers. Some of those principles were incorporated into certain commercial instruments for routine analysis. Hoeppler consistometer was one such instrument also used for deriving certain fundamental measurements e.g. viscosity and elastic modulus of hard and semi - hard cheese varieties. Studies to correlate measurements obtain with instruments and sensory texture properties of cheese yielded varying results, the correlations generally being high for hardness but low for springiness and other attributes. During the late fifties and sixties, considerable interest was witnessed in employing rheological measurements for process control (in terms of raw cheese ingredients etc.) in the manufacture of processed cheese. This interest has been subsequently maintained to a great extent primarily because of increasing process variables and sustained and growing demand for this product .

With the advent of the new generation rheological instruments such as the Instron machine, Ottawa texture measuring system, Bohlin's rheometers and several texture analyses (e.g. Steuren's, Micro stable etc.), rheological measurements of cheese has undergone a dramatic change. Instruments providing non - destructive dynamic measurements have been used for viscoelastic characterizations of cheese offering better understanding of cheese texture.

In spite of the impressive advances registered regarding the rheological measuring systems there is a long way to go before rheological measurements become a substitute for sensory texture. More specific in relation to cheese is its no homogeneity arising primarily from its constituents and the manufacturing process. A recent IDF publication provides an extensive review of various aspects of the rheology and fracture properties of different varieties of cheese, where the anisotropic nature of cheese resulting from pressing of curd, considered a major factor

contributing non-homogeneity.

Hard and semi - hard cheese varieties have been subjected to rheological measurements most frequently by uniaxial compression and to a lesser extent by deformation in tension or shear between two parallel plates. Sometimes three point bending of a cylindrical cheese sample has been employed to imitate the deformation seen while grading a cheese plug. The quantitative characterization of cheese can be achieved in terms various moduli especially the compression modulus as well as the relative deformation at fracture and fracture stress in a compression test. Toughness or the energy of fracture (the energy required from the onset of compression till the cheese sample fractures ) is also a useful parameter.

Texture profile analysis (TPA) using compression between parallel plates has been extensively used for cheese texture characterization but the TPA parameters have been stated to be of only a limited value in cheese texture characterization.

Biaxial extensional viscosity determined by using compression between parallel discs has been found to be particularly applicable to process cheese. The so-called lubricated squeezing flow technique for the determination of extensional or elongation viscosity has been used to measure the melting properties of processed cheese as also of mozzarella cheese. To a limited extent oscillation measurement have been made of Gouda and other cheese to obtain dynamic moduli reflecting the viscoelastic character of the product.

### **Factors affecting cheese rheology**

Cheese is a composite material. Its major constituents para-casein, fat and the aqueous phase, contribute each in a specific way to the structure and hence to the rheology of cheese. The para casein matrix imparts the product solidity through formation of 3-dimension structure. Thus composition is among the most important factors influencing cheese rheology. The moisture, fat and protein contents are major compositional variables in cheese. Fat is a key contributor of the temperature-caused variation in the rheological properties of cheese. The pH of Gouda cheese has been observed to affect the stress-strain curve. These rheological parameters of ripened cheese such as Gouda also vary with the period of ripening.

### **Regarding the rheological methodology for cheese the following are among the salient recommendation made by IDF.**

- a. A method that yields real and unequivocal rheological or fracture parameters should be used so that the results do not vary with test-piece size or with small variation in test conditions.
- b. The sample preparation should be such that it does not subsequently alter the product properties.
- c. The type, extent and time scale, of deformation should be in accordance with the conditions during the actual use of the cheese (e.g. eating, cutting or storage).
- d. Different mechanical methods may be used for the purpose of comparison and visible changes during deformation should also be observed.

### **7.5.2. Rheology of Butter**

Rheology measurements of butter are important from two main points of view : first, spread ability of butter as a functional texture attribute, and second, its pump ability or handling convenience. The most relevant factor in this connection is the high temperature coefficient for the consistency of this 'plastic' product, which necessarily needs to be stored under refrigeration in plants or in homes.

Several empirical instruments viz. cone penetrometer, sectilometer, extrusion devices such as FIRA- NIRD extruder etc. have been used for 'obtaining the subjective measurements that would correlate with the sensory assessment of spread ability of butter. The most common parameter that is sought to be measured by those methods is hardness of the product. Other less important texture measurements made on butter include its stickiness, oiliness

and brittleness but not all instruments give this information. Most popular the sectilometer is now available as a highly sophisticated microprocessor controlled instrument (Buttomat). The cone penetrometer has frequently been used for routine purposes in New Zealand, Australia and UK. Extruder thrust (From the NIRD instrument) has been found to correlate very well with sensory and spreadability of butter. Recently the Instron back extension test has been employed to compare the consistency of commercial butter made by different processes.

Beside temperature, compositional and other related factors such as moisture SNF, salting, ripening etc. have been found to influence the rheological behaviour of butter. The solid fat content seems to be the major determinant of butter rheology as also the state of fat crystals. Work softening, referring to the softening effect of working is important to butter handling. Rheological measurements such as yield stress have been used to study this phenomenon.

The processing parameters in conjunction with the physical properties of milk fat in butter govern the structure of butter (believed to be a dispersion of fat globules and aqueous phase in a continuous phase of liquid fat) which is responsible for the typical rheological behaviour of the product.

### 7.5.3. Rheology of Traditional Milk Products

Industrial production of traditional milk products is yet to come of age in this country. Although studies have been conducted on several technological and quality aspects of these products during the past four decades, their rheological behaviour has aroused little research interest in the past. Occasionally, certain empirical instruments such as cone penetrometer or similar contraptions for compression studies have been used. Process development studies in respect of rasogolla have benefitted by the use of cone penetrometer for determining the product's firmness. The penetrometer has been used for certain khoa - and chhana based sweets such as burfi, sandesh etc. In the first ever attempt to study the viscoelastic behavior of a traditional product like paneer at PAU, Ludhiana. The relaxation times have been worked out employing compression in an Instron machine. A mechanical model has also been proposed to describe the viscoelastic behaviour of paneer. Khoa may be a solid or semi - solid product depending on its type and / or moisture content. However, at high temperature such as those encountered during its manufacture this product is essentially a pseudoplastic fluid, the relevant power law parameters being a function of total solids.

The viscosity of khoa at 30°C as measured in Hoeppler consistometer has been found to range from  $2.0 \times 10^3$  to  $7.6 \times 10^3$  poise with the product TS ranging from 56 to 72 %. Texture profile parameters of khoa determined as a function of composition have been studied and Texture Profile Analysis (TPA) hardness has been found to exhibit a significant correlation with the corresponding sensory attribute of the product.

In recent times investigations have been carried out at different institutions with a view to generating the information on rheology of various indigenous products other than khoa viz., chhana and chhana-based sweets such as rasogolla, and sandesh, paneer, and khoa - based sweets such as kalakand, gulabjamun etc. Temperature and test conditions during parallel plate compression for TPA of these products are major factors affecting the measurements. Further, in most cases, the TPA hardness has been observed to be the single most important parameter.



## Lesson 8

### Viscoelastic Models

#### 8.1. INTRODUCTION

The fluids can be classified into following categories depending on the response to the applied shear force. Viscoelastic models are developed for Newtonian and non-newtonian fluids by different scientist considering different elements like dashpot and spring in series, in parallel and in combination. Widely used rheological models are Kelvin model, Maxwell Model and Burgers Models, which are described here.

Newtonian fluids are fluids which exhibit a linear increase in the shear stress with the rate of shear. These fluids exhibit a linear relationship between the shear stress and the rate of shear.

The equation for characterizing Newtonian fluid is

$$T = \mu (-dv/dx) \text{ ---- (Eq-1)}$$

Where, T = shear stress,  $\mu$  = dynamic viscosity ( $\eta = \mu/\rho$ ) ,  $-dv/dx$  = velocity gradient

A non-Newtonian fluid is broadly defined as one for which the relationship between shear stress and shear rate is not a constant. When the shear rate is varied, the shear stress doesn't vary in the same proportion. These fluids exhibit either shear thinning or shear thickening behaviour and some exhibit a yield stress.

The two most commonly used equations for characterizing non-Newtonian fluids are the power law model (Eq-2) and Herschel-Bulkley model (Eq-3) for fluids.

$$T = K (\dot{\gamma})^n \text{ -----(Eq-2)}$$

$$T = T_0 + K (\dot{\gamma})^n \text{ -----(Eq-2)}$$

Where, T =shear stress, K = consistency constant,  $\dot{\gamma}$  = shear rate, n = flow behaviour index,

$T_0$  = yield stress

#### 8.2. RHEOLOGICAL MODELS

Several models have been developed to describe the viscoelastic behaviour of materials. There are two basic viscoelastic models viz Kelvin and Maxwell. Other complex viscoelastic behaviors are described by using combinations of these basic models (Fig-8.1 & Fig-8.2).

##### (i) Kelvin model

The Kelvin model employs the spring (elastic component) and dashpot (viscous component) in parallel. In this stress is the sum of two components of which one is proportional to the strain and the other is proportional to the rate of shear. Since the elements are in parallel they are forced to move together at constant rate. When a constant load is applied to Kelvin model, initially a retarded deformation is obtained followed by a final steady

state deformation. When the load is removed the Kelvin model recovers completely but not instantaneously. The model is expressed mathematically as:

$$\epsilon_t = \sigma_0 / E [ 1 - e (-t/ Tret)] \dots\dots\dots(Eq-5)$$

where  $\epsilon_t$  is strain at time  $t$ ,  $\sigma_0$  is applied stress,  $E$  is elastic modulus and  $Tret$  is retardation time.

**(ii) Maxwell model**

The Maxwell model employs a spring and dashpot in series. In this model the deformation is composed of two parts, one purely viscous and the other purely elastic, When a constant load is applied to Maxwell body, instantaneous elastic deformation will take place followed by continuing viscous flow, which will continue indefinitely as it is not limited by the spring component. When load is removed, the Maxwell body recover instantly but completely. The Maxwell body shows stress relaxation but Kelvin body does not. stress-strain-time relationship in Maxwell model can be given as:

$$\epsilon_t = \sigma_0 / Ed [ 1 - e (-t/ Tret)] + E0\dots\dots\dots(Eq-6)$$

where,  $\sigma_t$  is stress at time  $t$ ,  $\sigma_0$  is fixed strain,  $Ed$  is elastic decay modulus and  $Tred$  is relaxation time and  $E0$  is equilibrium modulus.

**(iii) Burgers model**

This 4-element model is one of the best known rheological model which has been used to predict the creep behaviour in a number of materials. The model is composed of spring and dashpot in series with another spring and dashpot in parallel. When a burger's body is subjected to constant load, there is instantaneous deformation ( $E0$ ) is followed by retarded flow. When the load is removed there is instantaneous recovery followed by incomplete and slow recovery. The stress-strain time relationship can be given as:

$$\epsilon_t = \sigma_0 / Eo + \sigma_0 / Et ( 1 - e(-t/ Tret) ) + \sigma_0 t / nv\dots\dots\dots(Eq-7)$$

In terms of compliance function  $Jt$  which is reciprocal of Young's modulus ( $E$ ) the above equation can be given as:

$$Jt = J0 + Jt ( 1 - e(-t/ Tret) ) + t / nv \dots\dots\dots (Eq-8)$$

Where,  $J0$  is ( $1/E0$ ) initial compliance,  $Jt$  is ( $1/Et$ ) retarded compliance and  $t / nv$  is Newtonian compliance.

**(iv) Generalized Maxwell model**

A generalised Maxwell model is composed of  $n$  Maxwell elements with a spring in parallel with  $n$ th element. The elastic modulus  $E0$  of last spring corresponds to the equilibrium modulus in the stress relaxation test. The stress-strain time relationship is given by :

$$\epsilon_t = \sigma_0 ( Ed1 + e(-t/T1) + Ed2 e(-t/T2) + \dots\dots\dots+ Edn e(-t/Tn) + Eo)\dots\dots\dots(Eq-9)$$

where,  $T1, T2, \dots, Tn$  are relaxation times.

**(v) Generalised Kelvin model**

Experimental data on many viscoelastic materials including biological materials have shown more than one relaxation time or retardation time. For these materials, complete behaviour cannot be represented by a singly Maxwell or single Kelvin model or elements model. Each of these models has only one time constant. To represent viscoelastic behaviour more realistically a chain of Kelvin models, each with its own time retardation is assumed and the model is called a generalized Kelvin model. It consists of Kelvin elements connected in series with an initial spring and final 'viscous element. The equation for generalised kelvin model is:

$$\epsilon t = \left\{ \frac{1}{E_0} + \frac{1}{E_1 t_1} (1 - e^{-t/T_1}) + \frac{1}{E_2 t_2} (1 - e^{-t/T_2}) + \dots + \frac{1}{E_n t_n} (1 - e^{-t/T_n}) + \frac{t}{\eta} \right\}$$

----- (Eq-10)

where,  $T_1, T_2, \dots, T_n$  are relaxation times.

**(vi) Plasto - visco - elastic or Bingham model**

A more common type of body is the plasto-visco-elastic or Bingham body. When the stress is applied which is below the yield stress the Bingham body reacts as an elastic body. At stress values beyond the yield stress there are two components. One is constant and is represented by the friction element and the other is proportional to the shear rate and represents the viscous flow element. In a creep experiment with stress not exceeding yield value, the creep curve would be similar to the one for an elastic body. When the shear stress is greater than the yield stress, the strain increases with time similar to the behaviour of a Maxwell body. Upon removal of stress at time the strain decreases instantaneously and remains constant thereafter. The decrease represents the elastic components and the plastic deformation is permanent.

**(vii) Psychorheological Models:**

Psycho rheological models consist of a mathematical expression relating sensory rheological data to the corresponding mechanical data. These two sets of data are usually considered as output and input respectively. Associations between subjective and objective texture measurement may be expressed by graphical or mathematic / statistical terms. Various correlation coefficients quantify the relation between variables.

Using regression analysis, one can ascertain the relation itself beyond developing a measure of relatedness of two variables with the assumption of unilateral causality. Regression analysis helps the experimenter to : (a) select a variables, and (b) to estimate the parameters of that equation by statistical analysis.

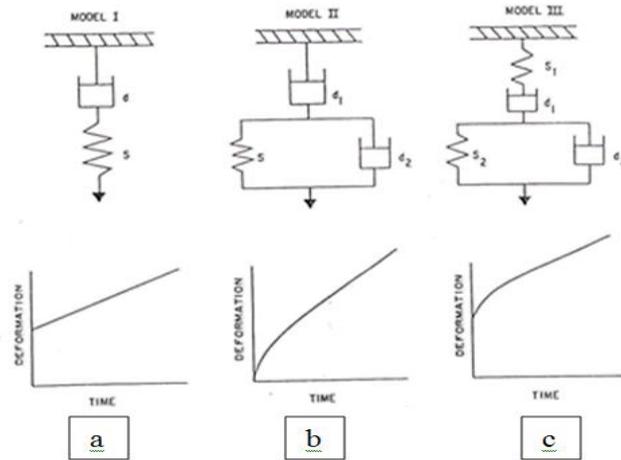
**8.5. VISCOELASTIC CHARACTERIZATION OF MATERIALS**

There are a number of tests which may be used to study viscoelastic materials and determine the relation among stress-strain-time for a given type of deformation and a given type of loading pattern. The most important tests include stress relaxation, creep and dynamic tests.

**(i) Creep measurement (Fig-8.1)**

In this test the stress is suddenly applied and held constant, and strain ( $\gamma$  or  $\epsilon$ ) is measured as a function of time. For a viscoelastic material the slope ( $dy/dt = \dot{\gamma}$ ) gives (from  $\sigma/\dot{\gamma}$ ) an apparent Viscoelasticity. The deformation  $\gamma_0$  is a measure of the elastic part. From the instantaneous shear modulus  $G_0$  may be calculated ( $\sigma/\gamma_0$ ) or the instantaneous compliance  $J_0$  ( $\sigma_0/\sigma$ ). The whole curve gives  $J_t$ , which, in principle, can be calculated to yield  $G_t$ . The

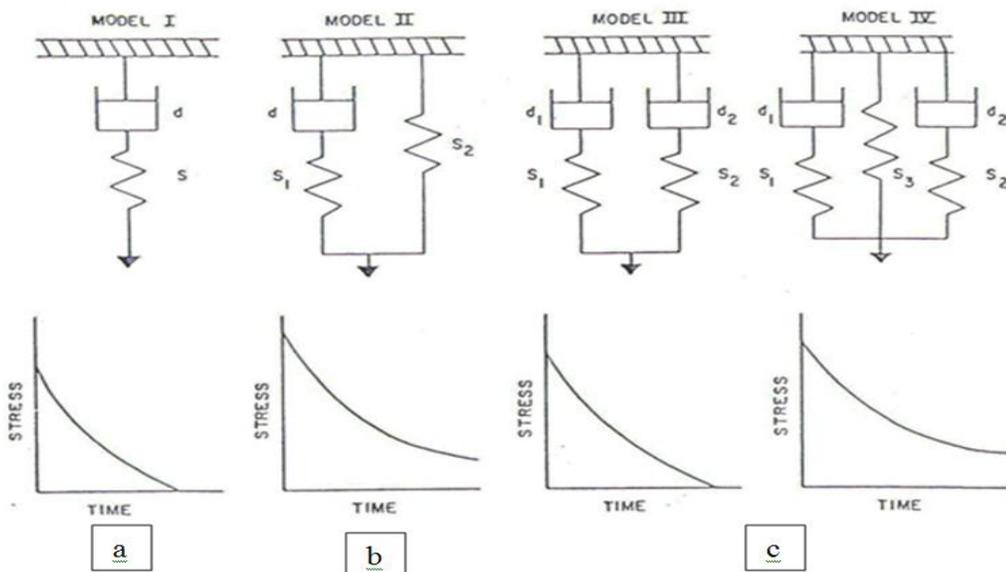
rheological model to represent the creep behaviour is the Kelvin model and 4 elements Burgers model. Creep measurement are very useful for studying stand up properties of foods. ( $\gamma$



**Fig-8.1: Typical creep curves for (a) Maxwell model (Model-I); (b) Kelvin Model (Model-II); (c) Burgers Model (Model-III)**

**(ii) Stress relaxation (Fig-8.2)**

In stress relaxation test the specimen is suddenly brought to a given deformation (strain), and the stress required to hold the deformation constant is measured as a function of time. The results are expressed in terms of time dependent modulus  $E_t$  in tension or compression,  $G_t$  in shear or  $K_t$  in bulk compression. The rheological models representing stress relaxation are Maxwell model and generalised Maxwell model. One of the most important viscoelastic parameters which can be obtained from stress relaxation test is the relaxation time. It is the time at which the stress in the body resembling a Maxwell model decay to  $1/e$  of initial stress. It is the measure of the rate at which a material dissipates stress after receiving a sudden force. There are a number of methods for treating experimental data on stress relaxation and finding the relaxation time.



**Fig. 8.2 Typical relaxation curves for (a) Maxwell Model (Model-I); (b) Three-element (Model-II); (c) Four-element Model (Model-III); Five-element (Model-IV)**

**(iii) Dynamic Measurement**

Despite the simplicity of creep and stress relaxation experiments, there are two disadvantages in these tests. The first disadvantage is that in order to obtain complete information about viscoelastic behavior of the material, it is necessary to take measurements over many decades of time scales. This in addition to prolonging the experiment may cause chemical and physiological changes in the specimen which will affect the physical behavior of the material. The second disadvantage is the impossibility of having a truly instantaneous application of load or deformation at the beginning of the experiment. These disadvantages can be overcome by dynamic tests in which the specimen is deformed by stress which varies sinusoidally with time.



## Lesson 9.

### Measurement of Food Texture

#### 9.1. INTRODUCTION

Texture is one of the major criteria which consumers use to judge the quality and freshness of many foods. When a food produces a physical sensation in the mouth (hard, soft, crisp, moist, dry), the consumer has a basis for determining the food's quality (fresh, stale, tender, ripe). The crispiness of a potato chip, the crunchiness of a pickle, the freshness of bread, cookies and crackers, the firmness of jam and preserve, the spreadability of butter, margarine and cheese and creaminess of puddings are just a few examples of texture and mouthfeel characteristics that make food appealing and satisfying to consumers.

In formulations of new foods, or modification of the existing products while maintaining the desirable sensory characteristics sensory evaluation plays a pivotal role. For instance arriving of minimum sensory standards in nutrient fortified foods for domestic as well as for export purposes, and the development of substitutes for consumers on special diets such as low-calorie, low-sodium, low-cholesterol or lactose-free foods. Sensory evaluation techniques have been used to assess the progress of the product development in the food industry. Many consumers purchase a product on the bases of the sensory experience which it delivers. Food technologist in general, and sensory analyst in particular, recognize the need to focus attention on measuring the perception of these characteristics. In similar manner, the textural measuring devices are helpful in evaluating the product quality.

#### 9.2. TEXTURE TERMS USED IN SENSORY TEXTURE PROFILING

A major challenge facing food developers is how to accurately and objectively measure texture and mouthfeel. To develop new product or to modify existing product to have better sensory and rheological attributes developer should understand different texture terms used in sensory texture profiling. The different texture terms used in sensory texture profiling are listed below:

- (i) Adhesiveness: Force required to remove the material that adhere to a specific surface (e.g. lips, palate, teeth).
- (ii) Hardness: Force required to deform the product to given distance, i.e. force to compress between molars, bite through with incisors, compress between tongue and palate.
- (iii) Cohesiveness: Degree to which the sample deforms before rupturing when biting with molars.
- (iv) Springiness: Degree to which the product returns to its original size/shape after partial compression (without failure) between the tongue and palate or teeth.
- (v) Fracturability: Force with which the sample crumbles, crakes or shatters. Fracturability encompasses crumbliness, crispiness, crunchiness and brittleness.
- (vi) Chewiness: Number of chews (at 1 chew/sec) needed to masticate the sample to a consistency suitable for swallowing.
- (vii) Guminess: Energy required to disintegrate a semi-solid food to a state ready for swallowing.

- (viii) Bounce: The resilience rate at which the sample returns to the original shape after partial compression.
  - (ix) Coarseness: Degree to which the mass feels coarse during product mastication.
  - (x) Denseness: Compactness of cross section of the sample after biting completely through with the molars.
  - (xi) Dryness: Degree to which the sample feels dry in the mouth.
  - (xii) Graininess: Degree to which a sample contains small grainy particles.
  - (xiii) Heaviness: Weight of product perceived when first placed on tongue.
  - (xiv) Moisture absorption: Amount of saliva absorbed by product.
  - (xv) Mouth release: Amount of wetness/juiciness released from sample.
  - (xvi) Mouth coating: Type and degree of coating in the mouth after mastication (for example fat/oil).
  - (xvii) Roughness: degree of abrasiveness of product's surface perceived by the tongue.
  - (xviii) Slipperiness: Degree to which the product slides over the tongue.
  - (xix) Smoothness: Absence of any particles, lumps, bumps, etc. in the product.
  - (xx) Uniformity: Degree to which the sample is even throughout.
  - (xxi) Uniformity of chew: Degree to which the chewing characteristics of the product are even throughout mastication.
  - (xxii) Uniformity of bite: Evenness of force through bite.
  - (xxiii) Viscosity: Force required to draw a liquid from a spoon over the tongue.
- Wetness: Amount of moisture perceived on product's surface.

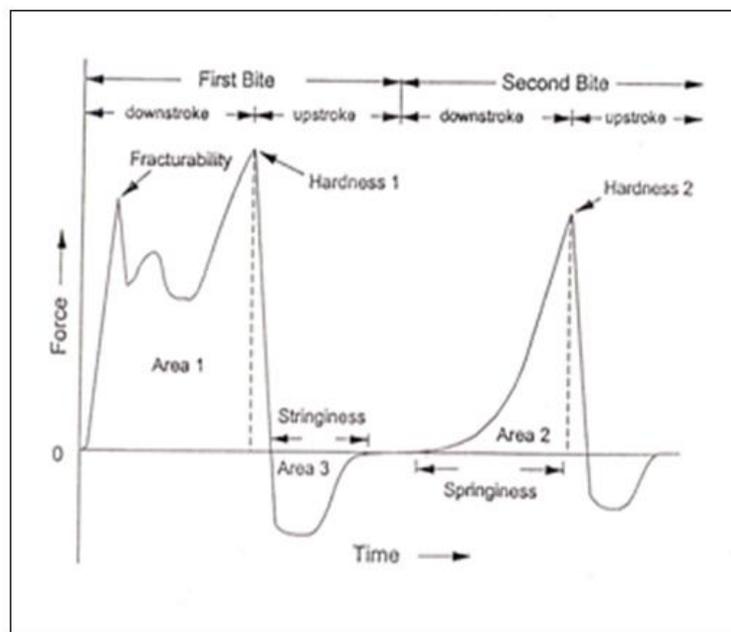
**Table- 1: Definition of textural characteristics**

Properties	Physical	Sensory
<b>Primary</b>		
Hardness	Force necessary to attain a give deformation	Force required to compress a substance between teeth
Cohesiveness	Extent to which a material can be deformed before rupture	Degree to which a substance is compressed between the teeth before it breaks
Springiness	Rate at which a material returns to its original condition	Degree to which a product returns to its original size
<b>Secondary</b>		
Fracturability	Force with which a material fractures	Force with which a sample crumbles
Chewiness	Energy required to masticate a food to a state ready for swallowing	Time required to masticate the sample to a state ready for swallowing
Gumminess	Energy required to disintegrate a semisolid food to a state ready for swallowing	Denseness that persists throughout mastication.

Sensory texture profile is defined as the organoleptic analysis of the texture complex of a food in terms of its mechanical, geometrical, fat and moisture characteristics, the degree of each present, and the order in which they appear from first bite through complete mastication. The data on these parameters is generally collected using either interval or ratio scales.

### 9.3. INSTRUMENTS FOR MEASURING TEXTURE PROPERTIES

There are diverse range of instruments for measuring texture properties of food products. The Instron universal testing machine is an instrument for measuring texture through tension and compression testing and it is a versatile instrument for applications in research, development of new products and quality control laboratories. It comprises of a standard load frame and drive unit, a load weighing system and a microprocessor based control system. A beam carrying a load cell (moving cross heads) is located between the base unit and the fixed crosshead at the top of the frame. The cross head moving in vertical direction at a selected speed is supported and driven by two lead screws. It contains a force sensing and recording system which measures the force during the test and transmits them to a strip chart recorder. The Instron can be programmed for automatic return, cycling and relaxation test etc. Fig. 9.1 shows response of Instron in the form of Instron curve, based on which major textural parameters are calculated, as follows:



**Fig. 9.1 Generalized texture profile curve obtained from the Instron**

(i) Hardness (Kgf): The force necessary to attain a given deformation, i.e. the highest point of peak in the first bite curve (Fig-1).

$$\text{Hardness} = H_1, \text{ Kgf}$$

(ii) Brittleness (Kgf): Force with which the sample crumbles, crakes or shatters

$$\text{Brittleness (or Fracturability)} = H_2, \text{ Kgf}$$

(iii) Adhesiveness: It is the work necessary to overcome the attractive forces between the surfaces of the sample and the other materials with which sample comes in contact. It is negative force area for the first bite curve (Fig-1)

Adhesiveness = A3

(iv) Cohesiveness: The extent to which a material can be deformed before it ruptures

Cohesiveness =  $A2/A1$

A1 = Area under the first bite curve before reversal of compression

A2 = Area under the second bite curve before reversal of compression

(v) Springiness (mm): The height sample recovers between the first and second compression, on removal of the deformation force

Springiness = S, mm

(vi) Gumminess (Kgf): It is the energy required to masticate a sample to a state ready for swallowing a product of hardness and cohesiveness

Gumminess = Hardness x Cohesiveness x 100

(vii) Chewiness (kg-mm): It is the energy required to masticate a sample to a state ready for swallowing. It is a product of hardness, cohesiveness and springiness

Chewiness = Hardness x Cohesiveness x Springiness



**Lesson 10.****Instruments for Rheological Measurement****10.1. INTRODUCTION**

There are diverse range of instruments for measuring texture properties of dairy and food products. Some of the equipments are described as below:

**(i) Wire Cutting Devices:**

A wire driven at a Constant speed to cut the sample is used for certain daily products. An advantage is that the sample area in Contact with the wire is constant throughout the test which minimizes the effect of friction and adhesion between the product and the test cell surfaces.

**(ii) Circular cutting devices**

The Cherry- Burrel Curd tension meter is used in the dairy industry to determine curd tension of milk and firmness of cottage cheese. A circular blade is driven at a constant speed of 2.54 cm per 7.5 sec. to cut the curd

**(iii) Cone Penetrometer of varying dimensions**

It consists of a cone of varying dimensions which is allowed to penetrate chhana, paneer, khoa or any other soft dairy product. The hardness values are read out on a mechanical linked graduated scale in terms of mm penetration.

**(iv) Pea Tenderometer**

It consists of a grid of shearing blades (test cell) rotated at constant speed through a second grid suspended, so that the force on the second, grid is counter balanced by a pendulum which is displayed by a pointer on a graduated scale. It is widely used by the pea industry.

**(v) The Warner – Bratzler Shaler Test**

A cylindrical sample usually 2.5 cm. in dia. is placed in a triangular hole in a thin blade of 0.25 cm thickness cut by pulling the blade through a slot and the shear force indicated by a spring scale. It is widely used for meat products.

**(vi) Kramer shear press**

It consists of a hydraulic press where the ram speed can be selected to complete its down stroke in 15 to 100 seconds. The ram operated by a hydraulic pump drives the moving components of the texture test cell into stationary component supported by the press frame. It is based on the principle of a multi- blade shear compression cell. Because of limitation of control by ram speed, the instrument does not give precise and accurate reading of force exerted.

**(vii) Instron Machine**

The Instron universal machine is an instrument for measuring texture through tension and compression testing within the force range of <1N to 5kN. It is a versatile instrument for application in research, development and quality control laboratories. It comprises of a standard load frame and drive unit, a load weighing system and a microprocessor based control system. A beam carrying a load cell (moving cross head) is located between the base unit and the fixed crosshead at the top of the frame. The crosshead moving in vertical direction at a selected speed is supported and driven by two lead screws. It contains a force sensing and recording system which measures the force during the test and transmits them to a strip chart recorder. The Instron can be programmed for automatic return, cycling and relaxation test etc.

**(viii) The Ottawa Texture Measuring System**

This machine is similar to the Instron Machine in design and operation except that it uses a single screw as drive instead of twin screws. The Ottawa cell consists of a rectangular metal box containing 8 or 9 thin stainless steel rods. The sample is compressed by a plunger and sheared and extruded through a wire-grid. It offers operational flexibility for research and quality control laboratories. It uses modern electronic system to record force, deformation and time precisely.

**(ix) General Foods Texturometer**

This instrument imitates the chewing action of the mouth for mastication of foods. The chewing forces are detected by strain gauges with the help of a position transducer and displayed on an oscilloscope. This helps ascertain the force required for teeth penetration into the food, thus reflecting the food texture.

**(x) Other Instruments**

The curd tension, curd firmness, consistency of cheese etc. can be determined by various techniques especially milk curcio-meter, containing a star shaped knife attached to a balance. Other texture measuring device employed for milk products include ball and needle penetrometers, extenders, gelographs.



**Lesson 11.****Thermal Properties of Frozen Foods****11.1. INTRODUCTION**

The food product properties of interest when considering the freezing process include density, specific heat, thermal conductivity, enthalpy, and latent heat. These properties must be considered in the estimation of the refrigeration capacity for the freezing system and the computation of freezing times needed to assure adequate residence times. The approach to prediction of property magnitudes during the freezing process depends directly on the relationship between unfrozen water fraction and temperature.

It is important to study thermal properties of foods because they affect the design of food processing equipment. The food products undergo changes in composition during such process as freezing, evaporation and dehydration. There are different methods available to measure the thermal properties of food, but the available data differ depending on the method used. The important thermal properties of food are as follows:

**11.2. DENSITY**

The density is mass per unit volume. Usually the density is expressed in grams per mL or cc. Mathematically a "per" statement is translated as a division. cc is a cubic centimeter and is equal to a ml Therefore,

$$\text{Density} = \frac{\text{mass}}{\text{volume}} \quad \text{g/ml}$$

The influence of freezing on food product density is relatively small but a dramatic change does occur at and just below the initial freezing temperature. This change can be predicted by the following equation, as discussed by Heldman (2001):

$$\rho = 1 / \sum ( m_{si} / \rho_{si} )$$

**11.3. SPECIFIC HEAT**

A measure of the heat required to raise the temperature of a substance. When the heat  $\Delta Q$  is added to a body of mass  $m$ , raising its temperature by  $\Delta T$ , the ratio  $C$  given in Eq. (1) is defined as the heat capacity of the body.

$$C_p = \Delta Q / \Delta T$$

The specific heat capacity of a food product can be predicted, based on product composition and the specific heat capacity of individual product components. The following expression was proposed:

$$C_p = \sum ( C_{psi} \cdot m_{si} )$$

where each factor on the right-side of the equation is the product of the mass fraction of a product component and the specific heat capacity of that component. The specific heat values for product components were estimated by

Choi and Okos (1986). The above equation can be used to predict the specific heat capacity of product solids by removing the term for the water fraction. These specific heat magnitudes for the product solids can be used in the prediction of product enthalpy and apparent specific heat.

$$C_p = 4.180 X_w + 1.711 X_p + 1.98 X_f + 1.547 X_c + 0.908 X_a, ; \text{ kJ/kg}^\circ\text{C}$$

.....Cho's and Oko's Model

Where,  $X_w$ : water fraction

$X_p$ : Protein fraction

$X_f$ : Fat fraction

$X_c$ : Carbohydrate fraction

$X_a$ : Ash fraction

#### 11.4. THERMAL CONDUCTIVITY

Thermal conductivity ( $\lambda$ ) is the intrinsic property of a material which relates its ability to conduct heat. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. Conduction takes place when a temperature gradient exists in a solid (or stationary fluid) medium. Conductive heat flow occurs in the direction of decreasing temperature because higher temperature equates to higher molecular energy or more molecular movement. Energy is transferred from the more energetic to the less energetic molecules when neighboring molecules collide.

Thermal conductivity is defined as the quantity of heat (  $Q$  ) transmitted through a unit thickness (  $L$  ) in a direction normal to a surface of unit area (  $A$  ) due to a unit temperature gradient (  $\Delta T$  ) under steady state conditions and when the heat transfer is dependent only on the temperature gradient. In equation form this becomes the following:

Thermal Conductivity = heat  $\times$  distance / (area  $\times$  temperature gradient)

$$\lambda = Q \times L / ( A \times \Delta T )$$

The thermal conductivity magnitudes of most food products are a function of water content and the physical structure of the product. Many models suggested for prediction of thermal conductivity are based on moisture content and do not consider structural orientation. The Choi's and Oko's Model for prediction of thermal conductivity is as follows.

$$K = 0.58 X_w + 0.155 X_p + 0.25 X_c + 0.16 X_f + 0.135 X_a, \text{ W/m}^\circ\text{K}$$

.....Cho's and Oko's Model

Where,  $X_w$ : water fraction

$X_p$ : Protein fraction

$X_f$ : Fat fraction

Xc: Carbohydrate fraction

Xa: Ash fraction

### 11.5. THERMAL DIFFUSIVITY

A measure of the rate at which a temperature disturbance at one point in a body travels to another point. It is expressed by the relationship  $K/dC_p$ , where  $K$  is the coefficient of thermal conductivity,  $d$  is the density, and  $C_p$  is the specific heat at constant pressure. Very little thermal diffusivity data are available, but it can be determined using relationship of specific heat, thermal conductivity and mass density of the food product.

### 11.6. FREEZING POINT DEPRESSION

Probably one of the more revealing properties of water in food is the freezing point depression. Since all food products contain relatively large amounts of moisture or water in which various solutes are present, the actual or initial freezing point of water in the product will be depressed to some level below that expected for pure water.

The magnitude of this freezing point depression becomes a direct function of the molecular weight and concentration of the solute in the food product and in solution in the water.

The expression or expression which predicts the extent of freezing point depression can be derived from thermodynamic relationships based on equilibrium between the states of a system. The final form is given by

$$\Delta T_F = \frac{R_g \cdot (T_{AO})^2 \cdot W_a \cdot m}{1000 L}$$

Where  $\Delta T_F$  is freezing point depression and  $m$  is molality in terms of moles of solute per kg solvent.  $L$  is the latent heat of fusion per unit mass.  $T_{AO}$  is the freezing point of pure liquid (A) (273°C in c.q.s. system)

$W_a$  = molecular weight of component in solution

$$m = \frac{MB \text{ (per 100 gm solvent)}}{W_b}$$

( $W_b$  = molecular weight of component in solution,  $MB$  = mass in kg)

$R_g$  is gas constant

$$R_g = w \times W_A = 0.462 \times 18$$

$$R_g = 8.316 \text{ Joules/mole } ^\circ\text{C}$$

$$W_A = \text{molecular weight of water} = 18 \text{ moles/gm}$$

$w$  = fraction of water

### 11.8. THERMODYNAMICS OF FOOD FREEZING

Freezing is one the more common processes for the preservation of foods. It is well known that lowering the temp reduces the activity of microorganisms and enzyme systems, thus preventing deterioration of the food products. In addition to the influence of temp reduction on m.o. and enzymes, crystallization of the water in the product tends

to reduce the amount of liquid water in the system and inhibit microbial growth or enzyme activity in the secondary action.

The engineering aspects of food freezing include several interesting areas. In order to design a refrigeration system that will serve a food freezing process, some indication of the refrigeration requirements or enthalpy change which occurs during product freezing is required. This aspect is related to the type of product being frozen. The second aspect of food freezing that is closely related to engineering is the rate at which freezing progresses. This aspect is related to the refrigeration requirement, but the temperature difference existing between the product and freezing medium are also of significance. The rate of freezing is also closely related to product properties and quality. Product properties resulting from very rapid freezing are significantly different from those obtained by slow freezing. This difference is dependent primarily on the manner in which ice is formed within the product structure. In addition, the rate of freezing will establish the rate of production for a particular food- freezing operation. For this purpose the most rapid rate of freezing is desirable provided that product quality is not sacrifice.

### Examples:

#### Example 11.1:

**A formulated food product contains the following components – water 80%, protein 2%, carbohydrate 17%, fat 0.1% and ash 0.9%. Predict the specific heat in W/kg K using Choi's and Oko's model.**

#### Solution:

$$\begin{aligned}
 C_p &= 4.180 X_w + 1.711 X_p + 1.98 X_f + 1.547 X_c + 0.908 X_a \\
 &= 4.180 (0.8) + 1.711 (0.02) + 1.98 (0.001) + 1.547 (0.17) + 0.908 (0.009) \\
 &= 3.651 \text{ kJ/kg}^\circ\text{C} \\
 &= 0.8726 \text{ kCal/kg}^\circ\text{C} \\
 &= 1.0147 \text{ W/kg}^\circ\text{C}
 \end{aligned}$$

#### Example 11.2:

**Calculate the thermal conductivity of milk using choi & OKOS model, if milk contains 87.5% water, 3.7% protein, 3.7% fat, 4.6% lactose and 0.5% ash at 100C.**

#### Solution:

$$\begin{aligned}
 K &= 0.58 X_w + 0.155 X_p + 0.25 X_c + 0.16 X_f + 0.135 X_a \\
 &= 0.58 (0.875) + 0.155 (0.037) + 0.25 (0.046) + 0.16 (0.037) + 0.135 (0.005) \\
 &= 0.49 + 0.005735 + 0.0115 + 0.00592 + 0.000675 \\
 &= 0.51383 \text{ W/m}^\circ\text{K}
 \end{aligned}$$

**Example 11.3**

Compute the temperature at which ice formation begins in an ice cream mix with the following composition: 10% butter fat, 12% solids-not-fat, 15% sucrose and 0.22% stabilizer.

$$\text{Molality, } m = \frac{M_b \text{ (per 100 g solvent)}}{W_b}$$

The solute accounted for in the ice-cream mix is sucrose ( $W = 342$ ) and lactose ( $W = 342$ ), which represents 54.5 % of the SNF in the mix. – Molality is computed as:

$$\text{Fraction solute} = 0.15 + 0.545(0.12) = 0.2154 \text{ g/ g product}$$

When expressed in terms of water fraction (62.78%), thus  $0.2154/0.6278 = 0.3431$  g solute/g solvent or 343.1 g solute / 1000g solvent

$$\text{And } m = 343.1/342 = 1.003$$

$$T_f = \frac{(0.462) (273)^2 (18) (1.003)}{1000 (333.22)} = 1.86 \text{ K}$$

Therefore initial ice formation will occur at  $(273-1.86)$  271.14 K or - 1.86 OC

\*\*\*\*\* 😊 \*\*\*\*\*

## Lesson 12.

### Prediction of Freezing Rates

#### 12.1. INTRODUCTION

The most important consideration associated with food freezing rate is the rate of the process. This rate not only establishes the structure of the frozen product but the time required for freezing is the basic design consideration for the process. An analysis of current literature indicates significant variation in the definition of freezing rate. Fennema, et.al(1973) have identified four methods to describe rate of freezing including: (a) Time-Temperature methods (b) velocity of ice front (c) Appearance of specimen and (d) Thermal methods. The most frequently encountered methods are time – temperature including (a) Temperature change per unit time or (b) time to transverse a given range of temperatures. The temperature change per unit time is the most appropriate indicator when the primary concern is structure of the frozen product and resulting influence on quality. It must be emphasized that temperature change per unit time will vary significantly during the freezing process and an average value has limited meaning.

The most appropriate indicator of freezing rate for purpose of process design is the time to transverse a given range of temperature. The international institute of refrigeration (1971) has proposed the following definition: The freezing rate of a food mass is the ratio between the minimum distance from the surface to the thermal center and the time elapsed between the surface reaching 0 ° C and the thermal center reaching 5 ° C colder than the temperature of initial ice formation at the thermal center. Where depth is measured cm & time in hour, the freezing rate will be expressed as cm/hr. A variation of the IIR definition is referred to as “thermal arrest time” and represents the time required for the slowest cooling point in the product to decrease 0 ° C to – 5 ° C. Long class used thermal wrest time to describe the rate of freezing in fish. The result of this research indicates two significant factors about the use of thermal arrest time. The first factor was the location of the temperature sensor. Small deviations in location of the temperature sensor from the slowest cooling or freezing point in the product resulted in considerable error in determining the thermal arrest time for a given product. The second factor was the influence of initial product temperature. Results reported by long (1955) indicated that an increase in initial product temperature decreased the thermal arrest time. In other words, the total freezing time was longer when the initial temperature was higher, but the time required to reduce the product temperature from 0 ° C to – 5 ° C was less, for purposes of the discussion which follows, the time required to reduce the product temperature at the slowest cooling location from the initial freezing point will be utilized as the time to describe freezing rate. Although this definition is not without limitations, it seems to provide the best compromise when considering advantages & disadvantages of other methods.

Fennema and Powrie (1964) have listed four factors which influence freezing rates: (a) The temperature difference between the product & cooling medium (b) The modes of heat transfer to from & within the product (c) The size, type & shape of the package containing the product & (d) The size, shape & thermal properties of the product. Although considerable information is available in heat transfer literature to assist in describing the rates of heat transfer in various shaped packages & products, the major limitation appears to be in the description of transient heat transfer with thermal properties being a function of temperature. The latter must be the case during the freezing of food products, since the apparent specific heat & thermal conductivity are both significant function of

temperature in the freezing zone or below the initial freezing point of the product. Many of the methods utilized to obtain expressions for freezing time have involved simplifying assumptions which do not account for the thermal diffusivity being a function of temperature, in an effort to obtain a solution to a complete heat conduction problem.



**Lesson 13.****Planck's Equation and related Problems****13.1. INTRODUCTION**

Freezing times are basic design criteria for freezing systems and represent the residence time for the food product within the freezing system required to achieve the desired level of freezing. The most widely accepted definition of freezing time is the time required to reduce the product temperature from some initial magnitude to an established final temperature at the slowest cooling location. An alternative definition changes the endpoint to the mass average enthalpy equivalent to the desired final temperature for the product. Freezing-time calculations are completed as a first step in the design of a food freezing system. The freezing time establishes the residence time for the product in the system. The final product temperature is established as the magnitude needed to maintain optimum product quality during storage. For a continuous freezing system, the resident time is dependent on the rate of product moves through the system and on the length of the system. More specific characteristics of the design will depend on the type of freezing system being considered.

**13.2. FREEZING TIME EQUATION (PLANCK'S EQUATION)**

The most straight forward expression available for computing freezing time was derived by plank. The equation utilized, for computation purpose be derived for various geometries of product. By reference to fig. given below, the case of one-dimensional freezing of a product slab can be illustrated the three basic equations utilized in a the derivation account for the first expression is the basic heat-conduction equation for the frozen product region which has a variable thickness  $x$  as follow:

$$q = \frac{A(T_s - T_f).k}{x} \dots\dots\dots(1)$$

Where  $T_f$  is the initial freezing point of the product and represent the temperature which exists in all unfrozen region of the product &  $k$  is the thermal conductivity of the frozen material.

The second expression describes the heat transfer from the product surface to the surrounding medium can be expressive as:

$$q = h_c A (T_\infty - T_s) \dots\dots\dots(2)$$

Where  $h_c$  is a convective heat transfer coefficient at the product surface.

Eq. (1) & (2) can be combined into one expression to account for heat transfer in series as follows:

$$q = \frac{A (T_\infty - T_f)}{\frac{1}{h_c} + \frac{x}{k}} \dots\dots\dots (3)$$

And eliminates the need for knowledge of the surface temperature.

The third equation, describing the rate at which heat is being generated at the freezing front is as follows:

$$q = AL \rho \cdot \frac{dx}{dt} \dots\dots\dots(4)$$

Where the differential  $dx/dt$  represent velocity of the freezing front.  $A$ =Area,  $L$ =Latent heat,  $\rho$  = Density

By equating Eq. (3) & (4) and by integration between the appropriate limits the following expression for freezing time is obtained

$$t_F = \frac{\rho L}{T_f - T_\infty} \left[ \frac{a}{2h_c} + \frac{a^2}{8k} \right] \dots\dots\dots (5)$$

Where  $a$  represent the total thickness of the slab being frozen. By introduction of appropriate

constants, the most general form of plank's equation is obtained as follows:

$$t_F = \frac{\rho L}{T_f - T_\infty} \left[ \frac{Pa}{h_c} + \frac{Ra^2}{k} \right] \dots\dots\dots(6)$$

Numerous equations and approaches to freezing-time prediction have been proposed and utilized. The best known and most used of the prediction methods is based on Planck's equation (1913):

$$t_F = \frac{\rho L}{T_f - T_\infty} \left[ \frac{Pa}{h_c} + \frac{Ra^2}{k} \right]$$

**where P and R are constants that depend on product geometry ( Table 13.1).**

The limitations to Planck's equation for estimation of freezing times for foods are numerous and have been discussed by Heldman and Singh (1981) and Ramaswami and Tung (1981). One of the concerns is selection of a

latent heat magnitude(L) and an appropriate value for the thermal conductivity (k). In addition, the basic equation does not account for the time required for removal of sensible heat from unfrozen product above the initial freezing temperature or for removal of frozen product sensible heat. There have been numerous attempts to modify Planck's equation or develop alternative expressions.

### The modifications made in the expression by number of scientists.

#### Limitations of Planck's Equation:

Use of equation requires assumption of some latent heat value and doesn't consider the gradual removal of latent heat.

The equation utilized only the initial freezing point and neglects the time required to remove sensible heat above the initial freezing point.

Constant thermal conductivity is assumed for the frozen portion. In fact thermal conductivity of the frozen region is temperature dependent and hence variable.

Density values for frozen foods are difficult to measure.

The initial and final temperature is not accounted for in the equation.

Even with these limitations, Planck's equation becomes most popular method for freezing time prediction.

#### Assumptions of Planck's Equation

Freezing starts with all water in the food unfrozen but at its freezing point and loss of sensible heat is ignored.

Heat transfer takes place sufficiently slowly for steady state conditions to operate.

The freezing front maintains a similar shape to that of the food.

There is single freezing point.

The density of food doesn't change.

The thermal conductivity and specific heat of the food are constant when unfrozen and then change to a different constant value when the food is frozen.

**Table- 13.1: Constants for Plank's Equation**

Geometry	<i>P</i>	<i>R</i>
Infinite slab	1/2	1/8
Infinite cylinder	1/4	1/16
Sphere	1/6	1/24



## Lesson 14.

## Problems on Planck's Equation

## Example 14.1:

Find out the diameter of the spherical product being frozen in an air-blast wind tunnel. The initial product temperature is 100C & cold air in the tunnel is at -120C. The product density is 1000 kg/m<sup>3</sup> and the convective heat transfer coefficient for the air blast is 50 W/m<sup>2</sup>K. The thermal conductivity of the product is 1.25 W/mK and the initial freezing temperature is -20C. The latent heat of fusion is 300 kJ/kg. Freezing time is 2.2 hrs. (Use Plank's Equation).

**Solution:**

$$t_F = \frac{\rho L}{T_F - T_\alpha} \left[ \frac{Pa}{h_C} + \frac{Ra^2}{k} \right]$$

$$7.920 = \frac{1000 \times 300}{(-2) - (-12)} \left[ \frac{(1/6)a}{50} + \frac{(1/24)a^2}{1.25} \right]$$

$$7.920 = 30000 \left[ \frac{a}{300} + \frac{10a^2}{300} \right]$$

$$10a^2 + a - 0.0792 = 0$$

$$a = 5.2 \text{ cm}$$

## Example 14.2:

Find out the diameter of the spherical product being frozen in an air blast air tunnel. The initial product temperature is 100C and cold air in the tunnel is at -120C. The product density is 1000 kg/m<sup>3</sup> and convective heat transfer coefficient for the air blast is 50 W/m<sup>2</sup>K. The thermal conductivity of the product is 1.25 W/mK. The initial freezing temperature is -20C. The latent heat of fluid is 300 kJ/kg and freezing time is 120 min.

**Solution:**

$$t_F = \frac{\rho L}{T_F - T_\alpha} \left[ \frac{Pa}{h_C} + \frac{Ra^2}{k} \right]$$

$$7.2 = \frac{1000 \times 300}{(-2) - (-12)} \left[ \frac{(1/6)a}{50} + \frac{(1/24)a^2}{1.25} \right]$$

$$10a^2 + a - 7.2 = 0$$

$$\text{Therefore, } a = 4.8 \text{ cm}$$

**Example 14.3:**

A spherical product is being frozen in an air blast wind tunnel. The initial product temperature is 10°C and that of cold air is -15°C. The product has a 7cm diameter with a density of 1000 kg/m<sup>3</sup> & the convective heat transfer coefficient for the air blast is 50 W/m<sup>2</sup>K. The thermal conductivity for the frozen product is 1.2 W/mK, the initial freezing temperature is -1.25°C and the latent heat of fusion is 250 kJ/kg. Compute the freezing time.

**Solution:**

Initial product temperature =  $T_i = 10^\circ\text{C}$

Air temperature =  $T_\infty = -15^\circ\text{C}$

Initial freezing temperature  $T_F = -1.25^\circ\text{C}$

Product diameter,  $a = 7 \text{ cm} = 0.07\text{m}$

Thermal conductivity of frozen product  $K = 1.2 \text{ W/mK}$

Latent heat  $H_L = 250 \text{ kJ/kg}$

Shape constant, so  $P = 1/6$  and  $R = 1/24$

Convective heat transfer coefficient  $h_c = 50 \text{ W/m}^2\text{K}$

Using Plank's equation,

$$t_F = \frac{\rho L}{T_F - T_\infty} \left[ \frac{Pa}{h_c} + \frac{Ra^2}{k} \right]$$

$$= \frac{(1000)(250)}{[-1.25 - (-15)]} \left[ \frac{(1/6)(0.07)}{50} + \frac{(1/24)(0.07)^2}{1.2} \right]$$

$$= 7.335 \text{ kJ/W}$$

$$= 7335 \text{ J/W}$$

Therefore,  $t_F = 7335 \text{ J/W}$

$1 \text{ W} = 1 \text{ J/s}$ , so  $1 \text{ J/w} = 1 \text{ s}$

Therefore,  $t_F = 7335/3600 = 2.0375 \text{ hr}$

**Example 14.4:**

Grape juice is being frozen in a 4cm diameter and 10cm tall can in an air blast freezer with 20 W/m<sup>2</sup>K as a surface heat transfer coefficient. The initial product temperature is 20°C and air used as a freezing medium is -20°C. Estimate the time required to freeze the product to -10°C, using Plank's Equation. Assume infinite cylinder geometry,  $T_F = -1.80^\circ\text{C}$  and  $L = 210 \text{ kJ/kg}$ .

**Solution:**

Using Plank's equation,

$$t_F = \frac{\rho L}{T_F - T_\alpha} \left[ \frac{Pa}{h_c} + \frac{Ra^2}{k} \right]$$

$$a = 0.04 \text{ m}$$

$$h_c = 20 \text{ W/m}^2\text{K}$$

$$\rho = 1050 \text{ kg/m}^3$$

$$K = 0.6 \text{ W/mK}$$

$$T_\alpha = -20^\circ\text{C}$$

$$T_F = -1.8^\circ\text{C}$$

L = Enthalpy change for freezing = 410 – 200 = 210 kJ/kg (15% TS)

$$t_F = \frac{(1050)(210)(1000)}{[-1.8 - (-20)] \times 3600} \left[ \frac{(1/4)(0.04)}{20} + \frac{(1/16)(0.04)^2}{0.6} \right]$$

$$= \frac{22050000}{33480} [0.0005 + 0.000167]$$

$$= 18.2$$

$$= 2.244 \text{ hr}$$

**Example14.5:**

Find out the diameter of the spherical product being frozen in an air-blast wind tunnel. The initial product temperature is 100C and cold air in the tunnel is at -120C. The product density is 1000 kg/m<sup>3</sup> and convective heat transfer coefficient for the air blast is 50 W/m<sup>2</sup>K. The thermal conductivity of the product is 1.25 W/mK. The initial freezing temperature is -20C, the latent heat of fusion is 300 kJ/kg and freezing time is 2 hr. Use Plank's equation for solving the problem.

**Solution:**

$$t_F = 2 \text{ hr} = 7200 \text{ J/W} = 7.2 \text{ kJ/W}$$

$$\rho = 1000 \text{ kg/m}^3$$

$$L = 300 \text{ kJ/kg}$$

$$T_F = -2^\circ\text{C}$$

$$T_\alpha = -12^\circ\text{C}$$

P = 1/6 and R = 1/24 for spherical product

$$h_c = 50 \text{ W/m}^2\text{K}$$

$$K = 1.25 \text{ W/mK}$$

$$t_F = \frac{\rho L}{T_f - T_\alpha} \left[ \frac{P \cdot a}{h_c} + \frac{R \cdot a^2}{K} \right]$$

$$7.2 = \frac{1000 \times 300}{(-2 - (-12))} \left[ \frac{(1/6) a}{50} + \frac{(1/24) a^2}{1.25} \right]$$

$$7.2 = \frac{30000}{10} \left[ \frac{a}{300} + \frac{a^2}{300} \right]$$

On solving the quadratic equation that would form, we find a = 0.048 m = 4.8 cm

## Questions:

Solve the following problems:	
1.	Apple juice is being frozen in a 5cm diameter and 12cm tall can in an air blast freezer with 25 W/m <sup>2</sup> K as a surface heat transfer coefficient. The initial product temperature is 30C and air used as a freezing medium is -18 0C. Estimate the time required to freeze the product to -120C, using Plank's Equation. Assume infinite cylinder geometry, TF = -2.2 0C and L = 230 kJ/kg.
2.	A spherical product is being frozen in an air blast wind tunnel. The initial product temperature is 150C and that of cold air is -200C. The product has a 6 cm diameter with a density of 1050 kg/m <sup>3</sup> & the convective heat transfer coefficient for the air blast is 75 W/m <sup>2</sup> K. The thermal conductivity for the frozen product is 1.1 W/mK, the initial freezing temperature is -1.800C and the latent heat of fusion is 300 kJ/kg. Compute the freezing time.
3.	Find out the diameter of the spherical product being frozen in an air blast air tunnel. The initial product temperature is 100C and cold air in the tunnel is at -25 0C. The product density is 900 kg/m <sup>3</sup> and convective heat transfer coefficient for the air blast is 60 W/m <sup>2</sup> K. The thermal conductivity of the product is 1.20 W/mK. The initial freezing temperature is -1.7 0C. The latent heat of fluid is 250 kJ/kg and freezing time is 180 min.
4.	Find out the diameter of the spherical product being frozen in an air-blast wind tunnel. The initial product temperature is 100C & cold air in the tunnel is at -180C. The product density is 1100 kg/m <sup>3</sup> and the convective heat transfer coefficient for the air blast is 80 W/m <sup>2</sup> K. The thermal conductivity of the product is 1.25 W/mK and the initial freezing temperature is -2.2 0C. The latent heat of fusion is 230 kJ/kg. Freezing time is 3.2 hrs. (Use Plank's Equation).
5.	Find out the diameter of the spherical product being frozen in an air-blast wind tunnel. The initial product temperature is 200C and cold air in the tunnel is at -25 0C. The product density is 1000 kg/m <sup>3</sup> and convective heat transfer coefficient for the air blast is 70 W/m <sup>2</sup> K. The thermal conductivity of the product is 1.20 W/mK. The initial freezing temperature is -1.2 0C, the latent heat of fusion is 280 kJ/kg and freezing time is 2.5 hr. Use Plank's equation for solving the problem.



## Lesson 15.

## Neumann's Problems and Tao solution

## 15.1. INTRODUCTION

The kinetic of freezing has been widely studied mathematically defined as a heat conduction process with phase change. The estimation of freezing times requires analysis of conductive heat flow through frozen and unfrozen layers, in addition to the heat transfer from the sample to the environment. The most common analysis are based on either Plank's or Neumann's Models, which are exact solutions valid for unidirectional freezing under the assumption of an iso-thermal phase change. While Plank's model assumes quasi-steady state heat transfer, the Neumann's model is more generally applicable and is based on unsteady state condition through frozen and unfrozen layers.

## 15.2. NEUMANN'S MODEL

Under conditions of unidirectional freezing, it has been established that the position of the freezing front varies with time as follows:

$$x = c \sqrt{t}$$

Where  $x$  is the position of the ice front,  $t$  is time and  $c$  is a kinetic constant. This equation is valid under the assumption of a planar freezing front. The equations following from Neumann's model are listed in Table 14.1. They can be solved analytically to result in a relationship similar to above.

$$X = 2 \delta \sqrt{a_1 t}$$

**Table: 15.1 Basic heat equations involved in Neumann's Model**

	Frozen layer	Liquid layer
Conservation equation	$\frac{\partial T_1}{\partial t} = a_1 \frac{\partial^2 T_1}{\partial x^2} \quad 0 < x < s$	$\frac{\partial T_2}{\partial t} = a_2 \frac{\partial^2 T_2}{\partial x^2} \quad s < x < x_i$
Initial conditions and boundary conditions	$T_1 = T_f, \quad x = 0, \quad t > 0$ $T_1 = T_m, \quad x = s, \quad t > 0$	$T_2 = T_0 \text{ for all } x, \quad t = 0$ $T_2 = T_0, \quad x \rightarrow \infty, \quad t > 0$ $T_2 = T_m, \quad x = s, \quad t > 0$
At the ice front	$-K_1 \frac{\partial T_1}{\partial x} + K_2 \frac{\partial T_2}{\partial x} + \rho_1 \Delta H_f \frac{ds}{dt}, \quad x = s$	

## 15.3. Tao Solution

Numerous attempts have been made to improve freezing time capability using analytical equations. These equations or approaches are also given by Tao (1974). In general all these approaches and solutions have been satisfactory for conditions closely related to defined experimental conditions. In addition to analytical methods, numerical procedure have been developed to predict freezing time.

## Lesson 16.

### Design of Food Freezing Equipment

#### 16.1. INTRODUCTION

Freezing is one of the common processes for preservation of foods. Preservation of food by freezing occurs by several mechanisms. The reduction of temperature to levels below 0 °C causes a significant reduction in growth rates for microorganisms and the corresponding deterioration of product due to microbial activity. In addition to this enzymatic and oxidation reactions will be slow downed or arrested. In addition, formation of ice crystals within the product changes the availability of water to participate in reactions. The engineering aspects of food freezing include:

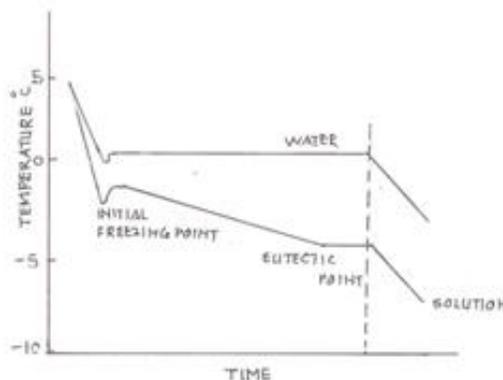
Design of food freezing system

Design of refrigeration system

Prediction of the rate at which freezing progresses.

#### 16.2. FREEZING PROCESS

Actual freezing process in food products is somewhat more complex than freezing of pure water. In water the temperature decreases as heat is removed from the system until freezing point is reached. After small amount of sub cooling / super cooling, the temperature remains constant as latent heat is removed from the water system. Following this latent heat removal, the temperature decreases again.

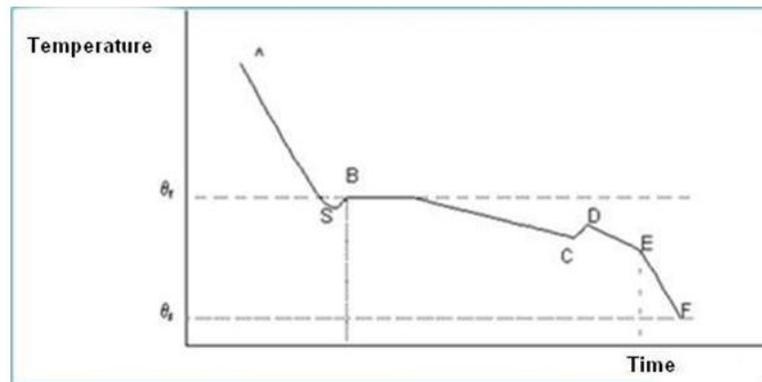


**Fig- 16.1: Freezing point depression**

In a food product removal of heat energy results in a temperature decrease until initial freezing point is reached. Initial freezing results in crystallization of a portion of the water, resulting in a concentration of the remaining solution and further reduction of the freezing point of that unfrozen portion. This results in additional decrease in temperature. This process continues till eutectic point of the solute present in the food product. In single solute

system, the removal of heat energy beyond this point does result in temperature decrease, but with crystallization of solute as well as ice crystal formation.

In actual food product system, it is very probable that more than one solute will be present. If the temperature is monitored at thermal center of a food (the point that cools most slowly) as heat is removed, the freezing curve obtained will be like



**Fig-16.2: Freezing curve for food product with more than one solute**

AS – The food is cooled to below its freezing point  $T_f$ , with the exception of pure water, is always below 0 °C. At point S the water remains as liquid, although the temperature is known as super 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 begins to form and latent heat of crystallization is released.

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

CD – One of the solute becomes super saturated and crystallizes out. The latent heat of crystallization is released and temperature rises to eutectic temperature \* for that solute.

DE – Crystallization of water and solute continuous. The total time,  $T_f$  taken 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 portion of water remains unfrozen at the temperature used in commercial freezers, the amount depends on type and composition of the food and temperature of storage.

Water contents and freezing points of selected foods:

<u>Food</u>	<u>water content (%)</u>	<u>freezing point (°C)</u>
Vegetables	78-92	-0.8 to -2.8
Fruits	87-95	-0.9 to -2.7
Meat	55-70	-1.7 to -2.2
Fish	65-81	-0.6 to -2.0
Milk	87	-0.5
Egg	74	-0.5

\* Temperature at which a crystal of an individual solute exists in equilibrium with the unfrozen liquid and ice.

**16.3. ICE CRYSTAL FORMATION**

The freezing point of a food is the temperature at which a minute crystal of ice exists in equilibrium with surrounding water. However before an ice crystal can form, a nucleus of water molecules must be present. There are two types of nucleation: homogeneous nucleation (the chance orientation and combination of water molecules) and heterogeneous nucleation (the formation of a nucleus around suspended particles or at cell wall). Heterogeneous nucleation is more likely to occur in foods and takes place during super cooling.

The length of super cooling period depends on the type of food and the rate at which heat is removed. High rates of heat transfer therefore produce a large number of small ice crystals. The rate of ice crystals growth is controlled by rate of heat transfer. The rate of mass transfer does not control the rate of crystal growth except towards the end of freezing period. The time taken for the temperature of a food to pass through the critical zone determines both the number and the size of ice crystals.

**16.4. ENTHALPY CHANGE DURING FREEZING**

One of the basic considerations in the design of a system for the freezing process is the refrigeration requirement for reducing the food product temperature to the desired level. The enthalpy changes required will reduce the product from some temperature above the freezing point to some temperature below the freezing point and can be represented by

$$\Delta H = \Delta H_s + \Delta H_u + \Delta H_L + \Delta H_F$$

where the terms on right hand side represent the sensible heat required to reduce the product solids temperature from initial to storage temperature ( $\Delta H_s$ ), the sensible heat removed to reduce the unfrozen portion of the product to the storage temperature ( $\Delta H_u$ ), the latent heat removed ( $\Delta H_L$ ), and the sensible heat removed to reduce the frozen water portion of the product to the storage temperature ( $\Delta H_F$ ).

Sensible heat  $\Delta H_s$  is given by,

$$\Delta H_s = M C_p (T_i - T_F) \text{ where } T_F = \text{freezing point temperature}$$

Evaluation of other components is somewhat complex because of changing state of product below initial freezing point. Mass of unfrozen product and frozen product are changing and are temperature dependant. Enthalpy change required to reduce the unfrozen portion of the product to various temperatures below initial freezing point,  $T_F$  is given by:

$$\Delta H_u = M_u (T) C_{p,u} (T) (T_F - T)$$

Similarly,

$$\Delta H_F = M_F (T) C_p, F (T_F - T)$$

these equations can be written in differential form as:

$$dH_u = M_u (T) C_{p,u}(T) dT \text{ and}$$

$$dH_F = M_F (T) C_p, F dT$$

Latent heat portion is given by:

$$\Delta H_L = M_F (T) L$$

Unfrozen and frozen portions of product at any temperature below the initial freezing point can be calculated by

$$\ln X_A = l' / R_g (1/T_{Ao} - 1/T_A)$$

Where,  $T_{Ao}$  - freezing point of pure liquid, K

$X_A$  - is mole fraction of water in solution

$R_g$  - gas constant , 8.314 kJ/ kg mol K.

$T_A$  - absolute temperature of aqueous solution, K

$l'$  - Latent heat of fusion, J/ mol (6003 J/ mol for dilute liquids)

After obtaining information on the frozen and unfrozen fractions as function of temperature and specific heat of unfrozen fraction the above equations can be evaluated by integration.

Volume changes:

The volume of ice is 9 % greater than that of pure water hence expansion of food after freezing is expected. The degree of expansion depends on:

1. Moisture content (higher moisture content produce greater changes)
2. Cell arrangement: Plant material with intra cellular air spaces will absorb internal increases in volume without large changes in their overall size.
3. The concentrations of solute: High concentrations reduce freezing point and do not freeze or expand.
4. Freezer temperature: This determines the amount of unfrozen water and hence the degree of expansion.

### Prediction of Freezing Rates/ Time

Most important consideration in food freezing problems is the prediction of time required to accomplish a given freezing process. The concept of “thermal arrest time”, which may be defined as the time required to reduce the temperature of the product to some stated temperature below the initial freezing point.

During freezing, heat is conducted from the interiors of a food to the surface and is removed by the freezing medium. The factors which influence rate of heat transfer are:

1. The thermal conductivity of food
2. The area of food available for heat transfer
3. The distance that the heat must travel through the food
4. The temperature difference between the food and freezing medium
5. The insulating effect of boundary film of air surrounding the food.

### **Prediction of Freezing Time is Complicated because of The Following Reasons:**

1. Differences in initial temperature of the food
2. Differences in initial size and shape of pieces of food
3. Differences in the freezing point and the rate of ice crystal formation with in different regions of pieces of food.
4. Changes in density, thermal conductivity, specific heat, and thermal diffusivity with reduction in temperature of food.

### **Factors Influencing Freezing Time**

There are several parameters that influence freezing time and that will influence the design of equipment used for food freezing.

Freezing medium temperature, where lower magnitude will decrease freezing time.

Product size will influence freezing time.

Convective heat transfer coefficient,  $h_c$  will influence freezing time significantly.

The initial freezing point.

Product properties ( $T_F, \rho, k, C_P$ ) will influence freezing time predictions.

### **Design Criteria For Selection Food Freezing Equipment**

It should be of sanitary design.

All product contact surfaces should be made of Stainless Steel.

The equipment should be adaptable for different food products.

It should have high efficiency.

Quick freezing & continuous operation.

Material of construction should be non-toxic, non-corrosive and odour less & taintless.

The equipment should be of simple design and easy to operate.

Type of product processed.

Reasonable freezing rates.

Airflow rates should be uniform and air should make intimate contact with the product.

## **Changes in Food during Freezing**

In any food freezing operation the amount of water getting frozen depends on

1. Initial water content
2. The way in which it is bound.

During freezing the water inside food is converted into the ice and freezing progresses i.e. the constituents like salts, acids, sugar etc., which are dissolved in the water, become more and more concentrated. This concentrated solution may adversely affect the properties of the product. Hence fast freezing is recommended. During rapid freezing the size of ice crystals will be small and the constituents are trapped inside them and almost in unchanged state. It is important to maintain lower temperature as frequent changes in temperature may lead to recrystallization of water in which the water molecules will migrate from the smaller ice crystals which have higher osmotic pressure, to larger ones which have lower osmotic pressure. Apart from rapid freezing, rapid thawing is also important to preserve biological value of foods. Rapid thawing by use of microwaves will prevent recrystallization.

## **Important Changes during Freezing**

### **1. Freezer burns:**

Due to irreversible drying of the surfaces leading to brown spots on the surface. This occurs due to changes in water vapour pressure in the product. This occurs mainly when the freezer is switched off –and- on frequently. Suppose during a particular interval of time the product has higher temperature which is the case when the freezer is switched on, the water from the product may come out and condense on colder surfaces. However when the temperature changes are reversed, the water does not return to original sites and this gives rise to freezer burns. This can be prevented by wrapping the food products in polyethylene films which are impervious to water vapor before freezing.

### **2. Destruction of cells:**

This takes place during freezing. The cause is not clear yet but reasons may be manifold.

Purely mechanical action of growing ice crystals may destroy cells.

Osmotic drying of cells due to increasing concentration of solution.

Concentrated solution of acid/sugar/salt may damage the cells.

To prevent this, addition of sugars like sucrose at 10%, gelatin etc has been recommended especially in freeze drying of eggs.

1. Change in proteins: Precipitation of calcium caseinate commonly called as denaturation by cold may take place.
2. Enzymes: Enzymes are not destroyed completely during freezing. Peroxides are found to be active even at  $-20^{\circ}\text{C}$ . Hence vegetables are given blanching treatment prior to freezing (either by steaming or boiling water). To prevent browning of fruits 0.1 % ascorbic acid or 0.1% citric acid solution is used.  $\text{SO}_2$  gas is also used to prevent browning.
3. Vitamins: No loss of A, B, D, E during freezing and some loss of C especially at below  $-20^{\circ}\text{C}$  may occur.
4. Microorganisms: They are inhibited – no growth. But psychotropic organisms may grow. Destruction of microorganisms by denaturation of protein is possible.
5. Metabolism: It is slowed down.

**Example 16.1:**

A milk chilling unit can remove heat from the milk at the rate of 41.87 MJ/hr. Heat leaks into the milk from the surroundings at an average rate of 4.187 MJ/hr. Find the time required for cooling a batch of 500 kg of milk from  $45^{\circ}\text{C}$  to  $5^{\circ}\text{C}$ . Take  $C_p$  of milk as 4.187 kJ/kg $^{\circ}\text{C}$ .

Solution:

Heat to be removed from milk  $Q_1 = 500 (45-5)(4.187) \text{ kJ}$

$= 8.374 \times 10^4$  or  $83.74 \times 10^3 \text{ kJ} = 83.74 \text{ MJ}$

Heat leakage to milk  $Q_2 = 4.187 \text{ MJ/hr}$

41.87 MJ of heat is removed in 60 min (1 hr)

Therefore, 83.74 MJ of heat will be removed in  $(83.74 \times 60)/41.87 = 120 \text{ min}$

Heat added in two hours  $= 4.187 \times 2 = 8.374 \text{ MJ}$

Now additional time required is determined as follows –

83.74 MJ of heat is removed in 120 min,

Then 8.374 MJ of heat is removed in 12 min

Therefore, total time required is  $120 \text{ min} + 12 \text{ min} = 132 \text{ minutes}$



**Lesson 17.****Study of Batch Ice cream Freezer****17.1 Introduction**

Ice cream freezers, apart from freezing a portion of water of ice cream mix, also incorporates air in the mix to obtain a swell in volume or 'overrun'. To get different freezing and good overrun in the ice cream it is very essential that the optimum quantity of the mix should be taken in the freezer for freezing. This quantity varies from freezer to freezer. The function of the freezer are:

- (i) To freeze a portion of the water of the mix to get a smooth product,
- (ii) To incorporate a predetermined amount of air uniformly into the mix to get proper overrun,
- (iii) To mix fruits and flavouring into the mix while being frozen.

Fast freezing is essential for a smooth product because ice crystals that are formed quickly are smaller than those formed slowly. Therefore, it is desirable to freeze and draw from the freezer in as short a time as possible. Failure to provide adequate refrigeration during freezing or hardening, results in formation of large ice-crystals in ice cream. Also, since freezing continues after the ice cream is placed in the hardening rooms; the ice crystals formed during the hardening period are larger because they form more slowly than in the freezer. For this reason, it is desirable to freeze the ice cream as stiff as possible and yet have it liquid enough to draw out of the freezer.

**Factors influencing the freezing time are: the mechanical factors and factors inherent in the mix itself.**

**Mechanical factors are**

- (i) Type and make of freezer
- (ii) Condition of the freezer wall and blades
- (iii) Speed of the dasher
- (iv) Temperature and flow rate of the refrigerant
- (v) Overrun desired and
- (vi) Rate of drawing the ice cream.

**Characteristics of the mix influencing the freezing time are:**

- (i) Composition of mix
- (ii) Freezing point of mix and method of processing the mix, and
- (iii) Kind and amount of flavours added.

**There are two types of ice cream freezers:**

- (I) Batch ice cream freezers and
- (II) Continuous ice cream freezers.

(I) Batch Ice Cream Freezer

### **17.2 Construction**

In the batch freezer a definite quantity of the mix is frozen at a time. It consists of a tubular chamber fitted with a rotating dasher (Fig-17(A)). The chamber is fitted with a mix tank and hopper for adding fruits and flavours. The chamber is surrounded by a refrigerated jacket in which ammonia or other suitable refrigerant is evaporated to provide the cooling effect.

The freezing chamber is made of a liner, usually of nickel silver or stainless steel, pressed inside a steel or copper tube which forms the inside wall of the cooling jacket. If the jacket is cooled by brine, it is constructed of copper with narrow passageways to increase turbulence and heat transfer. The outside is insulated with cork and covered with an airtight metal housing. If the cylinder is to be cooled by direct expansion of a refrigerant, the outer jacket is usually built of steel and properly insulated.

**The functions of the dasher are**

- (i) To scrape the frozen film from the cylinder wall, carry it to the centre, and circulate it from one end of the freezer to the other so that rapid and uniform cooling takes place,
- (ii) To beat the mix and hold air into it,
- (iii) To eject the frozen mix rapidly when the batch is finished.

The dasher consists of an outer frame carrying either two or more sets of scraper blades, which turn in one direction at a speed of 60-70 rpm. (Fig-17(B))The central part consists of beater having a series of longitudinal rods or paddles which rotate in opposite direction. The dasher is mounted on a shaft furnished with rotary seals, so that it can be completely taken apart for cleaning. It is important to have the dasher in proper alignment and the blades must be sharp.

### **17.3 Operation**

A batch of mix is dropped into the chamber, the refrigeration is turned on and dasher is started. The temperature of the refrigerant is very important and should be from -240C to -290C in order to get a rapid formation of ice crystals. The mix is cooled down to a temperature of about -50C in 6-10 minutes at which the refrigeration is turned off by means of a quick shut off valve and dasher allowed to rotate for 1-2 min to allow the mix to partially congeal. The mix will not absorb much air until a temperature of about -50C is reached. At this point, it will rapidly absorb air of 100-120% of its original volume. The ice cream is then drawn out of the chamber and into cans or packages which are placed in a room at temperature between -24 to -300C for hardening.

A slide or pivot valve on the bottom portion of the front door allows the ice cream to be drawn into containers or bulk cans. The dasher is designed to propel the product toward the discharge port. Subsequent batches are made

in the same manner. The size of the batch freezers varies from 18-40 liters of 100% overrun. If greater than 100% overrun is desired, the mix charge must be reduced enough to prevent overflow of ice cream during whipping.

The beaters promote whipping, but when freezing at temperatures below  $-50^{\circ}\text{C}$ , air is less readily incorporated, and some may even be expelled. Ice cream made with batch freezers has both larger ice crystals and bigger air cells than ice cream made with the same mix on continuous freezers. Overrun control to close tolerance is difficult with batch freezers, and it may vary by 80-100 from the beginning of drawing the batch to completely emptying the barrel. This occurs because whipping continues all during the drawing time.



FIG-17(A) Batch Ice Cream Freezer



FIG-17(B) Beater Assembly of Batch Ice Cream Freezer

**Lesson 18.****Study of Continuous Ice cream Freezer****18.1 Continuous Ice Cream Freezer**

The continuous ice cream freezer was developed in the early 1930's. The principle of operation is very similar to that of a batch freezer, except that the freezing is done under pressure (which increases the heat transfer rate) and the air is forced in or drawn into the freezing chamber continuously at a metered rate. The expanded and congealed ice cream is then forced out of the freezer cylinder, ready for filling in packages and containers. In a continuous freezer (Fig-18.1), about 30 second time is taken for partial freezing the mix. The ice crystal size is reduced to 45-55  $\mu\text{m}$  and the air voids are in the range of 100-150  $\mu\text{m}$  diameter.

The continuous freezer (Fig. 18.1) consists of a stainless steel shaft carrying a set of blades (dasher) rotating at 150-200 rpm inside a chromium-plated nickel surface of the freezing cylinder (Fig-18.2). The blades made of spring steel continuously scrape off the thin film of ice which form on the inner wall or the tube and at the same time thoroughly mix the ice cream as it is formed. A special eccentrically placed beater operates inside the dasher frame and is rotated by re-action with the ice cream. The eccentric position of the beater gives a thorough mixing of the ice cream as it freezes and is moved from one end of the cylinder to the other. For cooling, evaporating coolants in the temperature range of -20 to -300C are used in the cooling jacket.

The mix is pumped into a cylinder, which is flooded with liquid refrigerant. The freezing process is very rapid and the layer of the frozen mix on the cylinder wall is continuously scraped off with a rotating blade equipped mutator inside the cylinder.

The required amount of air is supplied continuously whilst the ice cream is worked in the freezer, so that the air is worked into the mix at the same time. This gives the ice-cream the desired texture before it is fed from the freezer through a pipe to a forming or filling machine.

**The advantages of the continuous or instant freezers are:**

- (i) Less stabilizer is needed because a larger amount of ice crystals can be formed and less viscosity is needed in the mix.
- (ii) A shorter ageing time is possible because less viscosity is needed and incorporation of air is less.
- (iii) Less flavoring material is needed because the smaller ice crystal melt more rapidly in the mouth and make the flavour slightly more pronounced.
- (iv) Smoother ice cream is obtained.
- (v) There is less tendency towards sandiness because rapid freezing favours small lactose crystals.
- (vi) Ice cream consistency is uniform due to continuous production

## 18.2 Pumps

Pumps of ice-cream freezers are usually of the rotary type with the capability to pump against pressure of 7-14 kg/cm<sup>2</sup>(690-1380 kPa) with reasonable volumetric efficiency. There are two general pumping arrangements, both designed as a part of the overrun system. The first employ a pump (or a pair of pumps or compound pump) to pump or meter the mix into the freezing cylinder, which is provided by a hold-back valve at the ice cream discharge port. The hold-back valve may be spring loaded with manual adjustment, it may have an air operator with adjustable air pressure supplying the operating power. The hold-back valve permits imposing a pressure on the cylinder during freezing which compresses the air admitted with the mix for overrun. Cylinder pressure of 3.5-4.0 atmospheres keeps the volume of air in the freezing cylinder sufficiently small so that it does not significantly lower the internal heat transfer out from and through the mix. That pressure is sufficient for proper air dispersion and small air cell size. Higher pressures may be imposed on the cylinder, but in most cases, the improvement of heat transfer and air cell size is not great enough to offset the disadvantages of increased pumping cost.

Ice cream freezer pumps are driven by various means, but all of these provide for varying pump speed. Usually the set of pumps for each cylinder is powered by one drive. Drives are of three types

- (i) Electric motor powering a mechanical variable speed;
- (ii) Frequency inverters with electronic speed control for standard electric motors. A gear reducer is always used between motor and pump;
- (iii) Hydraulic pumping systems connected to hydraulic motors on the pumps. The hydraulic pumping units may be located within the freezer housing or remotely outside the production room.

## 18.3 Controls and Automation

All continuous ice cream freezers have control for operation which include on-off switches for pump and dasher motors, and for air compressor motors (when these are part of the freezer), for solenoid valves on hot gas defrost lines, air lines and refrigerant supply lines, speed regulation of pumps, refrigeration supply and back pressure, pressure gauges for the refrigeration system and cylinder or air pressure and dasher motor ammeter, wattmeter or motor load indicator. In addition more sophisticated machines may have a viscosity meter and controller, and a programmable controller or micro-processor to operate and control most functions of the ice cream freezer.

The modern ice cream freezer consists of a micro-processor programmed to control all the function of operation including overrun, viscosity of product, cylinder pressure, all operating steps such as start up, routine or emergency shutdown, resumption of operation after an automatic shutdown when the reason for shutdown has been corrected. The micro-processor shows the time of day, mix flow rate, percentage of overrun, product rate, hours of operation, accumulated production in that time interval, the program step in operation, and various warnings. In case of an impending freeze-up, the warning is displayed and corrective action is taken. If a freeze-up should occur, the micro processor automatically causes defrosting of the cylinder and operation to be resumed when conditions are satisfactory. The display can be in one or more of several common languages.

The micro-processor programmed operation assures that all functions are performed in the proper sequences, and under the conditions envisioned by the designer of the freezer. This is especially beneficial to the ice-cream maker in preventing damage to the freezer in emergency situations, thus avoiding the incidental unplanned down time in production.

#### 18.4 Fruit & Nut Feeder:

Flavouring materials are added after the mix has been made. These may be added at the ageing or holding tanks, or in flavour tanks located just upstream of the ice cream freezer. Fruit juices, flavour extracts, colour and similar materials are added at these points. Pieces of fruit and purees should not be added to the mix prior to freezing in continuous freezers, as they tend to settle out in the tank with subsequent poor distribution in the frozen ice cream. Further, seeds in fruit or other gritty content harm the close-fitting pumps, the dasher bearing and seal, and dulls the scraper blades.

The ingredient feeders often referred to as fruit feeders have a hopper for the ingredient, an auger or other means for metering or proportioning the fruit, a rotator or plunger for inserting the ingredient.

##### 1. Packing, Extrusion and Moulding:

Ice cream is packed in cups, cones and containers (1 to 6 liters) in a rotary or in-line filling machine. These can be filled with various flavours, and the products may be decorated with nuts, fruits and chocolate. The packs are lidded before leaving the machine, after which they are passed through a hardening tunnel where final freezing down to -20 °C takes place. Before or after hardening the products can be manually or automatically packed in cartons or bundled.

Moulding of ice cream or water ices bars are made in special machines, also called stick novelty freezers, with pockets in which the ice cream or water ice is moulded. Ice cream is supplied direct from the continuous freezer at a temperature of approx. -30°C. The filled moulds are conveyed stepwise through a brine solution having a temperature of -40 °C, which freezes the ice cream or water ice solution. Sticks are inserted before the moulds are completely frozen. The frozen products are removed from the moulds by passing them through a warm brine solution which melts the surfaces of the products and enables them to be removed automatically by an extractor unit. After extraction of bars (novelties) may be dipped in chocolate before being transferred to the wrapping machine. Since the products are fully frozen, they can be taken straight to the cold store after wrapping and cartoning, otherwise go for hardening it in a hardening tunnel before wrapping and cartoning.

##### 2. Hardening & Cold Storage:

The manufacture of ice cream is not complete until it has been thoroughly hardened at a temperature of around -20 °C. For products produced in an extrusion line or a stick novelty freezer, the hardening operation is included in the process. Products packed immediately after freezing must however be transferred to a hardening tunnel, The faster the hardening, the better the texture. After hardening the products are transferred to the cold store where they are stored on shelves or pallet racks at a temperature of -25 °C. The storage life of ice cream depends on the type of product, the packaging, and maintenance of a constant low temperature. The storage period of ice cream at -18 °C ranges from 0 to 9 months in the ice cream cold storage.



FIG-18.1 Continuous Ice Cream Freezer



FIG-18.2 Dasher of Continuous Ice Cream Freezer

## Lesson 19.

### Care and Maintenance of Ice Cream Freezers and Hardening Cabinets:

#### 19.1 Introduction:

Care and Maintenance of Ice Cream Freezers and Hardening Cabinets:

Primary requirement for satisfactory performance of ice cream freezers and hardening cabinets are their careful installation, proper operation and regular maintenance. The batch freezer consist of refrigerator cylinder and a rotating dasher assembly to scrap, beat and mix the frozen ice cream in the cylinder. The continuous freezer employs the same fundamental principles except that here the ice cream mix flows under pressure. The freezing cylinder is made up of a stainless steel liner pressed inside a steel or copper tube which forms the inside wall of the cooling jacket. The dasher inside the freezing chamber, carrying the scraper and beaters, is directly coupled to the driving unit. An airtight metal housing is provided on the refrigeration space around the freezing chamber which in turn is provided with insulation and protective cover to prevent moisture ingress into insulation layer. To achieve the best freezer performance the refrigeration must be good, the blades must be sharp and free from burrs , the mix must be right and the freezer must be properly operated. The following criteria are intended to furnish convenient guidelines to facilitate the regular maintenance programme for the freezer and hardening cabinets.

#### 19.2 Dasher and Scraper assembly:

Scraper blades must function well to get the highest efficiency of the freezers. If the frozen film is not properly scraped off, the heat transfer will be low and the capacity of the freezer will suffer. The simple directions for care, maintenance and repair of scrapers involve the following:

- (i) Dull blades causes slow freezing because they do not remove the frozen film from the freezing cylinder. The scraper blades should be kept free from burr and should be sharp and straight.
- (ii) The burr formed on the upper side edge of the blade could be removed by drawing a fine file or stone lightly along the edge of the blade at an angle of 30°. This operation is necessary for two or three times week depending upon service performed by the freezer.
- (iii) If the blade is worn down its heel become wider. The excess heel is removed by means of hand filing with a file held parallel to the main flat side of the blade. Some power operated blade-sharpener grinders are fitted with fixture to automatically hold the blade at the correct angle. The heel should be brought down to 1/32 of an inch in width for batch freezers and practically eliminated for continuous freezers.
- (iv) The front edge of the blade should never be touched by the file.
- (v) If the service is available it is most advantageous to send continuous freezer blades to the nearest dairy equipment service agency for professional sharpening.
- (vi) If the blades are not sharp, the temperature of the refrigerant should be raised in order to allow them to scrape cleaner.

- (vii) Rubber friction ring of the rotary seal for mutator shaft should be kept in good condition. Replace it whenever necessary.
- (viii) Do not switch on the dasher and beater without any feed mix inside the freezer. It will result in the damage of blades.
- (ix) Do not change the alignment of the dasher, it may damage the freezing cylinder.

### 19.3 Refrigeration System:

Refrigeration system should be checked often to avoid any undue wear and tear on the system. By replacing the parts at the proper time the system is as good as the new system which not only adds to its life but keeps operating costs and capital expenditure to a minimum. The important maintenance criteria are as follows:

- (i) Pressure gauges are the main visible means to tell how the refrigeration system is operating. After being in use for some time the needle of these gauges may either stick or show too high pressure. False readings may lead to adjustment which will affect many things throughout the system. Most gauges have a screw, which will reset the needle to zero after allowing air to surround the stem. If the dial of gauges become rusty and hard to read, replace them, as the cost is very small when compared to cost of false adjustment.
- (ii) Thermostatic expansions valve should be checked once a month. Under normal conditions, these valves are set for 5°C to 6°C super heat, but if through normal wear or because of large particles of dirt, the valve opens wider, flooding occurs which will cause a frost back to the compressor.
- (iii) The float control valves are used in ammonia refrigeration system which serve to keep the liquid ammonia in the evaporators at proper level. If this valve is sticking closed, the evaporator is being starved of liquid, which cuts its capacity and increases the necessary time for compressor operation. If valve is allowed to be flooded with too much liquid, then there is a flooding of the suction back to the compressor which causes damage to compressor. Float controls should be checked very often and cartridge replaced if they do not respond to the adjustment.
- (iv) Back pressure regulating valves regulate the pressure on the suction line coming from the evaporator. A pressure gauge is attached to it for adjustment of back pressure through a regulating valve. This gauge should be checked quite often for its accuracy.
- (v) Defrost the evaporator coils as often as required because if frost or ice accumulates, the heat transfer is cut and efficiency of the entire system suffers.
- (vi) A refrigeration system is theoretically a vacuum system, and air and non-condensable gases can infiltrate in many ways. These tend to accumulate at the top of the condenser or other high points in the systems. Whether the system has non-condensable gases or not can be detected by installing a thermometer in the high pressure vapour line near condenser. If the temperature of gas does not correspond to the pressure on condensing pressure gauge it means system contains non-condensable gases or air which needs to be purged off. Thereafter, charge the system with correct refrigerant charge.
- (vii) The compressor will start to show wear after several years of operation. The simplest test is to check the compressor for over heating. Get the condition of the compressor checked as soon as the wear has been little more than normal. Do not wait until the compressor breaks down before replacing worn parts.

(viii) Loose compressor mounting bolts or vibrating unit tubing causes high level of noise and produces undue stress in the system. Tight the bolts and gently reform tubing to eliminate vibration. Check for the lubricating oil if the noise still persist.

(ix) Over charging raises the temperature and pressure above the desirable limits. Unit draws more current and consumes more power. With under charging lower than normal evaporator temperatures are maintained. The compressor motor gets overheated due to reduction in effective cooling by suction vapour. Motor winding finally burns out due to over heating. Recharge the unit with proper amount of refrigerant.

#### 19.4 Electric Motor and Controls:

The contemporary electric motor is one of the most efficient machine known today. Although they can operate with a minimum of attention, systematic motor care means not only fewer motor failures but also lower repair costs.

(i) Every effort should be made to keep water in liquid form from dripping on, splashing on or flooding on the motor unless the motor is of splash proof design. Whether the air-born moisture has produced a harmful condition in the motor can be determined by testing insulation resistance. When the resistance has dropped to a dangerous point the motor should be dried out without damage to the insulation.

(ii) Excessive bearing wear can produce misalignment and cause motor vibration. Even when the alignment is perfect vibration in the driven machine may be transmitted to the motor. Excessive vibrations can shake motor parts and electric connections loose, crystallize metal and multiply frictional wear. Vibrations should always be tracked down and it's cause eradicated.

(iii) To protect the compressor over load protector(OLP) is provided, which starts within a few seconds and trips off, due to very high or very low voltage. Use the voltage stabilizer, if necessary. If the OLP is under sized replace it with correct size OLP.

(iv) If the unit hums and shuts off it may be due to the low voltage or the inoperative relay. At low voltage current drawn by the motor is not sufficient to keep plunger of relays on and it drops earlier. At normal voltage if relay is of oversize, the start winding is not kept in circuit by relay for sufficient time. Use voltage stabilizer and the correct sized relay.

(v) Inoperative thermostat or incorrect thermostat setting may sometimes results in too cold cabinet temperature. Correct the setting or use the lower setting of thermostat. The thermostat may be re-calibrated by varying cut in and cut out temperatures.

In order to achieve the desired performance objectives, it is necessary to determine periodically the performance of each item of the ice-cream freezers and hardening cabinets and auxiliary equipment under actual operating conditions and correct any digression from the established norms. Immediately after new equipment is placed in service it begins to deteriorate. Even under idealized conditions the efficiency and performance of equipments progressively decreases with normal usage. Through periodic checks the actual performance can be determined. The laxity of operating and supervising personnel also needs to be detected and corrected. Set up a convenient file containing all manufacturers specifications, instructions, drawings and performance data for the units. No mal-performance should go unheeded or uncorrected. This would help the plant to remain in optimum performance condition at all times. Electric motor should be provided with soft starters and other means to maintain power factor above 0.95.

## Lesson 20.

## Design Problems on Batch Freezers

## 20.1. INTRODUCTION

Refrigeration requirements are expressed as the total heat to be removed in order to reduce the ice cream mix from an unfrozen state to some temperature in the freezing range.

Due to the composition of ice cream, the total heat load is divided into three parts:

- (a) Sensible heat required to reduce the mix temperature to the initial freezing point
- (b) Sensible heat required for unfrozen portion of mix at temperature below  $F_p$
- (c) Latent heat requirement

After reaching the initial freezing point, the last two contributions to total heat occurs simultaneously. Since, the composition of normal ice cream mix dictates that all two portions of total heat throughout the range of freezing temperatures encountered. Predictions of refrigeration requirements must include calculation of each phase. The beater assembly of batch ice cream freezer is designed based on dimensional analysis, considering different dimensional numbers like, Reynold's number, Nusselt's number, Prandtl's number etc, Reynold's number helps to design beater assembly and to optimize its speed to control ice crystal formation during freezing. The refrigeration requirement in kcal/kg may be written as:

$$Q = Q_S + Q_L + Q_H$$

$Q_S$  = Sensible heat of mix above initial freezing point

$Q_L$  = Latent heat

$Q_H$  = Sensible heat of semisolid frozen ice cream

Now, when the mix sensible heat is above the initial freezing point, then

$$Q_S = (\theta_1 - \theta_2) C_M$$

Where,  $\theta_1$  = Initial temperature of milk in  $^{\circ}\text{C}$

$\theta_2$  = Initial freezing temperature  $^{\circ}\text{C}$

$C_M$  = Specific heat of milk kcal/kg $^{\circ}\text{C}$

$$\text{Latent heat } Q_L = W_W \times W_F \times L$$

Where,  $W_F$  = Fraction of water frozen

$W_W$  = Fraction of water in mix

$L$  = Latent heat of fusion of ice in kcal/kg

$$\text{Sensible heat of semisolid of ice cream } Q_U = (\theta_2 - \theta_3) \cdot C_i$$

Where,  $\theta_3$  = Final freezing temperature of ice cream in the freezer

$C_i$  = Specific Heat of the ice cream

The total amount of heat which must be extracted from the ice cream freezer are:

The total heat extracted from the ice cream to freeze it partially in the freezer

The heat equivalent of work done in agitating the mix while being frozen

Radiation losses

## 20.2. Examples

### Example 20.2.1.

Find out the refrigeration load of an ice cream freezer in tones when capacity of freezer is 700 kg/hr, drawing temperature is  $-50^{\circ}\text{C}$ , initial temperature of mix is  $40^{\circ}\text{C}$ , initial freezing temperature of mix  $-2.50^{\circ}\text{C}$ , water content of the mix is 63%, specific heat of mix is 0.8 and specific heat of semi solid ice cream is 0.6. The water frozen at  $-50^{\circ}\text{C}$  is 47%. Assume that 85% of the heat equivalent of the work done by the motor appears as heat in the ice cream. The freezer requires 5 kW motor to drive the dasher, and radiation loss is 3% of the total heat.

#### Solution:

The total heat extracted from 1kg of ice cream:

$$\begin{aligned} \text{Using equation, } Q_S &= (\theta_1 - \theta_2) C_M \\ &= (4 - (-2.5)) \times 0.8 \\ &= 5.2 \text{ kcal} = 21.772 \text{ kJ} \end{aligned}$$

$$\begin{aligned} \text{Latent heat } \theta_L &= W_W \times W_F \times L \\ &= 0.63 \times 0.47 \times 80 \\ &= 23.7 \text{ kcal} = 99.232 \text{ kJ} \end{aligned}$$

$$\begin{aligned} Q_U &= (\theta_2 - \theta_3) \cdot C_i \\ &= (-2.5 - (-5)) (0.6) \\ &= 0.8 \text{ KCal} \end{aligned}$$

$$\text{Total heat} = 5.2 + 23.7 + 0.8 = 30.4 \text{ kcal/kg} = 127.285 \text{ kJ}$$

The heat equivalent of work done in agitation  $1 \text{ kW} = 860 \text{ kcal/h}$

Therefore, here work done  $= 5 \times 860 \times 0.85 = 3655 \text{ kcal/h} = 15303.485 \text{ kJ/h}$

Total heat  $= 700 \times 30.4 + 3655 = 24445 \text{ kcal/h} = 104402.845 \text{ kJ/h}$

Radiation losses  $= 0.03 \times 24445 = 733.35 \text{ kcal/h} = 3070.536 \text{ kJ/h}$

Therefore, total heat extracted  $= 25178.35 \text{ kcal/hr} = 107534.93 \text{ kJ/h} = 107534.93/12558 = 8.561$

TR

Therefore 8.561 TR, i.e. approx. 9.0 TR refrigeration plant capacity is required for the ice cream freezer

**Example 20.2.2.**

Find out the thickness of the ice layer immediately before scraping it off. The overall heat transfer coefficient is  $U = 500 \text{ kCal/m}^2\text{hr}^\circ\text{C}$ . The temperature difference is  $\Delta\theta = 25^\circ\text{C}$ . Speed of the scraper shaft is 150 rpm, number of blades is 2. Heat of solidification of ice is  $80 \text{ kCal/kg}$ . Density of ice is  $917 \text{ kg/m}^3$ .

**Solution:**

The heat removed  $Q = U.A. \Delta\theta$  serves only for the formation of a water-ice layer at the temperature of solidification.

$t$  = time interval between two scrapping operations  
 $= 1/(2 \times 2.5) = 0.2 \text{ seconds}$

Heat balance  $U.A. \Delta\theta = A.\delta.P_{\text{ice}}.L$

Where,  $A$  = surface area of heat transfer

$\delta$  = Thickness of ice layer

$P_{\text{ice}}$  = density of ice

$L$  = latent heat of ice

$$\delta = \frac{U.A. \Delta\theta}{P_{\text{ice}}.L} = \frac{500 \times 25 \times 0.2}{917 \times 80 \times 3600} = 9.4 \times 10^{-6} \text{m} = 9.4 \mu\text{m}$$

Ideally, it should be less than 20 micron.

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## Lesson 21.

### Design Problems on Continuous Freezers

#### 21.1. INTRODUCTION

In the design of freezing systems, it is necessary to know the amount of energy that should be eliminated from the food to change from the initial to the final temperature of the frozen product. To do this, one must know the enthalpy of the food at the beginning and end of the freezing process. Since enthalpy is a function of state, it should be given with respect to a reference temperature that, in the case of freezing processes, is  $-40^{\circ}\text{C}$ . This means that, at this temperature, the enthalpy of any product is considered null. In order to calculate the power needed to carry out the freezing process, it is necessary to determine the variation of enthalpy experienced by the product, since it is introduced in the freezer until the product reaches the final temperature. This can be achieved by using Equation 17.1. Another factor that should be calculated is the power that the freezing equipment should have to perform a given process. Such power is the total energy to be eliminated from the food per unit time and a measure of the capacity of the freezing system. Freezing power is calculated by the following equation:

$$\text{Pow} = m \Delta H / t \dots \dots \dots \text{Eq. 21.1}$$

Here,  $m$  is the total quantity of food to be frozen,  $\Delta H$  the increase of enthalpy experienced by the food from the initial to the final temperature, and  $t$  the time the food stays in the freezing equipment.

One of the basic considerations in the design of a system for the freezing process is the refrigeration requirement for reducing the food product temperature to the desired level. The enthalpy changes required will reduce the product from some temperature above the freezing point to some temperature below the freezing point and can be represented by

$$\Delta H = \Delta H_s + \Delta H_u + \Delta H_L + \Delta H_F$$

where the terms on right hand side represent the sensible heat required to reduce the product temperature to the initial freezing point ( $\Delta H_F$ ), the sensible heat removed to reduce the unfrozen portion of the product to the storage temperature ( $\Delta H_u$ ), the latent heat removed ( $\Delta H_L$ ), and the sensible heat removed to reduce the frozen portion of the product to the storage temperature ( $\Delta H_s$ ).

Sensible heat  $\Delta H_s$  is given by,

$$\Delta H_s = M C_p (T_i - T_F) \text{ where } T_F = \text{freezing point temperature}$$

Evaluation of other components is somewhat complex because of changing state of product below initial freezing point. Mass of unfrozen product and frozen product are changing and are temperature dependant. Enthalpy change required to reduce the unfrozen portion of the product to various temperatures below initial freezing point,  $T_F$  is given by:

$$\Delta H_u = M_u (T) C_{p,u} (T) (T_F - T)$$

Similarly,

$$\Delta H_F = M F (T) C_p, F (T_F - T)$$

these equations can be written in differential form as:

$$\Delta H_u = M u (T) C_{p,u}(T) dT \text{ and}$$

$$\Delta H_F = M F (T) C_p, F dT$$

Latent heat portion is given by:

$$\Delta H_L = M F (T) L$$

Unfrozen and frozen portions of product at any temperature below the initial freezing point can be calculated by

$$\ln X_A = \lambda' / R_g (1/T_{Ao} - 1/T_A)$$

Where,  $T_{Ao}$  - freezing point of pure liquid, K

$X_A$  - is mole fraction of water in solution

$R_g$  - gas constant, 8.314 kJ/ kg mol K.

$T_A$  - absolute temperature of solute, K

$\lambda'$  - Latent heat of fusion, J/ mol (6003 J/ mol for dilute liquids)

After obtaining information on the frozen and unfrozen fractions as function of temperature and specific heat of unfrozen fraction the above equations can be evaluated by integration.

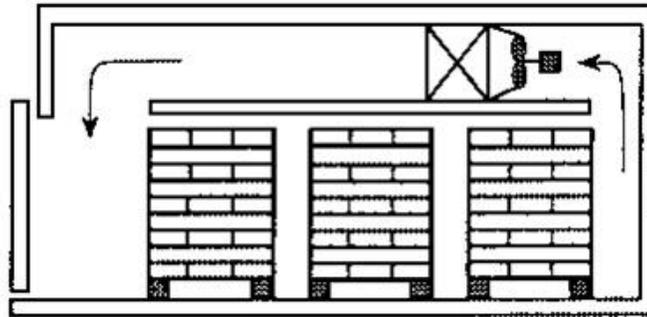


## Lesson 22.

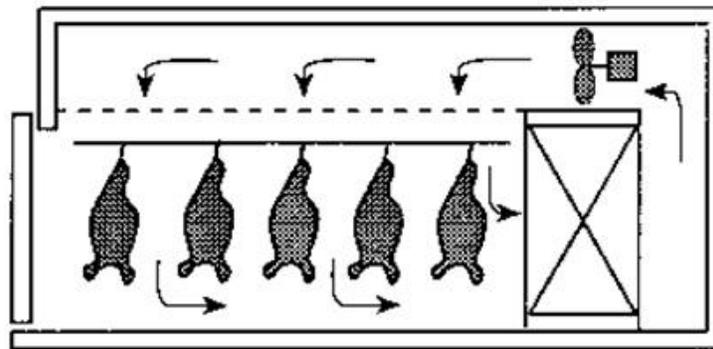
## Air Blast Freezers

## 22.1. INTRODUCTION

Air-blast freezers are the most common type of food freezer. Individual product items are placed in a recirculation air stream within a room or tunnel. The air is circulated by fans, which are often associated with the evaporator coils providing cooling. These freezers can be simple, operating in batch mode with manual loading and unloading of the product (Fig. 22.1, 22.2) or more complex, with automated continuous operation (Fig. 22.3, 22.4). Continuous freezers are best suited to processing large volumes of product. They have lower labor costs, and generally provide more uniform freezing conditions, but are less flexible.



**Fig-22.1:** Schematic diagram of a batch air-blast tunnel freezer with racks of product and horizontal air flow



**Fig-22.2:** Schematic diagram of a batch air-blast carcass freezing room with vertical air flow through a distribution plenum.

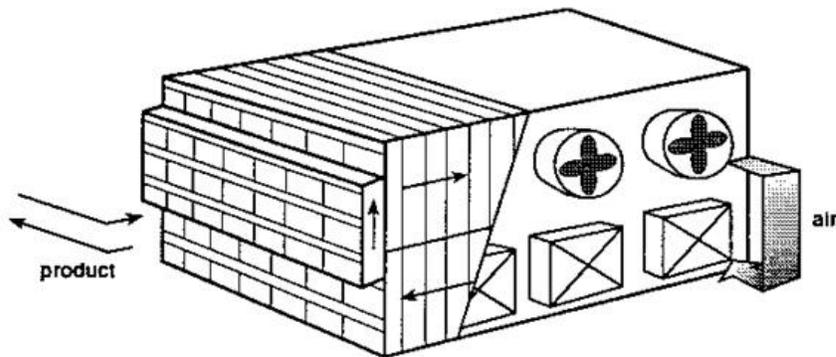


Fig- 22.3: Schematic diagram of a continuous air-blast carton tunnel freezer with cross-flow of air.

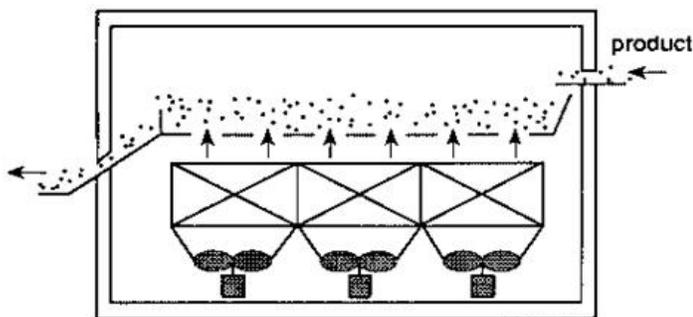


Fig-22.4: Schematic diagram of a continuous spiral belt freezer with vertical air flow.

Many different air and product flow configurations can be used. Horizontal air flow is probably most common, but there are a number of designs using vertical air flow, often to avoid air bypassing the product (Fig. 22.5). In continuous systems, air and product flows can be cocurrent, countercurrent (Fig.22.5) or cross-flow (Fig. 22.3, 22.4). The latter two configurations are most common as air temperature rise is small, so the temperature driving force for cooling and thus the rate of heat transfer are maximized. Methods to present the product to the air depend on the size, shape and packaging of the product, and include trays, racks, trolleys, hooks, conveyors, and belts. A wide range of product types, sizes, shapes, and packaging types can be handled by such freezers.

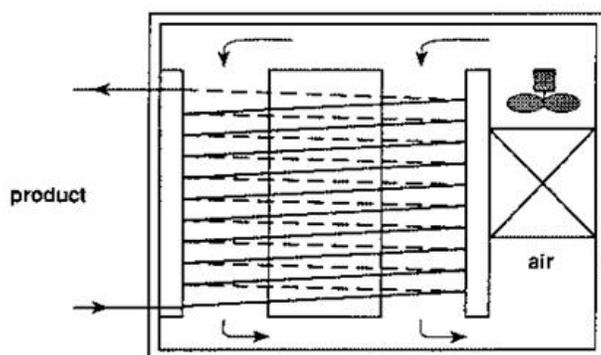


Fig-22.5: Schematic diagram of a continuous spiral belt freezer with vertical air flow

The major advantages of air-blast freezers are their simplicity and flexibility. The disadvantages are that using air limits the rate of heat transfer at the product surface, requires the use of substantial fan energy, and to achieve uniform air distribution can be difficult. Also, further disadvantages are that: evaporative weight loss can be significant from unwrapped product; bulging of packaged product can occur; defrosting evaporator coils or other means of frost prevention is required which can disrupt freezer operation; and the refrigeration system must operate with a low suction condition due to the air-to-refrigerant heat exchange.

## 22.2 Still Air Freezers

The simplest type of freezer is one in which the product is placed in a refrigerated room that is usually used to store frozen product. The process is historically referred to as sharp freezing. The shelves on which the product is placed within the room may be directly refrigerated, and the product may be bulk-stacked. Air flow over the product is minimal and the freezing rate is slow. Also, heat removal from the freezing product may cause undesirable temperature fluctuations in adjacent stored product.

## 22.3 Air-Blast Room and Tunnel Freezers

These freezers are commonly used for medium to large products where the rate of freezing is limited by the size of the product. The product does not need to be regular in shape. The product is placed on trays in racks or suspended so that air flow is possible around each individual product item. In continuous tunnel freezers, it is usual to have a mechanical system moving racks through the tunnel in a cyclic manner, with device for automatic loading and unloading of the product. Belt freezers are similar but product is transported on a perforated conveyor belt. Schematic diagram of a continuous spiral belt freezer with vertical air flow. racks, and product arriving and leaving on a conveyor system (Fig. 22.3). For batch freezers, the racks are manually loaded and positioned in the room or tunnel (Fig. 22.1, 22.2). In a tunnel system, the air is confined to flowing in the cross-section where the product is located. Also, the product is spaced evenly so that uniform air distribution and high air velocity is more easily achieved for a low total air flowrate and fan power. While most continuous tunnel freezers are restricted to one product size and shape in order to optimize the product loading configuration and air flow distribution, a range of products can be processed in the same tunnel if a variety of rack sizes and tray spacing are used. In a blast room there is often less strict control of the air flow pathway and bypassing of the air around the product can more easily occur.

## 22.3 Belt Freezers

Belt freezers involve the product passing continuously through a tunnel freezer on a perforated belt (Fig. 22.4). The air flow is directed vertically up through the belt and product layer. There may be multiple belt passes. Such freezers are commonly used for small unwrapped products with uniform shape in which a free-flow individually quick frozen (IQF) product is desired. The air velocities are typically in the range 1 to 6 m/s and the layer of product can be partially fluidized. This creates high rates of heat transfer between the air and product. Even distribution of the product across the belt is important to achieve uniform air distribution and freezing rate. Product transfers from one belt to another and/or mechanical devices are sometimes installed to reduce clumping and to redistribute the product. The belt speed can be varied to cope with changing production rates but care must be taken to maintain a uniform thickness of product on the belt.

## 22.4 Spiral Belt Freezers

Spiral freezers are a specialized type of belt freezer in which a continuous belt is stacked in a spiral arrangement up to 50 or so tiers high (Fig. 22.5). They allow very long belts (long product residence times) in a compact area as long as sufficient overhead space is available. Therefore, they are suitable for processing products with longer freezing times compared with other belt freezers (e.g., larger products and packaged products for which the packaging

impedes heat transfer). The size of the product is limited by the distance between each spiral tier and the total height of the stack. Air flow can be either horizontal across or vertical through the belts. Recent design improvements have included self-stacking belts to reduce mechanical wear and maintenance, and cleaning-in-place of the belt and freezer.

## 22.5 Fluidized Bed Freezers

Fluidized bed freezers are only suitable for small unwrapped IQF products of uniform size and shape, such as fruits and vegetables for which the energy requirements for fluidization are not excessive. In a manner similar to belt freezers, air is directed up through a perforated plate and bed of the product but at a flow rate high enough to fluidize the product (Fig.22.4). The product is fed in at one end and overflows out of the freezer at the other.

Fluidization

achieves good distribution of the product and prevents clumping, even with very wet incoming product, and the surface heat transfer is significantly enhanced. The product moves by flowing within the fluidized bed, but this can be aided by vibrating and/or sloping the air distribution plate. Individual items reside for different periods depending on the flow pattern in the bed. The average residence time is fixed by the feed rate and the volume of the bed, which is controlled by the height of the overflow weir. Fluidized bed freezers can be very compact because the small product size and high rates of convective heat transfer keep freezing times short.



## Lesson 23.

## Plate Freezers and Immersion Freezers

## 23.1. PLATE FREEZERS

Plate freezers consist of a series of parallel flat plates through which a coolant is circulated (Fig. 23.1). The plates can be mounted either horizontally or vertically. A hydraulic system is used to both open the space between plates for loading and unloading, and to close the plates so that effective contact with the food product occurs during freezing. Spacers or limit stops between plates and a pressure relief valve in the hydraulic circuit can be used to prevent the product being crushed unevenly or excessively flattened during plate closure. Vertical plate freezers are best suited to freezing unpackaged deformable products such as fish and meat. Blocks are formed by direct gravity feeding of the product between the plates. Plate heating and block ejection systems are required to remove the block at the end of the freezing process and cleaning may be required before reloading. Horizontal plate freezers are commonly used for either product packed into rectangular cartons or product formed into rectangular shapes by metal molds or trays. Although automated systems have been developed where individual plates are opened in order to facilitate simultaneous loading and unloading of rows of product from feed conveyors and continuous operation, plate freezers are more often manually loaded and operate in batch mode. For efficient operation, uniform and effective contact between the plates and the food product surface is important. This can be achieved by a high packing density of the product (low void space) within the package and/or by application of a moderate pressure to the plates. For packaged products, design of carton dimensions ensuring low voidage and minimal head space is crucial for good heat transfer. The major advantages of plate freezers are that: the rate of freezing is high even for packaged products; the product has very consistent size and shape and can be easily bulk stacked with high packing density and stability for subsequent transportation; they are very compact; infrequent defrosting of the plates is required; the total heat load and energy use are lower than for air systems (no fans and less infiltration and air interchange loads); and if evaporating refrigerant is used directly in the plates, the refrigeration system can operate at a higher suction temperature. The major disadvantages of plate freezers are the high capital cost, especially if they are automated to run continuously, and the limitation on product types that can be handled.

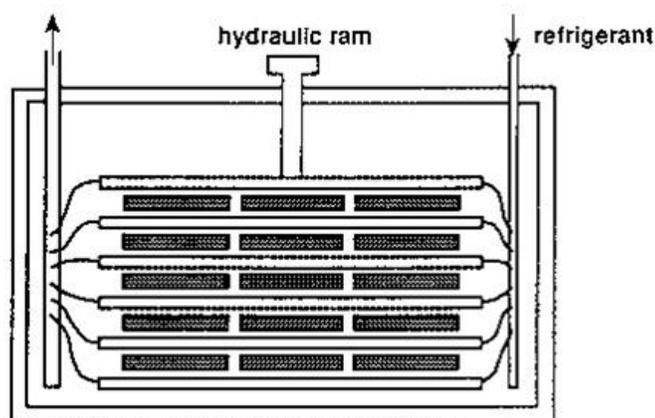


Fig- 23.1: Schematic diagram of a batch horizontal plate freezer

### 23.2. IMMERSION FREEZERS

In immersion freezers the product is immersed directly in, or sprayed with, a cold liquid such as a brine or glycol. The product is usually packaged to prevent cross-contamination between the liquid and the product. Products with irregular shapes are easily handled. Although high rates of freezing can be achieved, these types of freezers are now seldom used except for some fish, meat, and poultry products. The liquid is refrigerated either by circulation through a heat exchanger or by cooling coils and/or a jacket built into the liquid tank.

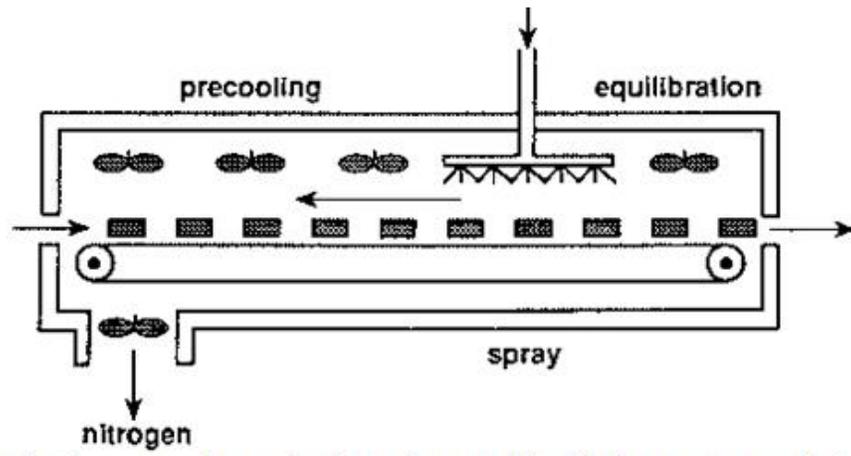
### 23.3. CRYOGENIC FREEZERS

The most commonly used cryogenics are liquid nitrogen (LN<sub>2</sub>) and liquid carbon dioxide (LCO<sub>2</sub>). Chlorofluorocarbons (CFCs) such as CFC-12 are no longer in use due to their ozone layer depletion effect. The cryogenics have low boiling points,  $-196^{\circ}\text{C}$  for LN<sub>2</sub> and  $-79^{\circ}\text{C}$  for LCO, giving large temperature differences and high rates of heat transfer. Other important properties of such cryogenics are that they are colorless, odorless, chemically inert, and nontoxic in normal concentrations. Therefore they are safe for direct contact with food. The product is either sprayed with, or immersed in, the cryogen at atmospheric pressure. Special care must be exercised with CO<sub>2</sub> because it forms a low density snow. Cryogenic freezers can operate continuously with the product being conveyed through a tunnel (Fig.19.2), but other

configurations are also used. Cryogenic freezers are generally only used for small to medium sized products because in larger products the rate of freezing is limited by heat transfer internal to the product. While the higher rate of freezing should lead to a higher quality product than using other freezer types, it is often forgotten that long-term storage negates these benefits. It has been shown that after about a month of conventional frozen storage, the quality of products was independent of the type of freezing system and rate of freezing used. LN<sub>2</sub> and LCO<sub>2</sub> are usually delivered as a high-pressure liquid, rather than being produced on-site, and are vented to the atmosphere after use. The cryogen storage system is a significant cost component. Effective insulation and/or refrigeration of the storage tank is necessary to prevent excess heat ingress and cryogenic loss. For LN<sub>2</sub>, the system losses are typically up to 1% of stored volume per day. For LCO<sub>2</sub>, the higher temperatures for the same storage pressure mean that a small supplemental mechanical refrigeration system can eliminate losses completely. For efficient use of the cryogen, the product and cryogen flows are usually countercurrent and the cryogen vent temperature is kept reasonably close to ambient conditions ( $-50^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ ). Because of the very high rates of heat transfer achieved, a product temperature equilibration stage is commonly included. Even then the product surface temperature will usually remain significantly colder than the center temperature at the freezer exit.

The main advantages of cryogenic freezers are: high rates of freezing achieved by the very cold temperatures and low refrigerant-to-product surface heat transfer resistance (resulting in lower weight loss and higher quality); ease of operation; compact size; low cost of the equipment; rapid installation and start-up; mechanical simplicity; and low maintenance cost. The main disadvantage is the high cost of the cryogenics. Cryogenic freezing (or alternatively liquid immersion freezing) can be used for rapid

crust freezing with completion of freezing in an air-blast freezer (often called combined cryomechanical systems). These systems aim to achieve the optimum balance between freezer operating costs and product moisture and quality loss. The principle is that most of the heat removal is performed by the mechanical system giving low operating costs while the initially rapid surface temperature pull-down minimizes product moisture and quality loss.



**Fig- 23.2:** Schematic diagram of a typical continuous liquid nitrogen tunnel freezer

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## Lesson 24.

### Storage of Frozen Foods

#### 24.1. INTRODUCTION

Food and dairy products are perishable in nature. They should be stored at low temperatures in order to increase their shelf life. Cold storages and deep freezers are used for this purpose. If the temperature in the room is up to 0 °C it is generally known as cold store and if temperature is 0 °C to – 22 °C it is known as deep freeze.

Food, on being stored, may get spoiled by three mechanisms:

- Living organisms may feed on the food and contaminate and spoil it
- Biochemical activity within the food itself (eg respiration, staling, browning, rancidity development, etc.) may in time diminish its quality & usefulness
- Physical processes (eg bursting & spillage of the contents of the package) may have the same effect

The three main factors of the storage environment that influence the storage life of a particular commodity are the temperature, humidity & the composition of the store atmosphere. In addition, rough handling, careless packing or unsuitable packaging can reduce storage life.

#### 24.2. TEMPERATURE

The rate at which biochemical reactions occur in food increases with increasing temperature. The logarithm of the reaction rate is a linear function of temperature. The lower the storage temperature, the more slowly do foods suffer degradation by those biochemical spoilage reactions listed above. In addition, the rate of growth of bacteria is reduced as the temperature falls and low temperature storage (frozen storage) has some bactericidal effect. Most insect activity is inhibited below about 40°C although some insect species and insect eggs are capable of surviving long exposures to those temperatures.

From all this, it might be inferred that a reduction in storage temperature inevitably results in an extension of the storage life. Foods containing water will freeze, if their temperature is lowered much below 0°C, the actual freezing temperature depending upon the nature of the aqueous solution in the food. The act of freezing and thawing alters the food, sometimes very extensively and the properties of the 'fresh' product such as fruits and vegetables are adversely affected should they freeze, the cans may burst and if such foods contain gels or emulsions, they may break down.

Even if held above the freezing temperature, deleterious physiological changes can result in the spoilage of fresh fruits and vegetables. Apples stored close to their freezing point can exhibit forms of injury not observed at slightly higher temperatures. Soggy or low temperature breakdown, internal browning, brown core or core flush result from storage at 0°C, but are not a problem at 3-4°C.

Chilling injury can be observed in a variety of tropical fruits & vegetables. There is evidence that ripe tomatoes can be stored at lower temperature than green tomatoes which can suffer cold injury below 7°C resulting in abnormal ripening and susceptibility to rots. Storage of potatoes below 3°C is undesirable as they are susceptible to chilling

injury. However, even above this temperature there can be a change in the starch – sugar balance leading to the accumulation of sugar in the tissues making the tubers unsuitable for processing into chips or crisps. Storage at 10-13°C is recommended to avoid this.

Another factor to be taken into consideration is the cost of storage when storage temperature is lowered. To the prime cost of foods put into storage must be added the cost of maintaining them under the chosen storage conditions. Thus, stored foods have increased costs even if they do not increase in value. Storage at below ambient temperature is more expensive than unrefrigerated storage & lower the storage temperature, higher the cost. Hence, storage temperatures need to be no more elaborate than those required to maintain the stored commodity in good condition up to the time of use.

This concept has been applied particularly to the storage and distribution of frozen food products. Here, provided the products are suitably packaged, the deterioration is almost entirely a function of temperature.

Three factors influence the choice of the storage temperatures for a particular commodity:

- The temperature dependence of the rate at which spoilage processes occur
- The risk of cold injury to the commodity
- The economic balance between storage costs and the maintenance of product quality

### 24.3. STORAGE HUMIDITY

If the humidity of a store atmosphere is below the equilibrium relative humidity of the food being stored that food will lose moisture to the atmosphere. Conversely, if it is above ERH of the food, the latter will absorb water. Thus, ideally the RH of the store atmosphere should be adjusted to the ERH of the stored product, for instance, granulated white sugar has a moisture content of about 0.02% & an ERH of about 60%. If the moisture content rises to 0.06%, the sugar is in danger of caking. Therefore, storage RH below 60% is recommended for this product. Conversely, brown sugar has a moisture content of 4% which must be maintained if the product is to retain a workable texture. So RH of 60-70% is recommended for long term storage. Again, peanuts become brittle and may split due to dehydration if the storage RH is below 70% and it is liable to mould spoilage above this RH. Thus, as with temperature, there is often an optimum condition for storage.

The ERH of a product has a considerable bearing on its vulnerability to microbial attack. When expressed as a fraction, instead of percentage, the ERH is known as the water activity of the material. Bacterial growth may be a major problem in foods with a high water activity, for instance, fresh fruits & vegetables, meat and fish. But in materials with lower water activity, it is the fungi that cause the most trouble. Insects can also flourish in foods with comparatively low water activity.

Packaging can be used to isolate the environment of the food from the store air and so allow foods to be held at ERH in storage atmospheres of undermined relative humidity. Occasionally, treatment of the surface of foods achieves the same purpose. Thus, shell eggs lose water freely and require high humidity environment if they are not to experience excessive weight loss. This may lend microbial growth on the egg shell and consequent tainting of the egg. Treating the shell with oil improves its water vapor barrier properties and allows the humidity of the store to be lowered, so avoiding more growth.

Recommended levels of store RH have been published for many products.

#### 24.4. COMPOSITION OF COLD STORE ATMOSPHERE

A variety of food materials are advantageously stored in atmosphere different from normal air. The most noteworthy example of this occurs in the refrigerated storage of fruit. Fresh fruits respire, taking up oxygen and evolving carbon dioxide. The rate of respiration can be reduced by cooling so extending storage life, but can be further reduced by storing the fruit in an atmosphere richer in carbon dioxide and poorer in oxygen than normal air. In the case of apples and pears, particularly worthwhile increase in storage life is possible and this technique which is known as controlled atmosphere or gas storage is in extensive commercial use. The oxygen and carbon dioxide levels used vary markedly between varieties and are controlled to optimum values, since too great a modification of the storage atmosphere can lead to secondary spoilage. This technique is used extensively for the storage of fruits such as apples, pears and oranges and is receiving some attention for improving the quality of vegetables in storage and transportation.

When strawberries and raspberries are cooled and transported in an atmosphere containing about 20% by volume of carbon dioxide in air, the development of fungal rots and ripening is delayed. Storage in carbon dioxide was at one time also used with meat. Chilled beef was shipped to England from Australia in an atmosphere of 10% carbon dioxide in air approximately doubled the life obtainable up to that time.

If grain is stored in an air tight silo, insects, mites and moulds can be controlled by the atmosphere they generate. These organisms use up the oxygen in the enclosed space and asphyxiate or suffocate themselves before becoming numerous enough to cause damage. Dry grain can be stored in this manner with little loss of its functional properties. However, wet grain will lose its power of germination, making it unfit for seed or malting and develop a taint which is transmitted to baked goods made from it – though it remains suitable for animal feed. Air tight storage is more satisfactory for non-viable food materials sufficiently dry to be protected against microbial growth, for example, ground roast coffee. In such cases, oxygen may be excluded from the container or package by replacing the air in it by inert gases like nitrogen or carbon dioxide or by a vacuum.

#### 24.5. ODORS AND TAINTS

Stored produce may pick up foreign odors and flavors from other food stuffs stored with it or from inappropriate packing materials or from storage chamber and environment. Foods with strong odors, like spiced meat, smoked fish, citrus fruits, etc and spoiled meat and fish are likely to cause tainting. Packaging materials may either themselves contribute odors or be contaminated during production. Adhesives and printing materials may also cause trouble. Finally the constructional materials of the store may become contaminated or taints may be absorbed from vapors entering the store from outside, while such taints do not alter the nutritional status of the food, its commercial value can be seriously affected.

Fatty foods are particularly liable to absorb odors. Butter is very sensitive to tainting and meat shipped to England has been found to be tainted by diesel and fuel oil fumes, smoke and fruits, particularly oranges. Eggs will also pick up taints fairly easily.

The most satisfactory method of avoiding problems of tainting during storage is to avoid taint absorbing foods in the presence of odoriferous materials. Suitable packaging can help to preserve food untainted and activated charcoal and ozone have been used for removing odorous volatiles from food stores. Unfortunately, the concentrations of ozone for efficient action are toxic and so require special care, both in their use and in the purification of air in the chamber afterwards. To be efficient, after these treatments, the surfaces of the chamber

and the refrigerator should be thoroughly cleaned treating all surfaces with a disinfectant. It is worth remembering that these processes are all the more effective when the chamber temperatures are high enough.

#### 24.6. LIGHT

The UV in the Sun Rays will quickly impart a taint to the butter and milk by oxidizing their fats, potatoes exposed to light turn green due to formation of chlorophyll. In storage buildings, the effect of light on produce is normally unimportant since daylight does not penetrate into them and a low level of artificial light is provided. Where high intensity lighting from fluorescent tubes is used to display foods, the UV rays from such lights are more intense than those from tungsten filament lighting and have been shown to be sufficient to oxidize fats, bleach colors and green the potatoes. Packaging in colored plastic film or the use of color filters on the light fittings will reduce the effects but are not satisfactory from commercial point of view.

#### 24.7. VARIABILITY IN STORAGE CONDITIONS

Both spatial and temporal variations may be found in the conditions in a good food store. Temporal variations may either be transient, resulting say from recently introduced material coming to an equilibrium state in the store – or they may be periodic in nature and a permanent feature of the storage situation. The main causes of variability in storage conditions are:

- The equilibrium of the products to storage conditions
- Respiratory activity in fruits and vegetables
- Variation of climatic conditions external to the store
- Fluctuations in the performance of refrigeration & other equipment designed to maintain the storage conditions at the desired levels
- The activities of operating personnel

The effect of such variations is often complex, inter-related changes occurring in the temperature, humidity and atmosphere composition throughout the store. The magnitude of spatial variations in storage conditions are considerably influenced by the mode of transfer of heat and gases within the stack of stored material. If the store air does not move through the stack diffusional mechanisms and thermal conduction predominate and larger variations will be observed than when the store air moves and promotes additional convective transfer. Thus, in order to maintain uniform conditions throughout the store, such air movement is desirable. The produce must therefore be stacked in the store that air flow through the stack is facilitated.

Air circulation through the stack may either be fan assisted or due solely to the thermally generated density gradients in the air. The latter system is more frequently used today because the cooling systems are less bulky and cheaper. The most frequently used forced convection systems use a cooling system and fan located in separate enclosures connected to the store by delivery and return air ducts located in a floor mounted vertical duct or built into a compact unit which may be suspended from the ceiling of the store. These units use fin tube heat exchangers.

It is sometimes advantageous of the fan and duct systems in forced ventilation stores are so constructed that the direction of air flow can be reversed. Periodic air reversal can reduce the spatial temperature variations during the initial cooling of a room full of, say, fruit to storage temperature.

## 24.8. MAINTENANCE AND CONTROL OF STORAGE CONDITIONS

### Temperature:

Refrigerated storage rooms are thermally insulated to reduce heat leakage. The insulation is normally fixed to the structural walls, ceiling and the floor of the room, though pre-fabricated panels have recently become more commonly used in conjunction with a steel or concrete load bearing framework. Insulation is sometimes desirable in unrefrigerated storage. For instance, root vegetables and potatoes can be stored in clamps or barns using either earth or straw as an insulating material. The purpose of the insulation is to minimize the effects of sudden ambient changes on the produce and so prevent frost damage. Canned foods may be transported in insulated vehicles for the same reason, while too little insulation would lead to high refrigeration costs and over insulation would initially be more expensive and will reduce the available storage space in the building, cabinet or container.

Another important source of heat leakage into a refrigerated store is air exchange at the door. This exchange is reduced by a variety of methods. The time the door is open may be minimized by automatic opening and closing mechanisms, double doors may be installed forming an air lock or an air curtain fixed above the outside of the doorway. This latter consists of a fan and a duct system that directs a stream of the external ambient air downwards and slightly outwards in a sheet across the door opening.

If the refrigeration requirements for a store are to be estimated, heat generation within the store and the cooling of the stored produce must be taken into account as well as heat leakage into or out of the store.

The magnitude of the heat load from all causes, except wall leakage and heat generation by the stored produce, during conventional store operation is approximately given by  $0.003 V \Delta t$  kJ/s for every  $1^\circ\text{C}$  difference between the inside and outside of the room and  $V$  is the volume of the room in  $\text{m}^3$ .

### Important Features of Construction of Cold Stores:

#### Air lock room:

At entrance we have air lock room. This is lightly insulated room having two insulated doors with automatic door closer arrangement. One door opens to outside and the other opens inside the cold store/deep freeze.

#### Insulated doors:

Cold store and deep freeze have special doors. These have sturdy frame grouted in RCC. Door has rubber gasket all around to make it air tight. It is made of teak wood battens and frame with two layers of thermocole of 5 to 15 cm thickness. Externally it is clad with aluminum sheet. The door handle is catch operated from both inside and outside. The deepfreeze door has heater in the frame. Cold store doors in the dairy plant are having special features like, long handle, soft wood, long hinges, insulation, special locking system, defrosting mechanism, air curtains etc. These doors are known as patch type of door.

#### Air curtain:

With a suitable blower, we form a curtain of air between hot outside air and cold inside air. These are installed generally at main door where chances of infiltration of atmospheric air are more.

**Lighting and emergency bell:**

Cold store should be provided with an emergency bell switch. There should be proper lighting inside. Emergency may arise at a time when there is no power supply. Power inverters of suitable range are available to connect lighting and bell circuits of cold store.

**Insulation:**

Expanded polysterene (thermocole) is used for insulation. For cold store 10 cm thick and for deep freeze 15 cm thick insulation is provided. For floor heavy density and for walls and ceiling normal density thermocole is used.

**Syphon lock for air in defrosting drains:**

The defrosting drains should have water siphon seal (U shape) for barring outside air to form convectional current with cold inside air. The drain pipe from diffuser drain section should slope outside.

**Protection to insulated walls and door:**

Guard railing is provided all along the walls for protection of wall insulation. Kota stone dado for better cleanliness may also be provided to avoid maintenance problems of painting up to 2 m height of wall.

**Flooring:**

For can cold stores cast iron tiles floor is provided. Alternate panels should be cast with flexible joint filler to withstand thermal shocks due to rise and fall of temperature.

**Diffuser unit:**

In dairy cold rooms we use high velocity, low temperature air for producing refrigeration effect. For this purpose packaged blast freezer i.e. diffuser unit is used. This unit has three main sections viz. fan section, coil section and drain section. For fan section, self aligning dry lubricated sealed bearings are used. Bearings are packed with soap stone or Teflon as dry lubricator. In some cases low temperature servogem-2 (N.P.2) grease may also be used.

**Defrosting:**

The product moisture and cold store's air moisture condenses and freezes at diffuser coil, it being the coldest point. This frosting ultimately restricts the air circulation through the coils there by increasing the cold room temperature. Frosting will also restrict proper heat transfer from refrigerant to air, there by reducing the plant efficiency. This may also lead to wet compression which is dangerous. Therefore defrosting should be done periodically.

When diffuser motor ampereage reduces to 75% of the actual running current, the unit should be defrosted.

Defrosting can be done by hot water spreader pipe arrangement after shutting down the plant. Alternatively hot gas defrosting can be done by running the compressor on reverse cycle by manifold or crossover system

**Receiver:**

- Horizontal cylindrical tank with level indicator, oil air purging valves, safety valve etc.

When the plant is in run - 1/3 full

When the plant is idel -  $\frac{1}{2}$  full

## Expansion valves:

- Direct expansion valve/ TEV is mostly used in small capacity plants employing freon group of refrigerants.
- Low side float valve/ Hand expansion valves are used in conjunction with accumulators in large industrial plants employing ammonia

## Controls :

- H.P and L.P cut out
- Oil failure switch
- Thermostat or ice thickness controller
- Solenoid valve
- Back pressure regulating valve
- Safety valves

## Note:

L.P cutout is set at 1.19 kg/cm<sup>2</sup> pressure for NH<sub>3</sub> system (IBT, cold store etc).

H.P cutout for condensing temperature of 30 °C is set at 11.2 kg / cm<sup>2</sup> and for 40 °C condensing temperature is set at 15.4 kg/cm<sup>2</sup>.

Thermostat bulb is kept 5 cm (2") away from coil surface and set at a temperature of -1 to -2 °C.

Recent Developments in cold stores:

- PUF panels.
- Walk in coolers

Recent Developments in insulation techniques:

- Mass insulation: By replacing a shorter path of heat flow of lower resistance with a larger heat flow path of higher resistance.
- Reflection insulation.
- Vacuum insulation
- PUF- excellent vapour barrier so does not require any other vapour barrier.

The space required for storage of different dairy products:

Milk cold store (cans) - 360 lit/m<sup>2</sup>

Milk cold store (pouches) - 400 lit/m<sup>2</sup>

Milk cold store (bottles) - 250 lit/m<sup>2</sup>

Butter cold store/ deep freeze - 100 kg/m<sup>2</sup>

Cheese ripening in cold store - 250 kg/m<sup>2</sup>

### 24.9. Problem on Cold Stores

#### Example 20.9.1

Determine the inside wall temperature and rate of heat gain through the wall of a cold store maintained at -15°C. The walls are of 15cm cork with 2 cm plaster on each side and outside temperature is 30°C. Inside and outside heat transfer coefficients are 9.3 W/m<sup>2</sup> K. Thermal conductivity of cork is 1.16 W/m K and that of plaster is 11.6 W/m K.

**Solution:**

The overall heat transfer coefficient 'U' is:

$$U = \frac{1}{1/h_i + 1/h_o + x_1/k_1 + x_2/k_2 + x_3/k_3}$$

$$h_i = h_o = 9.3 \text{ W/m}^2 \text{ K}$$

$$x_1 = x_3 = 0.02\text{m}$$

$$x_2 = 0.15\text{m}$$

$$k_1 = k_3 = 11.6 \text{ W/ m K}$$

$$k_2 = 1.16 \text{ W/m K}$$

$$U = \frac{1}{(1/9.3) + (1/9.3) + (0.02/11.6) + (0.15/1.16) + (0.02/11.6)}$$

$$= 2.875 \text{ W/m}^2 \text{ K}$$

$$Q = U.A.(T_o - T_i)$$

$$= 2.875 \times 1 \times (30 - (-15)) = 129.38 \text{ W}$$

If the inside wall temperature is  $t_i$ , then,  $Q = h_i \times A \times (T_i - (-15))$

Therefore,  $T_i = -1.09 \text{ }^\circ\text{C} = 271.9 \text{ K}$

#### Example 24.9.2

Calculate the size of the compressor required for a 6m x 3m x 6m (outside dimensions) of refrigerated room, having 10cm of cork insulation. The room is to be maintained at 0°C. The outside air is at 32°C dry bulb temperature and relative humidity is 60%. The product is 1000 kg milk at 31°C to be cooled to 10°C in 24 hrs/ The electric load in the room is 200 watts.

**Solution:**

The surface area of the room is 90m<sup>2</sup>.

From the table we take that for a temperature difference 320C, the heat gain for 10cm cork insulation is 1838 kJ/m<sup>2</sup> day. The wall heat gain is 90 x 1838 kJ/day = 165420 kJ/day. Assuming that the walls are 0.3 m thick, the internal volume of the room is 5.4 x 5.4 x 2.4 = 69.98 m<sup>3</sup>(approx. 70 m<sup>3</sup>).

Also from the table, number of air changes per day for 70 m<sup>3</sup> is found to be 14 and heat required to cool the outside air is 93.4 kJ/m<sup>3</sup>. The air change load is 70 x 14 x 93.4 = 91532 kJ/day.

The specific heat of milk is 3.89 kJ/kg K.

The product load is 1000 x 3.89 x (31-1) = 116700 kJ/day

The load due to electrical equipment in the room is 200 x 3600 x 24/1000 = 17280 kJ/day

Parameter	kJ per 24 hr
Wall gain	165420
Air change	91532
Product	116700
Electrical	17280
Calculated load	390932
10% safety	39093
Total load	430025

For 16 hr operation of the compressor, the load becomes 430025/16 = 26877kJ/h

The size of compressor needed will be 26877/12560 = 2.14 TR (1 TR = 12560 kJ/h)



**Lesson 25.****Water activity and mass transfer****25.1. INTRODUCTION**

Drying is defined as the removal of moisture from a product, and in most practical situations the main stage during drying is the internal mass transfer. The mechanisms of water transfer in the product during the drying process can be summarized as follows:

Water movement due to capillary forces

Diffusion of liquid due to concentration gradients

Surface diffusion

Water vapor diffusion in pores filled with air

Flow due to pressure gradients

Flow due to water vaporization–condensation

In the pores of solids with rigid structure, capillary forces are responsible for the retention of water, whereas in solids formed by aggregates of fine powders, the osmotic pressure is responsible for water retention within the solids as well as in the surface. The type of material to be dried is an important factor to consider in all drying processes, since its physical and chemical properties play a significant role during drying due to possible changes that may occur and because of the effect that such changes may have in the removal of water from the product.

A hygroscopic material is one that contains bound water that exerts a vapor pressure lower than the vapor pressure of liquid water at the same temperature. It is expected that products made mainly of carbohydrates will behave in a hygroscopic way, since the hydroxyl groups around the sugar molecules allow formation of hydrogen bonds with water molecules. The interaction between the water molecules and the hydroxyl groups causes solvation or solubilization of sugars. In water soluble proteins, as in most of the globular proteins, the polar amino acids are uniformly distributed in the surface, while the hydrophobic groups are located towards the inside of the molecule. This arrangement allows formation of hydrogen bonds with water, which explains the solubility of this type of proteins.

Dehydration involves the simultaneous transfer of heat, mass and momentum in which heat penetrates into the product and moisture is removed by evaporation into an unsaturated gas phase. Owing to the complexity of the process, no generalized theory currently exists to explain the mechanism of internal moisture movement. Although it is now accepted that in most practical situations of air drying of foods the principal rate-determining step is internal mass transfer, there is no agreement on the mechanism of internal moisture movement. In the case of capillary-porous materials such as fruits and vegetables, interstitial spaces, capillaries and gas-filled cavities exist

within the food matrix and water transport takes place via several possible mechanisms acting in various combinations. The possible mechanisms include:

liquid diffusion caused by concentration gradients,

liquid transport due to capillary forces,

vapour diffusion due to shrinkage and partial vapour-pressure gradients (Stefan's law),

liquid or vapour transport due to the difference in total pressure caused by external pressure and temperature (Poiseuille's law),

evaporation and condensation effects caused by differences in temperature,

surface diffusion in liquid layers at the solid interface due to surface concentration gradient,

liquid transport due to gravity.

Most foods are classified as capillary porous rigid or capillary porous colloids. Therefore, it is often proposed that a combination of capillary flow and vapour diffusion mechanisms should be used to describe internal mass transfer. Water activity, rather than moisture content, influences biological reactions. In the regions of water adsorption on polar sites or when a mono-molecular layer exists, there is little enzyme activity. Enzyme activity begins only above the region of mono-molecular adsorption. When the moisture content of a substrate is reduced below 10 %, microorganisms are no longer active. It is necessary however to reduce the moisture content to below 5 % in order to preserve nutrition and flavour.

## 25.2. WATER ACTIVITY

Water activity and moisture content of the material are very important in food unit operations. During processing and storage, many chemical and physical factors are influenced by the water activity and moisture content level. Chemical changes that are enhanced by water activity include enzymatic reactions, nonenzymatic browning, and microbial activity. In many food products, enzymes are not inactivated during the heating process. Consequently, enzymatic reactions can take place at even low moisture contents. Water activity also affects the nonenzymatic browning reactions in foods. When water is present, carboxyl and amino compounds are involved as reactants, products, or catalysts in the browning process. Bacterial growth is also affected at fairly high water activity levels. If water activity is maintained at a value below 0.90, most bacteria remain dormant. Most yeasts and molds, however, can grow and multiply at water activity levels as low as 0.80. Physical changes such as texture and aroma can depend greatly on water activity. Textural changes are most often seen in freeze drying and subsequent storing of foods, particularly meats and fish. The water activity in dried foods can also affect the retention of aroma. Different foods that are stored together will be altered if their individual relative humidities (water activities) are different. Under the action of a driving force created by a difference in water activities changes in the moisture and water activities of these foods will follow their own isotherm curve until an equilibrium water activity is achieved.

Water activity ( $a_w$ ) is measured as the equilibrium relative humidity (ERH), the percent relative humidity (RH) of an atmosphere in contact with a product at the equilibrium water content.  $a_w$  is also ratio of the partial pressure of water in the headspace of a product ( $P$ ) to the vapour pressure of pure water ( $P_0$ ) at the same temperature

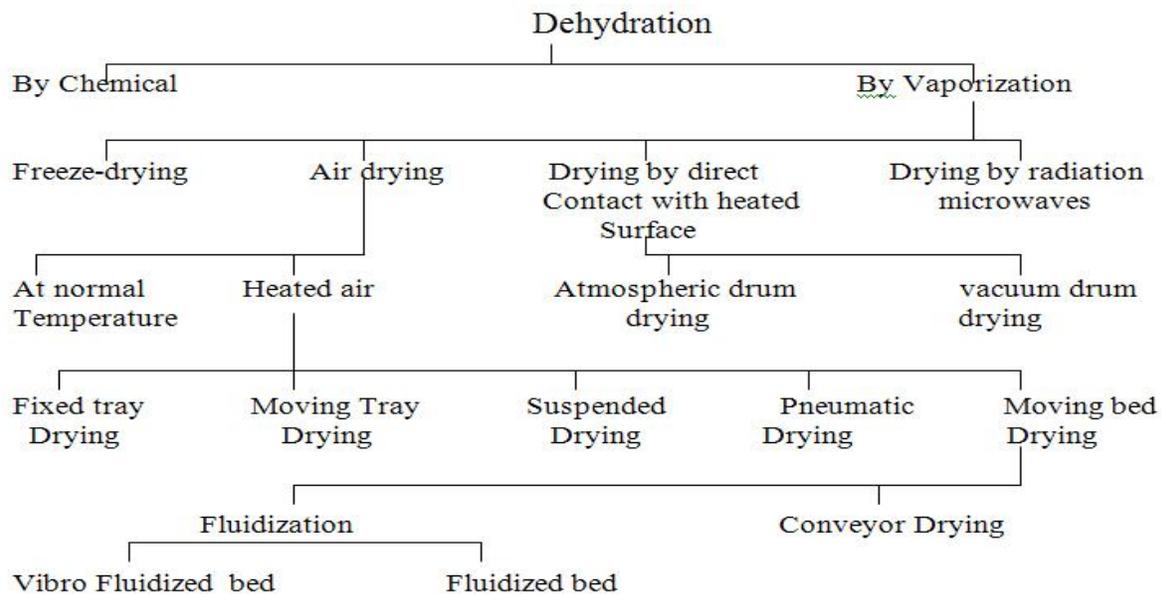
$$a_w = ERH = P/P_0$$

The relationship between  $a_w$  and the rate of deteriorative reactions is very important to design dehydration systems. Reducing  $a_w$  below 0.7 prevents microbiological spoilage. However, although microbiological spoilage does not occur at  $a_w = 0.7$ , prevention of other deteriorative reactions needed to preserve a dried food product successfully reduction of  $a_w$  to below 0.3.

**25.3. MASS TRANSFER**

During dehydration, water is vapourized only from the surface. The transfer of water vapour from the wet surface to a stream of moving air is analogous to convection heat transfer, therefore, a mass transfer coefficient is used. Moisture flux is proportional to the driving force which is the difference in vapour pressure on the surface and the vapour pressure of water in air surrounding the surface. At the same time that water is removed from the surface, water diffuses from the interior of a solid towards the surface. The later is a general form of diffusion which is analogous to conduction heat transfer. The differential equations for conduction also apply to diffusion, but mass diffusivity is used in place of thermal diffusivity.

**25.4. CLASSIFICATION OF DEHYDRATION SYSTEMS**



Dehydration equipments can be classified as

- |                        |  |
|------------------------|--|
| Domestic               | Open sun drying<br>Solar drying  |
| Small scale            | Roller drying<br>Tunnel drying<br>Cabinet/ Tray<br>Trough drying<br>Microwave drying<br>Dielectric |
| Medium and Large scale | Spray<br>Fluidized bed<br>Freeze<br>Puf<br>Vacuum<br>Bin<br>Pneumatic<br>Rotary                    |

**Example 25.5.**

A dry food product has been exposed to a 30% RH environment at 15 oC for 5 h without a weight change. The moisture content has been measured and is 7.5 % (wet basis). The product is moved to a 50% RH environment and a weight increase of 0.1 kg/kg product occurs before equilibrium is reached.

Determine water activity of the product in the first and second environment.

Compute moisture contents of the product on dry basis in both environments.

**Solution**

Equilibrium RH = 30% in first environment.

Product moisture content is 7.5% (wet basis) in first environment.

Weight gained in second environment = 0.1 kg / kg product.

The water activity is equilibrium RH divided by 100. so water activities are 0.3 and 0.5 in first & second environment respectively.

Moisture content in first environment is 7.5 % wet basis i.e., 0.075 kg H<sub>2</sub>O / kg product.

$$= \frac{0.075 \text{ kg H}_2\text{O} / \text{kg product}}{0.925 \text{ kg solids} / \text{kg product}} = 0.08108 \text{ kg H}_2\text{O} / \text{kg solids}$$

Moisture content in second environment is

$$= \frac{(0.075 + 0.1)}{1.1} * 100$$

$$= 15.91 \% \text{ (wet basis)}$$

or

$$= \frac{0.1591}{(1 - 0.1591)} * 100$$

$$= 18.92 \% \text{ (dry basis)}$$

## Lesson 26.

### The Stages of Drying

#### 26.1. INTRODUCTION

The removal of moisture from a food product is one of the oldest preservation methods. By reduction of water content of food product to a very low levels the opportunity for microbial deterioration is eliminated and rates of other deterioration reactions are reduced significantly. In addition to preservation, dehydration reduces product weight and volume by significant amounts and improves efficiency of product transportation and storage. Often, the dehydration of a food product results in a product that is more convenient for consumer use.

#### 26.2. MECHANISM OF DRYING

Dehydration or drying of foods is a complex phenomenon involving momentum, heat and mass transfer, physical properties of the food, air and water vapour mixtures, and macro and microstructure of food product. There are many possible drying mechanisms, but those that control the drying of a particle product depend on its structure and the drying parameters – drying conditions, moisture content, dimensions, surface transfer rates and equilibrium moisture content. These mechanisms fall in to three classes: (i) evaporation from a free surface (ii) flow as a liquid in capillaries, and (iii) diffusion as a liquid or a vapour. The first mechanism follows the laws for heat and mass transfer for a moist product. The second mechanism becomes difficult to distinguish from diffusion when one sets the surface tension potential to be proportional to the logarithm of the moisture potential (or water activity). The third set of mechanism follows Fick's second law of diffusion, which is analogous to Fourier's law of heat transfer when the appropriate driving force is used.

All solid materials have a certain equilibrium moisture content when in contact with air at a particular temperature and humidity. The material will tend to lose or gain moisture over a period of time to attain this equilibrium value. Fig. 26.1 shows various moisture content regions of a food material such as bound, unbound and free.

In conventional drying the heating medium, generally air, comes into direct contact with the solid. Various oven, rotary, fluidized bed, spray and flash dryers are typical examples. In conduction drying, the heating medium is separated from the solid by a hot conducting surface. Examples are drum, cone, and trough dryers. In radiation dryers, the heat is transmitted as radiant energy. Some dryers also use microwave energy to dry food materials at atmospheric pressure or at vacuum.

When hot air is blown over a wet food, heat is transferred to the surface, and latent heat of vaporization causes water to evaporate. Water vapour diffuses through boundary film of air and is carried away by moving air as shown in the figure. This creates a region of lower water vapour pressure at the surface of the food and a water vapour pressure gradient is established from the moist interior of the food to the dry air. This gradient provides the 'Driving force' for water removal from the food. Water moves to the surface by following mechanisms.

Liquid movement by capillary forces.

Diffusion of liquids caused by difference in concentration of solutes in different regions of the food.

Diffusion of liquids, which are absorbed in layers at the surface of solid components of the food.

Water vapour diffusion in air spaces with in the food caused by vapour pressure gradients.

Foods are characterized as hygroscopic and non-hygroscopic. Hygroscopic foods are those in which the partial pressure of water vapour varies with the moisture contents. The difference is found by sorption isotherms. When food is placed into a dryer, there is short initial settling down period as surface heats-up to the wet bulb temperature. Drying then commences and, provided that water moves from the interior of the food at the same rate as it evaporates from the surface, the surface remains wet. This is known as constant rate period and continues until a certain critical moisture content is reached. In practice different areas of food surfaces dry out at different rates, and overall, the rate of drying declines gradually during the constant rate period. Thus the critical point is not fixed for a given food and depends on the amount of food in the dryer and the rate of drying. The three characteristics of air that are necessary for successful drying in the constant rate period are:

1. A moderately high dry bulb temperature.
2. A low RH.
3. A high air velocity.

The boundary film of air surrounding the food acts as a barrier to the transfer of both heat and water vapour during drying. The thickness of the film is determined primarily by the air velocity. If air velocity is too low, water vapour leaves the surfaces of the food and increases the humidity of the surrounding air, to cause a reduction in water vapour pressure gradient and rate of drying.

When the moisture content of the food falls below the critical moisture content, the rate of drying slowly decreases until it approaches zero at equilibrium moisture content. This is known as falling rate period. Non-hygroscopic foods have single falling rate period whereas hygroscopic foods have two periods. In the first period the plane of evaporation moves inside the food, water diffused through dry solid to the drying air. It ends when plane of evaporation reaches the center of the food and the partial pressure of water falls below the saturated water vapour pressure. The second period occurs when the partial pressure of water is below the saturated vapour pressure as drying is by desorption.

During falling rate period the rate of water movement from the interior of the food to the surface falls below the rate at which water evaporates to the surrounding air. The surface therefore dries out. This is usually the longest period of drying operation.

The surface temperature of the food remains close to the wet bulb temperature of the drying air until the end of the constant rate period, due to cooling effects of evaporating water. During the falling rate period the amount of water evaporating from the surface gradually decreases but as the same amount of heat being supplied by the air the surface temperature rises until it reaches the dry bulb temperature of the drying air. Most heat damage to food occurs in the falling rate period.

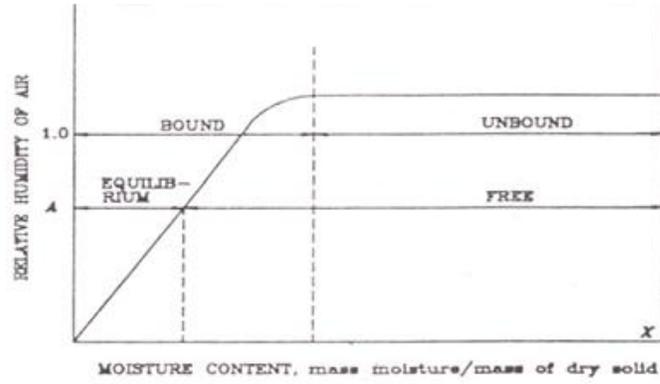


Fig- 26.1: Equilibrium moisture isotherm for a material showing various moisture content

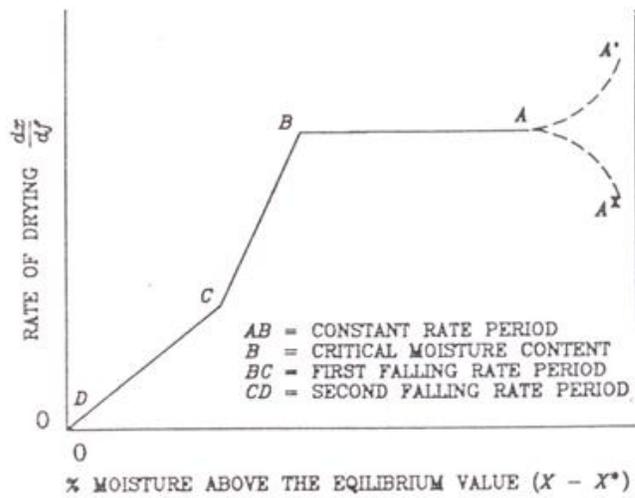


Fig- 26.2: General rate of Drying Curve for solid material

\*\*\*\*\* 😊 \*\*\*\*\*

## Lesson 27.

## Estimation of Drying Time for Food Products

## 27.1. INTRODUCTION

In order to determine the time required to achieve the desired reduction in product moisture content, the rate of moisture removal or drying rate must be predicted. The rate of drying depends on properties of drying air (the dry bulb temperature, RH, and velocity of air and the surface heat transfer coefficient), the properties of food (moisture content, surface to volume ratio and the surface temperature) and rate of moisture loss. The size of the pieces has an important effect on the drying rate in both the constant and falling rate periods. In the constant rate period, smaller pieces have a larger surface area available for evaporation where as in falling rate period smaller pieces have a shorter distance for moisture to travel through the food. Other factors which influence the rate of drying include:

1. The fat content of the food (higher fat contents generally results in slower drying, as water is trapped with in the food).
2. The method of preparation of food (cut pieces lose moisture more quickly than losses through skin.
3. The amount of food placed in a dryer in relation to its size (in a given dryer faster drying is achieved with smaller quantities of food).

For constant rate drying period the following general expression would apply:

$$R_c = \frac{dw}{dt} = \frac{w_0 - w_c}{t_c} \text{-----(1)}$$

Where,

$w_0$  = Initial Moisture Content (kg water / kg dry solid )

$w_c$  = Critical moisture content (kg water / kg dry solid ) and

$t_c$  = Time for constant rate drying.

During falling rate drying, the following analysis would apply.

$$- \frac{dw}{dt} = R_c / w_c (w) \text{ or}$$

$$\frac{w_c}{R_c} \int - \frac{dw}{w} = \int dt$$

Where the limits of integration are between critical moisture content  $w_c$  of end of constant rate drying,  $t_c$  and some desired final moisture content,  $w$ .

On integration:

$t - t_c = wc/Rc \ln(wc/w)$  or time for falling rate becomes

$t_f = wc/Rc \times \ln(wc/w)$  -----(3) and

The total drying times becomes

$t = (w_o - w_c) / Rc + wc/Rc \times \ln(wc/w)$  -----(4)

The above equation indicates that the time for complete drying from some initial moisture content 'wo' to a desirable final moisture content w depends on knowledge of critical moisture content 'wc', the time for constant rate drying tc, and the rate for constant drying Rc.

### Example-27.2

A tunnel dryer is being designed for drying apple halves from initial moisture content of 70 % (wet basis) to final moisture content of 5 % (wet basis). An experimental drying curve for the product indicates that the critical moisture content is 25 % (wet basis) and the time for constant drying is 5 min. Based on the information provided, estimate the total drying time for product.

Solution

Initial product moisture content  $w_o = 0.7 / 0.3 = 2.33$  kg H<sub>2</sub>O / kg solids

Critical moisture content  $w_c = 0.25 / 0.75 = 0.333$  kg H<sub>2</sub>O / kg solids.

Final moisture content  $w = 0.05 / 0.95 = 0.0526$  kg H<sub>2</sub>O / kg solids.

Time for constant rate drying  $t_c = 5$  min

Required:

Total drying time

Solution:

$Rc = (w_o - w_c) / t_c = (2.33 - 0.33) / 5 \text{ min} = 0.4$  kg H<sub>2</sub>O / kg solids min

Final drying time  $t_f = wc/Rc \times \ln(wc/w)$

$= 0.333/0.4 \times \ln(0.333 / 0.0526)$

$= 1.54$  min

Total drying time becomes  $t = 5 + 1.54 = 6.54$  min.

### Example-27.3

Estimate the drying rate and time needed to reduce the moisture content of a 100 μm diameter spherically shaped droplet, falling in a spray dryer from 60 to 35 %. The initial density of the droplet is 900 kg/m<sup>3</sup>. The droplet

is in an air stream such that  $T_a = 200$  oC,  $p = 101.3$  k Pa,  $h = 200$  w/m<sup>2</sup> oC and  $T_{wb} = 60$  oC. Assume that constant rate drying applies over the total drying process and droplet doesn't change in size.

### Solution

Diameter of the particle =  $100 \mu\text{m} = 0.0001$  m

Density of the droplet =  $900$  kg / m<sup>3</sup>

Dry bulb temperature of air =  $60$  oC

Convective heat transfer coefficient  $h = 200$  w/m<sup>2</sup> oC

Pressure in the chamber is  $101.3$  kPa.

The surface of the droplet will be assumed to be at the wet bulb temperature of the air, thus  $T_s = T_{wb} = 60$  oC.

#### Solution:

The surface area of the droplet is  $\pi D^2 = \pi (0.0001)^2 = 3.14 \times 10^{-8}$  m<sup>2</sup>

The volume of the droplet is  $(\pi D^3)/6 = \pi/6 \times (0.0001)^3 = 5.24 \times 10^{-13}$  m<sup>3</sup>

The initial mass of the droplet  $m_i$  is  $\rho \times V = 900 \times 5.24 \times 10^{-13}$   
 $= 4.71 \times 10^{-10}$  kg

applying solids balance:  $m_i \times 0.4 = m_f \times 0.65$

so final mass of the product  $m_f = m_i \times 0.4 / 0.65 = 2.9 \times 10^{-10}$  kg.

$$\text{Drying rate } R = \frac{h A (T_a - T_s)}{L \times 1000}$$

where,

$L$  = latent heat of evaporation corresponding to given pressure in kJ / kg.

$$= \frac{200(3.14 \times 10^{-8})(200 - 60)}{2261.7 \times 1000}$$

$$= 3.89 \times 10^{-10} \text{ kg s}$$

The drying time is given by  $t = (m_i - m_f) / R = (4.71 - 2.9) \times 10^{-10} / 3.89 \times 10^{-10}$   
 $= 0.47$  seconds.



The constant rate period is characterized by a rate of drying independent of moisture content. During this period, the solid is so wet that a continuous film of water exists over the entire drying surface, and this water acts as if solids were not there. As long as the rate of surface evaporation continues, the rate of drying is governed by equation:

$$\frac{dw}{d\theta} = \frac{h \cdot A (t_a - t_s)}{\Delta H_v} = k_a \cdot A \cdot (H_s - H_a)$$

Where,

w = kg of moisture

$\theta$  = time

h = heat transfer coefficient between air and moisture kcal/ kg hr °C

$t_a$  = dry bulb temperature of air, °C

$t_s$  = surface temperature, °C

A = area of heat temperature, m<sup>2</sup>

$\Delta H_v$  = heat of vapourisation at  $t_s$ , kcal/ kg

$K_a$  = mass transfer coefficient (kg/ hr m)

$H_s$  = humidity of saturated air at the surface temperature.

$H_a$  = humidity of air

The constant rate period ends when the migration rate of water from the interior of the surface becomes less than the rate of evaporation from the surface. The period subsequent to the critical point is called 'the falling rate period'. Beyond this point, the surface temperature rises, and the drying rate falls off rapidly. The falling rate period takes a far longer time than the constant rate period, even though the moisture removal may be much less. The drying rate approaches zero at some equilibrium moisture content.

Drying in falling rate period involves two processes:

- a) movement of moisture within the material to the surface
- b) removal of the moisture from the surface.

The method used to estimate drying rates and drying times in the falling rate period depends on whether the solid is porous or non porous. In a non porous material, once there is no superficial moisture, further drying can occur only at a rate governed by diffusion of internal moisture to the surface. In a porous material other mechanism appears, and drying may even take place inside the solid instead of at the surface.



## Lesson 29.

### Diffusion Controlled Falling Rate Period

#### 29.1. INTRODUCTION

The method used to estimate drying rates and drying times in the falling rate period depends on whether the solid is porous or nonporous. In a nonporous material, once there is no superficial moisture, further drying can occur only at a rate governed by diffusion of internal moisture, and drying may even take place inside the solid instead of at the surface. One important point to note is that non-hygroscopic foods have a single falling rate period, whereas hygroscopic foods have two falling rate periods.

#### 29.2. FIRST FALLING RATE PERIOD

The plane of evaporation moves inside the material being dried, and water diffuses through the dry solids to the drying air. It represents a condition whereby the surface is no longer capable of supplying sufficient free moisture to saturate the air in contact with it. Under these conditions, the rate of drying depends very much on the mechanism by which moisture from inside the material is transferred to the surface. This is usually the longest period of a drying operation and in some foods, where the initial moisture content is below the critical moisture content the falling rate period is the only part of the drying curve to be observed.

#### 29.3. SECOND FALLING RATE

At the end of the first falling rate period it may be assumed that the surface is dry and that the plane of separation is moving in to the solid and the vapour reaches the surface by molecular diffusion through the material. The forces controlling the vapour diffusion will determine the final rate of drying, and these will be largely independent of the conditions outside the material. During the falling rate period, the factors that control the rate of drying change. Initially the important factors are similar to those in the constant rate period, but gradually the rate of mass transfer becomes the controlling factor. This depends mostly on the air and the thickness of the food. It is unaffected by both the relative humidity of the air and the velocity of the air. The air temperature is therefore controlled during the falling rate period, whereas the air velocity and temperature are more important in the constant rate period. In practice foods may differ from these idealized drying curves owing to shrinkage, changes in the temperature and rate of moisture diffusion in different parts of the food and changes in the temperature and humidity of the drying air. The surface temperatures of the food remain close to the wet bulb temperature of the drying air until the end of the constant rate period, due to the cooling effect of the evaporating water. During the falling rate period the amount of water evaporating from the surface gradually decreases but as the same amount of heat is being supplied by the air the surface temperature rises until it reaches the dry bulb temperature of the drying air. Most heat damage to the food therefore occurs during falling rate period.

#### Example 29.4

A 50  $\mu$ m diameter droplet of a liquid food is being dried in a spray. Experiments have indicated that the constant rate drying period for this type of situation requires 2 s. If the product entering the spray dryer has 10 % total solids

and critical moisture content is 35 % (wet basis), determine the moisture removal rate during constant rate drying. Assume droplet size does not change during the drying and the product density is 1050 kg / m<sup>3</sup>

**Solution**

Droplet diameter = 50μ

Drying period = 2s

Initial moisture content  $w_o = 90 \% = 0.9/0.1 = 9 \text{ kg H}_2\text{O} / \text{kg solid}$ .

Critical moisture content  $w_c = 35 \% = 0.35/0.65 = 0.54$

$\rho = 1050 \text{ kg} / \text{m}^3$

Solution:

Initial volume of the droplet =  $(\pi D^3)/6 = (\pi)/6 \times (0.00005)^3 = 6.545 \times 10^{-14} \text{ m}^3$

Initial mass of the product  $m_i = \rho V = 6.87 \times 10^{-11} \text{ kg}$ .

Final mass of the product  $m_f = m_i \times 0.1 / 0.65 = 1.057 \times 10^{-11} \text{ kg}$

Moisture removed =  $m_i - m_f = 5.813 \times 10^{-11} \text{ kg}$ .

Moisture removal rate =  $m_i - m_f / \text{drying period} = 2.9065 \times 10^{-11} \text{ kg/s}$

$$= 2.9065 \times 10^{-11} / 0.687 \times 10^{-11} = 4.23 \text{ kg H}_2\text{O} / \text{kg solid s}$$

Second method:

$w_o = 90 \% = 0.9 / 0.1 = 9 \text{ kg H}_2\text{O} / \text{kg solid}$ .

$w_c = 35 \% = 0.35/0.65 = 0.5385 \text{ kg H}_2\text{O} / \text{kg solid}$ .

Drying rate =  $w_o - w_c / t = 4.23 \text{ kg H}_2\text{O} / \text{kg solid s}$ .

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## Lesson 30.

## Heat and Mass Balance of Continuous Dryers

## 30.1. DEHYDRATION SYSTEM DESIGN

The design of dehydration systems involves several considerations. The parameters that have a direct influence on capacity of a system include the quality and characteristics of air available for drying along with the drying time required for individual pieces of the product being dried.

Mass and Energy Balance:

By application of mass and energy balance analysis to an entire dehydration system several parameters influencing design are accounted for.

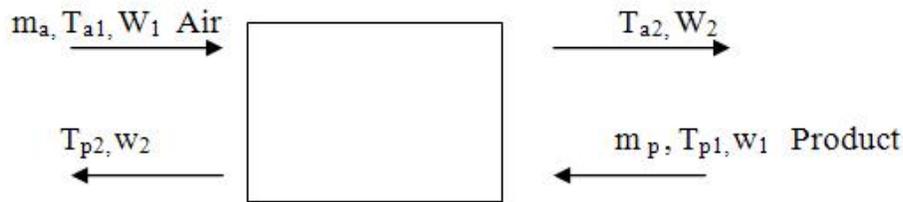


Fig. 30.1 Mass And Energy Balance For Dehydration System

Moisture balance on the system gives:

$$m_a W_1 + m_p w_1 = m_a W_2 + m_p w_2$$

Where,

$m_a$  = Air flow rate (kg dry air / h),  $m_p$  = Product flow rate (kg dry solids / h),  $W$  = Absolute humidity (kg water / kg dry air) and  $w$  = Product moisture content (kg water / kg solid)  $T_a$  = Temperature of air (°C)  $T_p$  = Temperature of product (°C) and 1 is inlet condition; and 2 is the outlet condition.

Energy balance for the system gives:

$$m_a H_{a1} + m_p H_{p1} = m_a H_{a2} + m_p H_{p2} + Q_l$$

Where,  $Q_l$  = Heat losses from dehydration system,  $H_a$  = Heat content of air (kJ / kg dry air) and  $H_p$  = Heat content of product (kJ / kg dry solids).

Considering 0 °C as the reference temperature the expressions for heat content of air and product are :

$$H_a = 1.005 T_a + W (2500.5 + 1.884 T_a)$$

$$H_p = C_{pp} T_p + w C_{pw} T_p$$

Where,

$C_{pp}$  – Specific heat of product solids (kJ /kg K)

$C_{pw}$  – Specific heat of water (kJ /kg K),

$T_p$  – Product temperature.

Using these equations, the quality of air required for drying an established amount of product over known moisture content range can be determined. In addition, for known inlet conditions of air, the moisture characteristics of air at the system outlet can be established.

The rate of moisture removal by a drum dryer is essentially a constant rate of water evaporation as the product is continuously feed between the drums and the dried product is removed. The equation governing the rate of evaporation in a drum dryer is:

$$\frac{dw}{d\theta} = \frac{UA\Delta t_m}{\Delta h_v}$$

Where,  $U$  = overall heat transfer coefficient

$A$  = effective surface area of drum

$\Delta t_m$  = Temp. of steam inside – Temp. of evaporation at the outer surface =  $t_s - t_a$

$\Delta h_v$  = latent heat of vaporization.

The overall coefficient is from 1160 to 2100 W/ m<sup>2</sup> K under optimum condition, although it may be only 1/10 of these values when conditions are adversed. Since the thickness of drum wall is small compared to the diameter of the drum, the area  $A$  can be regarded simply as the outer surface area of the drum. The  $U$  depends on  $h_s$ ,  $k$  and  $h_p$  and other coefficients.

$$U = \frac{1}{\frac{1}{h_s} + \frac{x}{k} + \frac{1}{h_p} + \frac{1}{(h_c + h_r + h_e)}}$$

Where,  $h_s$  : equivalent film coefficient of steam (W/ m<sup>2</sup> K)

$x$ : thickness of metal (m)

$k$  : thermal conductivity of metal (W/ m K)

$h_p$  : equivalent film coefficient of product (W/ m<sup>2</sup> K)

$h_c$  : convection coefficient (W/ m<sup>2</sup> K)

$h_r$ : radiation coefficient (W/ m<sup>2</sup> K)

$h_e$  : evaporation film coefficient (W/ m<sup>2</sup> K)

The factor having the greatest effect on  $U$  is the condition of the liquid film and the drum speed. Drying rates for drum dryers can be extremely high when thin film of low viscosity is evaporated, and it is thus permissible to use high temperature. In addition to assuring the adequate heat transfer the drying system must provide for removal of water vapour. If the speed of a particular drum is measured, then the  $U$  value and the moisture content of the product will be increased, if the conditions are unchanged. The overall thermal efficiency of drum dryer is 35 – 80

% The moisture content  $x$  of a milk product containing  $m_w$  amount of water and  $m_s$  amount of dry matter including fat is given by:

$$\text{(wet basis)}$$

$$x = \frac{m_w}{(m_w + m_s)}$$

The proportion of dry matter (TS) is given by :

$$T_s = \frac{m_s}{(m_w + m_s)} = 1 - x$$

During the evaporation of a product from the original moisture content  $x_0$  containing amount of water  $m_{w0}$  to a final moisture content  $x$  containing an amount of water  $m_w$ , the following amount of water is removed.

$$m_{w0} - m_w = \left[ \frac{x_0}{1 - x_0} - \frac{x}{1 - x} \right] m_s$$

Calculated as a fraction of the water originally present, the following is obtained:

$$\frac{m_{w0} - m_w}{m_{w0}} = 1 - \left[ \frac{x(1 - x_0)}{x_0(1 - x)} \right]$$

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**Lesson 31.****Fixed Tray Dehydration****31.1. INTRODUCTION**

The design of industrial dryers is based largely on empirical knowledge, while modeling and simulation can generalize and improve the design procedure. The diversity of drying processes and dried products has resulted in a multitude of drying equipment, specific for each class of products. Thus, selection of a particular dryer becomes as important as the engineering design of the equipment. In recent approach to the design of convective dryers, the thermo physical, transport, and equilibrium (isotherms) properties of the material are very important in specifying the proper dryer and drying conditions. Mechanical properties of solids and solid particles are important in handling and processing of the various materials. Drying rates (kinetics of moisture removal) are useful for preliminary estimation of the drying time. The estimated time is taken as the approximate mean residence time in the dryer, an important parameter in dryer design. The specifications of an industrial dryer should be listed in an equipment specification form, and should include the properties of the wet and dried material, the temperature sensitivity and water activity of the product, the capacity and evaporation duty (kg/h), the energy supply and cost, the environmental impact, and the relationship to the other plant operations. There are about 40 classes and over 100 subclasses of dryers, which are classified by different methods, based on type of operation (batch, continuous), type of feed (liquid, suspension, paste, granules, fibrous solids, porous solids, dense solids, and sheets), heating method (convection, contact, radiation, dielectric), product sensitivity (vacuum, low temperature). The size of dryers can be small (up to 50 kg/h), medium (50-1000 kg/h), or large (above 1000 kg/h). The capacity of the dryers can be expressed also as kilograms of water evaporated per unit surface and unit time, which is very high in rotary dryers (about 50 kg/m<sup>2</sup>h) and low in tray dryers (about 1 kg/m<sup>2</sup>h). The cost of drying is an important factor in dryer design, especially for large volume products of relatively low value. Energy (fuel) is the major cost in drying operations (62%), followed by capital and labor costs.

The major energy use is for the evaporation of water (moisture), which varies considerably for the different dryers, e.g., from 3 MJ/kg water (spray dryers) to 6 MJ/kg (tray dryers). The energy efficiency of the dryers (ratio of the heat of evaporation to the heat input to the dryer) depends strongly on the type of dryer. It is higher in contact than in convective drying, e.g., (40-80%) versus (20-40%). Rotary dryers are more efficient than tray, fluid bed, and spray dryers. Four categories of industrial dryer problems have been identified by Kemp and Gardiner: a) Underperforming (corrected by performing material and energy balances, by drying kinetics, and by applying moisture equilibria); b) materials handling; c) product quality; and d) mechanical breakdown.



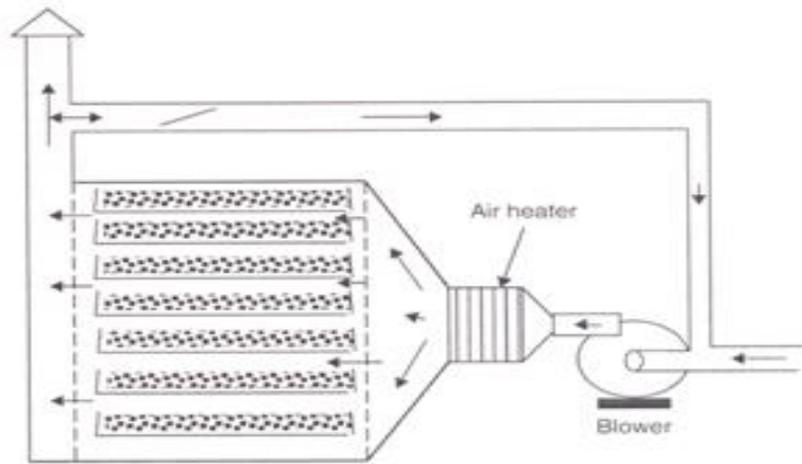
## Lesson 32.

### Cabinet drying

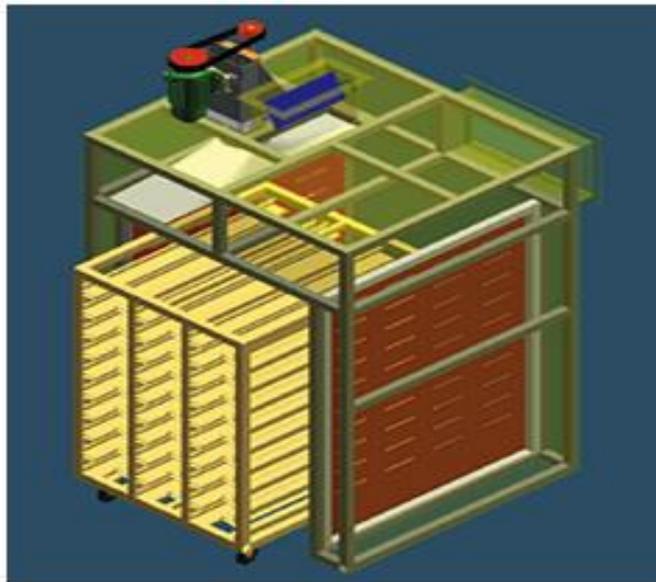
#### 32.1. INTRODUCTION

Cabinet/tray dryers are used for batch drying of solid foods at small to moderate scale (say, 2000 to 20 000 kg per day). They are inexpensive and simple to construct. Cabinet dryers consist of a closed compartment in which trays containing the food to be dried are placed( Figure 32..1). The trays rest on shelves with adequate spacing between them. Heated dry air circulates between the shelves. Very often, tray bottoms are slotted or perforated, in order to provide some air flow also through the trays. the moisture content of the material, depends on its position on the tray. The material located closest to the entrance of dry air has the lowest moisture content. In order to secure more uniform drying, the direction of air flow may be reversed or the trays may be rotated periodically. The cabinet is usually equipped with movable baffles, adjusted so as to have uniform distribution of the drying air throughout the cabinet. Cabinet driers are frequently found in rural installations where they are used for drying fruits (grapes, dates, apples), vegetables (onion, cabbage) and herbs (parsley, basil, mint, dill). Air inlet temperatures are usually in the range of 60–80°C. Air velocity is a few m.s<sup>-1</sup> and must be adjusted according to the size, shape and density of the food particles so as to avoid entrainment of dry particles with the wind. Depending on the product and the conditions, the duration of a batch is typically 2 to 10 hours. Most cabinet dryers feature means for adjustable recirculation of the air. The rate of recirculation is increased as drying progresses, when the air exiting the cabinet is warmer and less humid. Recirculation results in considerable saving in energy cost.

This is a multi-purpose, batch-operated hot air drier. It consists of an insulated cabinet, equipped with a fan, an air heater and space occupied by trays of food. In Cabinet dryers, food may be loaded on trays or pans in comparatively thin layers up to a few centimetres. Fresh air enters the cabinet by the fan through the heater coils, and is then blown across the food trays to exhaust. Here, the air is heated by the indirect method. Screens filter out any dust that may be in the air. The air passes across and between the trays in some designs, whereas some other designs have perforated trays and the air may be directed up through these. The air is exhausted to the atmosphere after one pass rather than being re-circulated within the system. Re-circulation is used to conserve heat energy by reusing part of the warm air. In re-circulating designs, moist air, after evaporating water from the food, may have to be dried before being re-circulated to prevent saturation and slowing down of subsequent drying. In such case, this air could be condensed out by passing the moist air over cold plates or coils. But when the exhaust air is not dried for re-circulation, then the exhaust vent should not be close to fresh air intake area, otherwise the moist exhaust air will be drawn back through the drier and drying efficiency will be lost. Cabinet driers are usually for small operations. They are comparatively inexpensive and easy to set in terms of drying conditions. They may run up to 25 trays high and operate with air temperatures of about 95°C dry bulb and with air velocities of about 2.5-5m/sec across the trays. They commonly are used to dry fruit and vegetable pieces, and depending on the food and the desired final moisture, drying time may be of the order of 10 or even 20 hours.



**Fig- 32.1: Cabinet Dryer (a)**



**Fig- 32.1: Cabinet Dryer (b)**

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## Lesson 32.

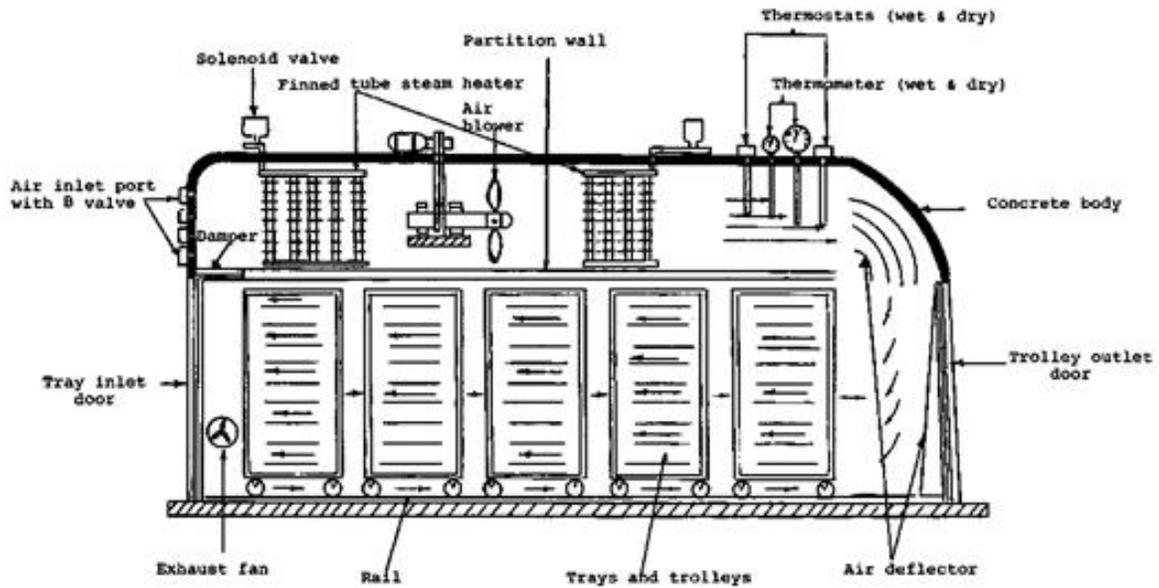
### Tunnel Drying

#### 33.1. INTRODUCTION

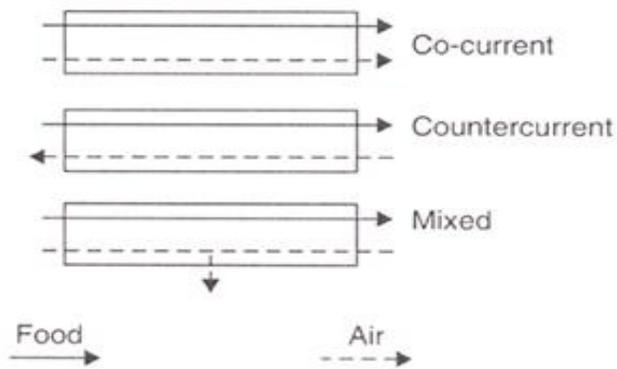
These type of driers consist of long insulated tunnel either square or rectangular. Tray loads of the wet material are assembled on trolleys which enter the tunnel at one end. The trolleys travel the length of the tunnel and exit at the other end. Heated air also flows through the tunnel, passing between the trays of food and/or through perforated trays and the layers of food. The air may flow parallel to and in the same direction as the trolleys. This is known as concurrent tunnel. Other designs featuring counter current, co-current and cross flow of air are available. For large operations, tunnel driers with elongated cabinets, through which carts pass, are used. A main construction feature by which tunnel driers differ has to do with the direction of airflow relative to tray movement. In a counter flow, or countercurrent pattern the hottest and driest air contacts the nearly dry product, whereas the initial drying of entering carts gets cooler, moister air that has cooled and picked up moisture going through the tunnel. This means that the initial temperature and moisture gradient will not be as great, and the product is less likely to undergo case hardening or other surface shrinkage, leaving wet centers. Further, lower final moisture can be reached because the driest product encounters the driest air. In contrast, co-current flow tunnels have the incoming trays and incoming hottest driest air travelling in the same direction. In this case, rapid initial drying and slow final drying can cause case hardening and internal splits and porosity at centers, which sometimes is desirable in special products.

Tunnel dryers consist of long tunnels through which trucks carrying stacks of trays travel with or against a stream of drying air ( Figure 33.1). The material to be dried is evenly spread on the trays. Typical tray loading for wet vegetables is in the order of 10–30 kg per m<sup>2</sup>. As one truck with wet material is introduced into the tunnel at one end, another truck, carrying dehydrated product, exits at the other end. Depending on the size of the trucks and the tunnel, the trucks are moved manually or mechanically, e.g. with the help of chains. With respect to the relative direction of movement of the air and the trucks, tunnel dryers operate in co-current, countercurrent or mixed current fashion.

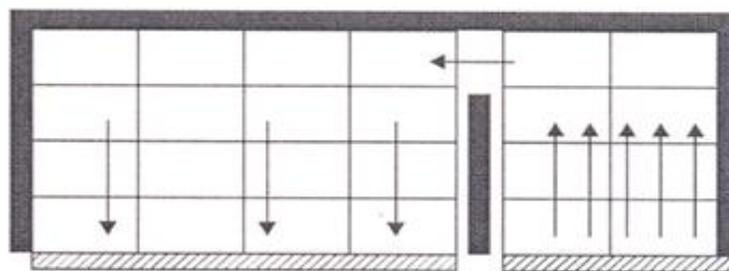
In the case of the co-current tunnel, air with the highest temperature and lowest humidity meets the food with the highest humidity and lowest temperature. This provides the highest 'driving force' for drying and therefore the most rapid rate of water transfer at the entrance to the tunnel. If the feed material is sufficiently humid, its temperature remains low despite the contact with hot air. The 'driving force', however, diminishes as the food travels towards the exit. The air at the exit end of the tunnel is the most humid and the coolest. Consequently, the final residual moisture content of the product may not be as low as desired. The contrary occurs in the case of counter current tunnels. The starting rate of drying is lower but it is possible to dehydrate the product to the lower final moisture content. The mixed flow, central exhaust tunnel functions as two tunnels in series. Its first portion is co-current and provides the desired high initial drying rate. Its last portion is countercurrent and gives the desired finishing effect. Unlike cabinet drying, tunnel drying provides the possibility of exposing the product to a changing profile of external conditions. In addition to air temperature and humidity, it is possible to vary air velocity by reducing the cross sectional area normal to the direction of flow (Figure 32.2).



**Fig- 33.1: Tunnel Dryer**

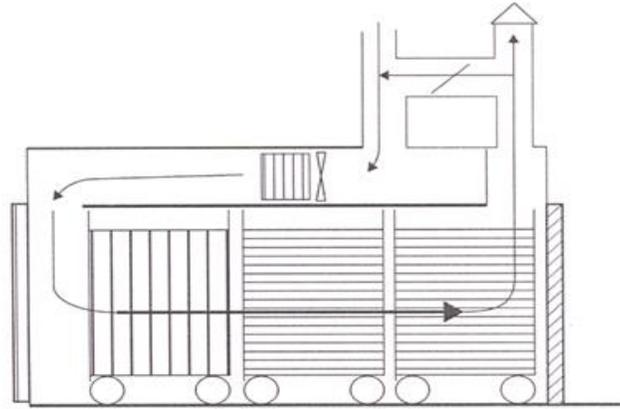


Flow patterns in tunnel dryers



Two-stage tunnel dryer

**Fig- 33.2: Two Stage Tunnel Dryer**



**Fig- 33.3:** Short Tunnel Dryer



**Fig- 33.4 :**Industrial Tunnel Dryer

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**Lesson 34.****Problems on Drying****Example 34.1**

Find out the evaporation rate in a drum dryer for given data: steam temperature = 150 °C , vapourisation temperature of milk 103 °C, overall heat transfer coefficient 1.3 kw / m<sup>2</sup> -K, drum diameter = 60 cm, length of the drum = 100 cm, latent heat of vapourisation = 2261 kJ / kg. The product is scraped at  $\frac{3}{4}$  of a revolution of the drum. Assume that there are no heat losses to the surroundings.

Solution

heat transfer area,  $A = 1 \times 0.6 \times \pi \times \frac{3}{4} = 1.413 \text{ m}^2$

$dw / d\phi = 1.3 \times 1.413 (150-103) / 2261$

= 0.038 kg/s

= 137.5 kg/h

**Example 34.2**

A drum dryer is designed for drying a product from an initial TS of 12 % and a final moisture content of 4 %. An average temperature difference between the roller surface and the product of 65 °C will be used and the overall heat transfer coefficient is 1.74 kw / m<sup>2</sup> -K. Determine the surface area of the roller required to provide a production rate of 50 kg product / hr.

Solution : Basis :1 kg of product  $P = F - V$

F : amount of feed / kg of product

V : amount of vapour / kg of product.

Solid balance:

$0.96 \times 1 = 0.12 F$

$F = 8 \text{ kg} ; V = 7 \text{ kg}$

To obtain 50 kg of product,  $F = 50 \times 8 = 400 \text{ kg/hr}$

Vapour removed =  $50 \times 7 = 350 \text{ kg/hr}$

$$\text{Using equation: } \frac{dw}{d\theta} = \frac{h \cdot A (t_a - t_s)}{\Delta H_v}$$

$$350/3600 = 1.74 \times A \times 65 / 2261$$

$$\text{Thus, } A = 1.94 \text{ m}^2$$

The effective surface area needed for drying is 1.94 m<sup>2</sup>. Assuming that about ¼ of the surface area would not be used. Then the total surface area required would be : 1.94 x 4/3 = 2.586 m<sup>2</sup>. If the length of the drum is taken as 1.37 m, then the diameter of the drum d will be:

$$\pi d \times 1.37 = 2.586$$

$$\text{Thus, } d = 0.6 \text{ m}$$

### Example 34.3

Milk of 18.5 % TS is dried to 3.8 % moisture on a drum dryer at a rate of 10.5 kg of dried product / hr. The diameter of the drum is 60 cm and length 90 cm and the product is scrapped at ½ of a revolution. The steam temperature is 160 °C and vaporization point of the moisture is 104 °C. Find out the overall heat transfer coefficient.

Solution:

Basis: 1 kg of milk

$$V + P = 1 \text{ (material balance)}$$

Where, V = amount of water evaporated

P = amount of the product

$$0.185 + 1 = 0.962 \text{ (material balance)}$$

$$\text{Thus, } V = 0.808 \text{ kg and } P = 0.192 \text{ kg / kg wt.}$$

Where, P = 10.5 kg, then,

$$dw/d\theta = 10.5 \times 0.808 / 0.192 = 44.18 \text{ kg / hr}$$

$$\text{The heat transfer area, } A = 0.9 \times 0.6 \times \pi/2 = 0.84$$

$$\frac{dw}{d\theta} = \frac{UA\Delta t_m}{\Delta h_v}$$

$$44.18 = U \times 0.847 (160 - 104) / 540$$

$$\text{Thus, } U = 0.5029 \text{ kcal / hr m}^2 \text{ }^\circ\text{C}$$

**Example 34.4**

500 kg of milk containing 40 % TS is dried in a spray dryer to a powder containing 3 % moisture. Air temperatures at the entry and exit of air heater are 30 °C and 150 °C respectively. Feed and product temperatures at the entry and the exit of spray dryer are 20 °C and 54°C respectively. Air temperatures at the entry and the exit of spray dryer are 150 °C and 90 °C respectively. Calculate ,

(a) the amount of air required (m<sup>3</sup>) to dry the milk. (b) thermal efficiency of air drying (c) the amount of steam required at 7.2 kg/cm<sup>2</sup> pressure to heat the air if the efficiency of the air heater is 80 % (d) the amount of steam required/ kg of water evaporated, and (e) the overall thermal efficiency if the radiation loss in the air heater is 10 %,

Solution:

Basis: 1 kg of milk

$V + P = 1$  (material balance)

Where, V = amount of water evaporated

P = amount of the product

$0.4 \times 1 = 0.97 P$  (material balance)

Thus,  $P = 0.413$  kg and  $V = 0.587$  kg / kg wt.

The amount of dried product from 500 kg milk =  $500 \times 0.413 = 206.5$  kg

Total amount of water removed =  $500 \times 0.587 = 293.5$  kg

Heat supplied to milk = sensible heat to raise the milk temperature from 20 °C to 54 °C + latent heat of vapourisation.

The latent heat of vapourisation corresponding to a saturation temperature of 90 °C is about 2282 kJ/kg

Heat supplied to dry 500 kg milk =  $500 (54 - 20) \times 3.894 + (293.5 \times 2282)$

= 735963.5 kJ

The specific heat of air can be taken as 1.005 kJ/ kg K and the mass density of air at the mean temperature i.e. 120 °C is 0.9 kg/m<sup>3</sup>

Using eq.:

$$q = m_a c_{pa}(T_{a1} - T_{a2})$$

$$735963.5 = W \times 1.005 (150 - 90)$$

Thus,  $W = 12205 \text{ kg}$

The amount of air required to dry the milk =  $12205 \text{ kg/h}$

Or

$$= 12205 / 0.9$$

$$= 13561 \text{ m}^3 / \text{h}$$

**(b)**

The temperature of hot air should have been brought down to  $54^\circ\text{C}$  i.e. equal to the temperature of dried milk, but in actual the air outlet temperature is  $90^\circ\text{C}$ .

$$\text{The maximum amount of heat which can be given up by the hot air} = m_a c_{pa}(T_{a2} - T_{p2})$$

$$= 12205 \times 1.005 \times (150 - 54) = 1177541.6 \text{ kJ}$$

But the actual amount of heat which is used to dry  $500 \text{ kg}$  milk =  $735963.5 \text{ kJ}$

The thermal efficiency of air drying =  $735963.5 / 1177541.6 = 62.5 \%$

**(c)**

The amount of air required in  $\text{kg} = 12205 \text{ kg}$

Heat taken by air in the air heating section =  $12205 \times 1.005 (150 - 30)$

$$= 1471923 \text{ kJ}$$

At  $7.2 \text{ kg/cm}^2$  absolute pressure, the latent heat of steam about  $2065.5 \text{ kcal/kg}$

The amount of steam required at  $80 \%$  heating efficiency =

$$1471923 / (2065.5 \times 0.8) = 890.7 \text{ kg}$$

**(d)**

The amount of steam required per  $\text{kg}$  of water evaporated =  $896.7 / 293.5 = 3.05 \text{ kg}$

**(e)**

Using eq.:

$$\text{Thermal Efficiency} = \frac{\left(1 - \frac{R}{100}\right)(T_{a1} - T_{a2})}{(T_{h0} - T_{hi})}$$

Where,

R = % radiation heat loss

Thi = Air temperature at the inlet of air heater

Tho = Air temperature at the outlet of air heater

Th0 = Tai

$$= (1 - 0.1)(150 - 90) / (150 - 30) = 0.45$$

Example 34.5

1000 kg/hr of dried product (4 %moisture) is produced in a spray dryer. The atmospheric air at 30 °C and 40 % RH is heated to 190 °C and it is exhausted at 80 °C . the concentrated milk having 45 % TS by weight. Feed temperature of concentrated milk is 30 °C. dried product comes out at 50°C. heat losses from the dryer is 104675 kJ/h. Find out the air flow rate required.

Solution:

Based on enthalpy and moisture balance:

ma = Mass flow rate of air (kg dry air/h)

ms = Mass flow rate of solid (kg dry solid/h)

Ta1 = temperature of air at the inlet = 190 °C

Ta2 = temperature of air at the exit = 80 °C

Tp1 = temperature of feed at the inlet = 30 °C

Tp2 = temperature of product at the exit = 50 °C

Ha1 , Ha2 are enthalpy content of air at the inlet and exit ( kJ/ kg dry air)

Hp1 , Hp2 are enthalpy content of feed and product ( kJ/ kg dry air)

W1 , W2 are moisture content in air at the entry and exit (kg moisture/ kg dry air)

w1 , w2 = moisture content in feed and product (kg moisture/ kg dry solid)

C<sub>pp</sub> = specific heat of dry solids

C<sub>pw</sub> = specific heat of water

From psyc. Chart:

Air contains 0.011 kg water/kg of dry air = W1

Assuming dry milk solids have specific heat of 2.32 kJ / kg

Feed rate = 1000 x 0.96 x 100 / 45 = 2133 kg / hr

$$m_s = 1000 \times 0.96 = 960 \text{ kg solid/h}$$

$$w_1 = 53745 \text{ moisture/ solid concentration of milk}$$

$$= 1.22 \text{ kg of water /kg of dry solids}$$

$$w_2 = 4/96 = 0.042 \text{ kg of water / kg of dry solids.}$$

Enthalpy:

$$H_{a1} = 1.005 T_{a1} + W_1 (2500.5 + 1.884 T_{a1})$$

$$= 1.005 \times 190 + 0.011 (2500.5 + 1.884 \times 190)$$

$$= 222.39 \text{ kJ / kg air}$$

$$H_{a2} = 1.005 T_{a2} + W_2 (2500.5 + 1.884 T_{a2})$$

$$= 1.005 \times 80 + W_2 (2500.5 + 1.884 \times 80)$$

$$= 80.4 + 2651.22 W_2$$

$$= 222.39 \text{ kJ / kg air}$$

$$H_{p1} = C_{pp} T_{p1} + w_1 C_{pw} T_{p1}$$

$$= 2.32 \times 30 + 1.22 \times 4.187 \times 30$$

$$= 222.84 \text{ kJ/ kg dry solid}$$

$$H_{p2} = C_{pp} T_{p2} + w_2 C_{pw} T_{p2}$$

$$= 2.32 \times 50 + 0.042 \times 4.187 \times 50$$

$$= 124.8 \text{ kJ/ kg dry solid}$$

Enthalpy balance:

Enthalpy in system = Enthalpy out system

$$m_a H_{a1} + m_s H_{p1} = m_a H_{a2} + m_s H_{p2} + Q_l$$

$$m_a \times 222.39 + 960 \times 222.84 = m_a (80.4 + 2651.22 W_2) + 960 \times 124.8 + 104675$$

$$142 m_a - 2651.22 m_a W_2 = 224483 \text{ ----- eq. (1)}$$

Moisture balance:

Moisture lost by product = moisture gained by air

$$m_s(w_1 - w_2) = m_a (W_2 - W_1)$$

$$960 (1.22 - 0.042) = m_a (W_2 - 0.011)$$

$$m_a(W_2 - 0.011) = 1130.88 \text{ ----- eq. (2)}$$

By solving both equations:

$$m_a = 26663 \text{ kg/hr}$$

$$W_1 = 0.011$$

From eq.(2)

$$W_2 = (1130.88 / m_a) + 0.011$$

$$W_2 = 0.0534$$

Humidity of air exhaust is 0.0534 kg/kg dry air

Example 34.6

From the following data given for the spray dryer, determine air flow rate and steam consumption.

TS in feed = 42%

TS in product = 97%

Powder production rate 2000 kg/h

Specific humidity of outdoor air (32°C, 40 % RH) = 0.0119 kg water/ kg of dry air

Specific humidity of outlet air (90°C) = 0.052 kg water/ kg of dry air

Spray dryer inlet air temp = 200 °C

Efficiency of steam air heater = 80 %

Steam pressure at the air heater = 21 kg/cm<sup>2</sup>

Condensate is discharged at saturation temp.

Specific heat of air  $C_{pa} = 1.005 \text{ kJ/kg}$

Solution :

$$w_1 = 58 / 42 = 1.380 \text{ kg of water/ kg of dry solid}$$

$$w_2 = 3 / 97 = 0.0309 \text{ kg of water/ kg of dry solid}$$

$C_p$  = specific heat of air = 0.24 kcal/ kg of dry air

$t_{ho}$  = outlet air temperature of air at the air heater = 200 °C =  $t_{a1}$

$t_{hi}$  = inlet air temperature of air at the air heater = 32 °C

$H_s$  = enthalpy of steam at inlet of heater = 2800 kJ / kg

$H_c$  = enthalpy of condensate at the outlet = 895.6 kJ / kg

$\eta$  = efficiency = 80%

moisture balance:

moisture lost by the product = moisture gained by the air

thus,  $2(970)(1.38 - 0.0309) = m_a (0.052 - 0.0119)$

thus,  $m_a = 65268.18$  kg/h

steam consumption (kg/h) =  $m_a \cdot C_{pa} \cdot (t_{hi} - t_{ho}) / [(H_s - H_c) \cdot \eta]$

=  $65268.18 \times 1.005 (200-32) \times 0.8 / (2800-895.6)$

= 7233 kg/h

= 7233 kg/h (by putting values)

Total water evaporated in dryer / h = total quantity of concentrated milk – total powder

=  $((2000 \times 0.97) / 0.58) - 2000$

= 3344.83-2000

=1344.83 kg/h

Specific steam consumption = kg of steam / kg of H<sub>2</sub>O evaporated

=  $7233 / 1344.83$

= 5.378 kg steam / kg water evaporation

Example 34.7

From the following data given for a spray dryer determine hot air flow rate and humidity of air at the exit of the dryer and quantity of fuel oil requirement for the air heater.

TS in feed = 41%

Moisture content in product = 3.5 %

Temp. of feed = 45 °C

Temp. of product at the exit of dryer = 60 °C

Feed rate = 50000 kg / hr

Specific humidity of inlet air (33°C, 45 % RH) = 0.14 kg water/ kg of dry air

Inlet and exit air temperatures are 210 °C and 85 °C resp.

Specific heat of feed = 2.32 kJ/kg

Heat losses from the dryer is  $2 \times 10^5$  kJ/h

The calorific value of oil = 42000 kJ/kg,

Heat transfer efficiency in the air heater = 85%

Solution:

$$w_1 = 59 / 41 = 1.439 \text{ kg of water/ kg of dry solid}$$

$$w_2 = 3.5 / 96.5 = 0.03626 \text{ kg of water/ kg of dry solid}$$

$$C_{pp} = 2.32 \text{ kJ/kg}$$

$$T_{a1} = 210 \text{ }^\circ\text{C}, T_{a2} = 85 \text{ }^\circ\text{C}$$

$$T_{p1} = 45 \text{ }^\circ\text{C}, T_{p2} = 60 \text{ }^\circ\text{C}$$

$$Q_l = 2 \times 10^5 \text{ kJ/h}$$

$$\text{Quantity of feed } m_s = (5000 \times 0.965) = 4825 \text{ kg/h}$$

$$H_{a1} = 1.005 T_{a1} + W_1 (2500.5 + 1.884 T_{a1})$$

$$= 1.005 \times 210 + 0.014 (2500.5 + 1.884 \times 210)$$

$$= 251.6 \text{ kJ / kg air}$$

$$H_{a2} = 1.005 T_{a2} + W_2 (2500.5 + 1.884 T_{a2})$$

$$= 1.005 \times 85 + W_2 (2500.5 + 1.884 \times 85)$$

$$= 85.42 + 2660.64 W_2$$

$$H_{p1} = C_{pp} T_{p1} + w_1 C_{pw} T_{p1}$$

$$= 2.32 \times 45 + 1.22 \times 4.187 \times 45$$

$$= 375.53 \text{ kJ/ kg dry solid}$$

$$H_{p2} = C_{pp} T_{p2} + w_2 C_{pw} T_{p2}$$

$$= 2.32 \times 60 + 0.03626 \times 4.187 \times 60$$

$$= 148.31 \text{ kJ/ kg dry solid}$$

$$m_a H_{a1} + m_s H_{p1} = m_a H_{a2} + m_s H_{p2} + Q_l$$

$$m_a \times 256.1 + 4825 \times 375.53 = m_a (85.42 + 2600.64 W_2) + 4825 \times 148.31 + 2 \times 10^5$$

$$\text{or } 170.68 m_a - 2660.64 m_a W_2$$

$$= 915595.75 \text{ ----- eq (1)}$$

$$m_s(w_1 - w_2) = m_a (W_2 - W_1)$$

$$\text{or } 4825(1.439 - 0.03626) = m_a (W_2 - 0.014)$$

$$\text{or } m_a (W_2 - 0.014) = 6768.22 \text{ ----- eq(2)}$$

by solving eq (1) and (2)

$$m_a = 141821.56 \text{ kg/h, } W_2 = 0.0617 \text{ kg/kg dry air}$$

$$\text{thus total energy requirement / h} = m_a \times C_{pp} (210 - 33)$$

$$= 25227928 \text{ kJ/h}$$

$$\text{Or } 7007.75 \text{ kW}$$

$$\text{Quantity of oil requirement} = (42000 \times 0.85) / 35700 \text{ kg/h} = 706.66 \text{ kg/h}$$

Example 34. 8

Find out the steam consumption of roller dryer for the given data:

$$\text{Water evaporation rate} = 25 \text{ kg H}_2\text{O / hr} \cdot \text{m}^2$$

$$\text{Initial feed concentration} = 30 \% \text{ TS, Field temperature } 45^\circ\text{C}$$

$$\text{Final product TS} = 96 \%$$

$$\text{Drum diameter} = 1.5 \text{ m, drum length} = 2.5 \text{ m}$$

Solution:

$$\text{Total surface area} = 2\pi r l = 11.78 \text{ m}^2$$

$$\text{Total water evaporated /hr} = 25 \times 11.78 = 294.52 \text{ kg H}_2\text{O}$$

$$\text{For 100 kg of feed, feed with TS} = 30\% \text{ and final TS} = 96 \%;$$

$$\text{Total water evaporated} = \text{Feed} - \text{product}$$

$$= 100 - (100 \times 0.3) / 0.93 = 68.75 \text{ kg/hr}$$

$$\text{For 294.52 kg water evaporated, kg of powder} = 31.25 \times 294.52 / 68.75$$

$$= 133.87 \text{ kg/hr --- (1)}$$

$$\text{Feed rate, } F = \text{kg water evaporation} / \text{kg product} = 428.39 \text{ kg/hr}$$

$$\text{Heat supplied by steam} = \text{heat gained by the product}$$

$$\text{Thus, steam quantity} \times \text{latent heat of steam at } 2 \text{ kg/cm}^2$$

$$= m \cdot s \cdot dt + (\text{heat of vapourisation} \times \text{Quantity of vapour})$$

$$M_s \times 2204.04 = 428.39 \times 2.32 \times (100 - 45) + 294.52 \times 2261$$

$$M_s = 326.94 \text{ kg/hr}$$

$$\text{Steam consumption} = 326.94 \text{ kg steam / hr}$$

(it is assumed that condensate is coming out at saturation temperature)

Thus, specific steam consumption

$$= (\text{kg of steam / hr}) / (\text{kg of water evaporated/hr})$$

$$= 326.93 / 294.52 = 1.11 \text{ kg of steam / kg of water evaporated}$$

Questions:

Solve the following examples

Example-1

Skim milk of 89% water content is evaporated to 54% moisture content. Find out the % water evaporated based on original water content.

Example-2

Find out the evaporation rate in a drum dryer when steam temperature is 145 °C, vapourisation temperature of milk is 104 °C, overall heat transfer coefficient 1300 kcal/hr m<sup>2</sup> °C, drum diameter = 50 cm, drum length 90 cm, and latent heat of vapourisation = 539 kcal/kg. The product is scraped at 7/8 of a revolution of the drum.

Example-3

A drum dryer is designed for drying a product from initial total solid content of 16% and a final moisture content of 4%. An average temperature difference between the roller surface and the product of 70 °C will be used, and overall heat transfer coefficient is 1400 kcal/ m<sup>2</sup> hr °C. Determine the surface area of the roller required to provide a production rate of 40 kg product / hr.



**Lesson 35.****Principle of Freeze Drying****35.1. INTRODUCTION**

Preservation of food products by drying is an established method. However, when heat is used as a method of removing moisture, certain heat sensitive food products are likely to get damaged. Moisture removal from food products can also be accomplished by freeze drying, which involves the sublimation of water from the frozen state directly to the vapor state. The advantage of freeze dehydration process is that moisture removal or dehydration can be accomplished without exposing the product to high temperatures. This now one hundred year old system involves eliminating the water contained in food or other products in order to keep it stable at room temperature and facilitate its storage.

**35.2. DEFINITION**

Freeze drying defines the process of preserving food products by freezing them, and then evaporating the water (in the form of ice) directly into vapour by sublimation. Freeze drying produces one of the highest quality food products obtainable through any drying method, and allows for rapid and near complete re-hydration.

Freeze-drying a product consists of three stages. First, the product is frozen so that the water contained in it becomes ice. Second, the ice in the product is made to vaporize without passing through the liquid phase; this process is known as sublimation. This vapour is collected by use of condensers, and, once removed from the freeze-drying chamber, becomes ice again. Finally, secondary desiccation involves eliminating the water that was not converted into ice during the first stage.

**35.3. PRINCIPLE**

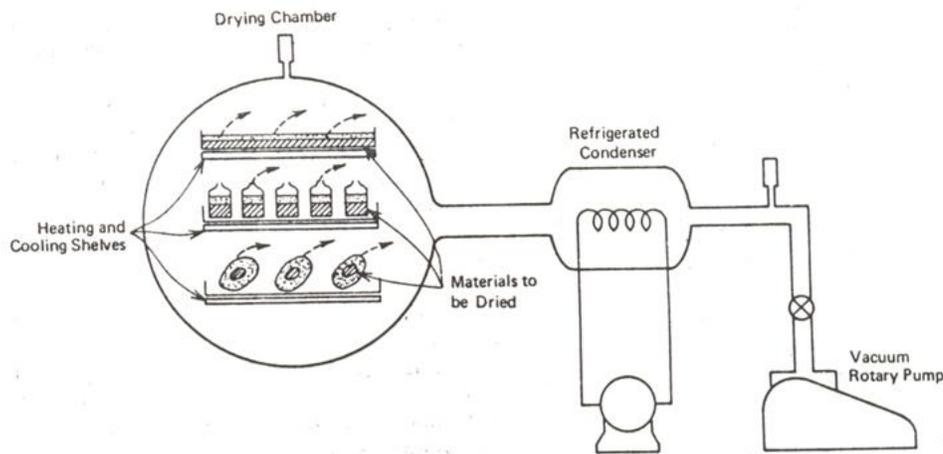
Freeze drying also called sublimation drying is the drying of a product in frozen state. The ice evaporates without passing through the liquid state i.e., it sublimates. Conditions of sublimation of pure ice therefore exists below the triple point (0.01 oC and 610.8 Pa) at which all three states of matter can exist. Freeze drying is always done under vacuum. The sublimation temperature is determined by the value of the reduced pressure. It should be noted that sublimation process is only possible below the so-called 'eutectic' point.

The first stage of freeze-drying is to freeze the food in conventional freezing equipment. Rate of freezing affects the quality of product as well as rate of drying. Rapid freezing produce small ice crystal, which do little damage to the structure of the product but, they leave behind very small pores and capillaries, which offer a greater resistance to the passage of the vapour. Slow freezing produces large crystals and they make rapid drying possible. But, disadvantage of large crystals is that they damage cells; produce separation and denaturation of protein.

If the water vapour pressure of a food is held below 610.8 Pa and the water is frozen, when the food is heated the solid ice sublimates directly to vapour without melting. Water vapour is continuously removed from food by keeping the pressure in the freeze dryer cabinet below vapour pressure at the surface of the ice, removing vapour with a

vacuum pump and condensing it on refrigeration coils. As drying proceeds 'sublimation front' moves into food. Latent heat of sublimation is either conducted through the food to the sublimation front or produced in the food by microwaves. After vapour travels out of the food through channels formed by the sublimed ice and is removed.

Foods are dried in two stages; first by sublimation to approximately 15% moisture content (wet basis) and then by evaporative drying (desorption) of unfrozen water to 2% (wet basis). Desorption is achieved by raising the temperature in the drier to near ambient temperature while retaining the low pressure. The rate of drying depends on the resistance of the food to heat transfer and to a lesser extent on the resistance to vapour flow through the sublimation front.



**Fig-35.1:** Schematic diagram of freeze drying process

In common with almost all materials, water can exist in three different states of phases; a liquid, a solid, or gas. By plotting a graph of pressure versus temperature over an appropriate range, the boundaries of the three states can be seen. This is called phase diagram. The triple point is the state where ice, liquid and water vapour can exist together in equilibrium.

Advantages of Freeze Drying:

1. Minimum damage to, and loss of activity in, heat labile materials
2. Creation of porous, friable structure
3. Speed and completeness of rehydration
4. The ability to sterile filter liquids just before dispensing (if needed)

Disadvantages are as follows:

1. High capital cost of equipment
2. High energy cost
3. Lengthy process time

4. Possible damage to products due to change in pH and tonicity when solutes concentrate as pure water freezes into ice

Freeze-drying is slower than conventional dehydration. Energy costs for refrigeration are high and production of partial vacuum is an additional expense. This together with high capital investment results in high production costs. Hence freeze-drying is used for expensive foods, microbial cultures, coffee, tea, egg, milk products, fruit, fruits juices, certain vegetables, etc.

**Table-31.1: Differences Between Conventional Drying and Freeze Drying**

Conventional Drying	Freeze drying
1. Successful for easily dried foods.	1. Successful for most foods.
2. Temperature range is 37 – 95 °C.	2. Temperature below freezing point.
3. Atmospheric pressure.	3. Reduced pressure (29 – 133 Pa).
4. Evaporation of water from surface of food.	4. Sublimation of water from ice front.
5. Case hardening.	5. No case hardening.
6. Stress in solids foods causes structural damage and shrinkage.	6. Minimal structural changes or shrinkage.
7. Slow and incomplete rehydration.	7. Rapid and complete rehydration.
8. Products having higher density than original food.	8. Lower density than original food.
9. Odour and flavour frequently abnormal.	9. Odour and flavour frequently normal.
10. Colour frequently darker.	10. Colour usually normal.
11. Costs generally low.	11. Costs generally high.



## Lesson 36.

## Heat And Mass Transfer In Freeze Dehydration

## 36.1. INTRODUCTION

In most conventional freeze drying systems, the vapor pressure gradient necessary for sublimation is attained by maintaining the total pressure in the drying chamber at a low level of the order of 0.1 to 2.0 torr (13.5 to 270 N/m<sup>2</sup>). A condensing system is provided to remove the water vapor formed and a heating system to supply the necessary latent heat of sublimation to the frozen material. Such a system is shown schematically in the fig. 36.1

In such a system, the two main factors affecting the rate of drying are the rate of movement of water vapor from the ice surface through the porous layer of the dry material and the rate of transfer of heat to the ice front. The movement of water vapor through the porous layer of the dried material has been discussed by many workers. By considering the flow of vapor through the dried meat as being analogous to flow through a bundle of capillary tubes, with slip flow conditions prevailing the mass flow rate of gas,  $m$ , at constant temperature is given by an expression of the form:

$$m = a/l (A \cdot \Delta P (P_m + b)) \dots\dots\dots (1)$$

where,  $\Delta P$  = Pressure drop across the dried layer

$P_m$  = Arithmetic mean of pressures at both faces of dried layer

$l$  = Length of the flow path

$A$  = area normal to the direction of flow of the gas

$a, b$  = constants

Such an expression applies at pressure below 10 torr (1.35 kN/m<sup>2</sup>)

More recent work uses a more general equation to represent the rate of flow of vapor through the solid layer:

$$\frac{dw}{dt} = \frac{A \cdot b (P_i - P_D)}{l} \dots\dots\dots (2)$$

where,  $dw/dt$  = mass flow rate of vapor through the dry layer

$b$  = permeability of the dry layer

$P_i$  = Vapor pressure of ice at specified temperature

$P_D$  = Partial pressure of water vapor

$l$  = thickness of the dry layer

In order to achieve the maximum rate of drying, the ice temperature should be as high as possible, consistent with the product quality. Unless the heat of sublimation is supplied to the ice at a sufficient rate, the ice temperature will fall and consequently will the drying rate. In a system where the heat is transferred to the ice through the dried layer only and where drying takes place from the heated surface, then the rate of heat input,  $dQ/dt$  is given by:

$$dQ/dt = (K_d.A.(T_D - T_i)/l) \dots\dots\dots(3)$$

Where,  $K_d$  is the thermal conductivity of the dried layer

$T_D$  is the temperature of the dried layer

$T_i$  is the temperature of the ice surface

An energy balance combining equations (2) and (3), gives

$$- L_s. A.b. (P_i - P_d)/l = (K_d.A.(T_D - T_i)/l) \dots\dots\dots(4)$$

Where  $L_s$  is the latent heat of sublimation at  $T_i$

Ideally, to carry out the freeze drying process correctly, all the liquid present in the food should be frozen. However, in practice this is not feasible, provided the amount of unfrozen liquid remaining small. The product quality is not seriously affected. The optimum rate of freezing for freeze drying depends largely on the nature of the product, variations in the rate of freezing affects ice crystal size and hence pore size in the dried product and so can be expected to influence the rate of drying and the characteristics of the dried product, particularly its reconstitutability. Optimum rates of freezing should be determined experimentally.

### 36.2. HEAT AND MASS TRANSFER

There are three methods of transferring heat to the sublimation front.

**Heat Transfer Through The Frozen Layer:** The rate of heat transfer depends on thickness and the thermal conductivity of ice layer. As drying proceeds the thickness of ice is reduced and the rate of heat transfer increases.

**Heat Transfer Through Dried Layer :** The rate of heat transfer to sublimation front depends on thickness and area of the food, the thermal conductivity of the dry layer and temperature difference between the surface of the food and ice front. At a constant cabinet pressure the temperature of ice front remains constant. The dried layer of food has a very low thermal conductivity and therefore offers high resistance to heat flow. As drying proceeds, this layer becomes thicker and the resistance increases. As in other unit operations, a reduction in size or thickness of the food and an increase in the temperature difference increase the rate of heat transfer.

**Heating By Microwaves :** Heat is generated at the ice front and the rate of heat transfer is not influenced by thermal conductivity of ice or dry food or the thickness of dry layer.

### 36.3. RATE OF MASS TRANSFER

When heat reaches sublimation front it raises the temperature and water vapour pressure of ice. Vapour then moves through the dried food to a region of low vapour pressure in drying chamber. 1g of ice forms 2 m<sup>3</sup> at vapour at 67 Pa and it is therefore necessary to remove several hundred cubic meters of vapour per second through pores in the dry food.

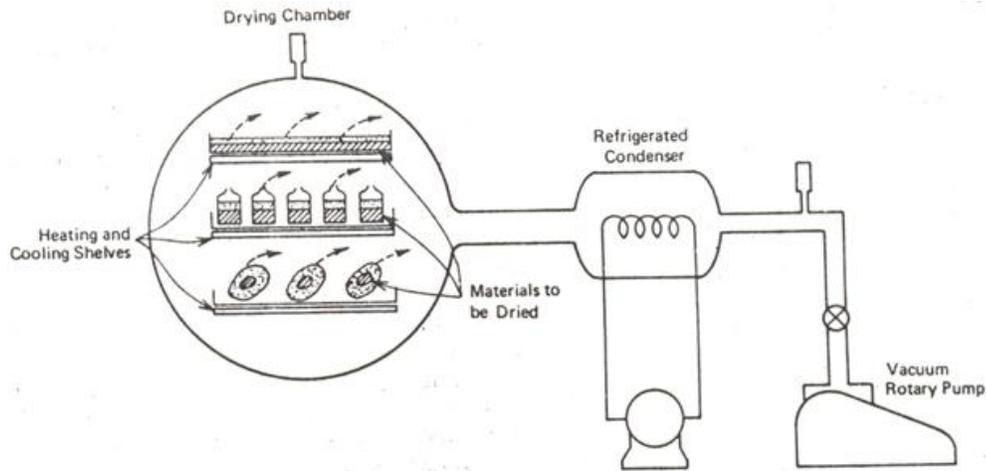
The Factors That Control The Water Vapour Pressure Gradient are:

- Pressure is in drying chamber.
- The temperature of the vapour condenser, both of which should be as low as possible.

- Temperature of ice at sublimation front, which should be as high as possible.

In practice the lowest economical chamber pressure is approximately 13 Pa and the lowest condenser temperature is  $-35^{\circ}\text{C}$ .

### 36.4. HEAT AND VAPOUR MOVEMENT



**Fig: 36.1 Schematic diagram of Freeze Dryer**

The heat and mass transfer taking place during freeze-drying is shown in the above figure.

The frozen products rests on a contact heating plate, which is at  $0^{\circ}\text{C}$ . The amount of heat passing through the frozen product from the plate to the ice front is given by;

$$Q_c = -k_{fr} \frac{d\theta}{dz} = k_{fr} (\theta_c - \theta_s)/X \quad \text{assuming linear temperature change.}$$

In addition, the surface of the product receives radiant heat from radiant heater. This heat passes through already dried product to the subliming ice surface.

$$Q_r = k_{dr} \frac{d\theta}{dz} = k_{dr} (\theta_o - \theta_s)/(x_0 - x) \quad \text{assuming linear temperature change.}$$

Neglecting the change in heat capacity of dry product all the heat supplied is utilized to sublime the amount of ice  $m_v$ .

$$m_v = -b/\mu \quad dp_v / dz$$

$$= b/\mu \frac{p_v - p_{v0}}{x_0 - x} \quad \text{assuming linear change in vapour pressure.}$$

where,  $b/\mu$  = is mass conductivity in  $\text{kg} / \text{s m Pa s}$ , which describes the mass transfer per unit distance and unit pressure difference.

A general expression for relationship between heat and mass exchange in the product can be obtained if the heat of sublimation  $l_s$  is known ( generally  $l_s = 2840 \text{ kJ/kg}$ )

$$-b/\mu \quad l_s \quad dp_v / dz = k_{dr} \quad d\theta/dz - k_{fr} \quad d\theta/ dz$$

where,

$k_{dr}$  = Heat conductivity of dry part.

$k_{fr}$  = Heat conductivity of frozen part.

$b/\mu$  = Mass conductivity of dry product.

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## Lesson 37. Industrial Freeze Dryers

### 37.1. INTRODUCTION

The general commercial freeze dryer process is comprises of (1) Preparation of the material; (2) freezing; (3) conditioning of the frozen mass; (4) drying, that is, sublimation and desorption; and (5) conditioning the product. .

### 37.2. BATCH FREEZE DRIERS

The main parts of a plant for batch freeze-drying are: A freezing cabinet, a freeze-drying cabinet, an ice condenser. Auxiliary equipment necessary includes plant for the production of heat, cold and vacuum.

The products are frozen separately and are subsequently put into trays and placed on the heating plates in the freeze drying cabinet. The drying cabinet and the condenser are then evacuated as quickly as possible and the heating is switched on. The vapor is condensed into ice in the ice condenser, which consists of tubes or plates whose temperature is mostly about 15 to 20 OC lower than the sublimation temperature. The condenser which actually is evaporator coils of refrigeration system therefore acts as a vacuum pump with a very great suction capacity for the condensable gases.

The pumps, which are connected after it, only have the function of maintaining the vacuum in the plant and of removing the non-condensable gases which are liberated during drying or which have gained access through leakage.

The layers of ice, which form on the condensers, are removed from time to time by defrosting. For continuous operation several condensers are used. They are alternately separated from the drying cabinet by vacuum valves, air is admitted, they are warmed for defrosting, cooled again after discharge of the water, evacuated and connected again to the cabinet by opening the valve.

### 37.3. CONTINUOUS FREEZE DRIERS

Continuous freeze dryers are designed like cabinet drier which is still much in use. It consists of stacks of heating plates whose area may be up to 40 m<sup>2</sup> per cabinet. Between these plates the trays containing the product are placed either by hand or, all at once, by a mobile tray bearing trolley. The mobile cable trolley shortens the loading time and thus minimizes the danger of thawing.

Some of the industrial freeze-drying plants are based on the principle of the cable trolley operating as the product tray carrier. The cars operate automatically and move intermittently through the plant, which is composed of a number of cabinets, is separated from the rest of the plant by inlet and outlet locks with gates and chambers. Differences in temperature between the cabinets are possible.

In these cabinet driers the product remains undisturbed during the whole of the drying operation. The driers are very flexible in use. They can be easily adjusted to changes in throughput as well as the size and shape of the product.

### 37.4. INDUSTRIAL FREEZE DRYING

#### Construction Material

Chamber, door, hinges, shelf modules, trays and vapour condenser are mostly constructed from AISI 304 stainless steel.

#### Chamber

Shelf module and vapour condenser are contained inside chamber.

Viewing ports are provided in the door, allowing observation of both the vapour condenser and product trays during the drying cycle.

Chamber is fitted with stainless steel pneumatically operated valves that isolate the vacuum line connection, drain, water defrost and vacuum release.

#### Modular Shelf Heating Plates

Plates are usually fabricated from type 304 stainless steel. Shelf module is removable from the chamber for maintenance or cleaning, and is done by rolling onto a trolley which is provided.

#### Trays

Trays have two sets of Type 304 stainless steel trays are provided as standard. Tray trolleys are optional.

#### Heating System

Heating system has thyristor controlled electric boiler, connected in series with the heat plates.

Heating fluid is glycol based and is circulated by a centrifugal pump, allowing heated or cooled fluid to be circulated through the plates on demand of the electronic load controller. A cooling heat exchanger is provided in the circuit for reducing the temperature of the plates.

#### Vacuum System

Roots blower is provided for developing vacuum. Roots blower and backing pump are connected to the chamber by heavy duty PVC lines and pneumatic isolating valve. Pump exhaust is vented to the exterior of the building housing the freeze dryer.

#### Refrigeration

Refrigeration condensing units are purpose-built specifically for each freeze drying system with capacity control to allow economical use of the low-temperature R507 refrigerant. It includes water cooled condenser.

#### Vapour Condenser

Vapour condenser has type 304 stainless steel tube in parallel circuits to form a direct expansion refrigerated coil.

Defrosting ice after a product cycle is by water. Hot water defrost optional using heat recovery from the refrigeration system.

### Low Temperature Option

The equipment has an option of operating in low temperature if required, giving  $-55^{\circ}\text{C}$  vapour condenser temperature, and  $-35^{\circ}\text{C}/+70^{\circ}\text{C}$  shelf freezing/heating.

### Control System

Automated systems will reduce energy to govern sublimation pressure to pre-set parameters.



Fig: 37.1 Industrial Freeze dryer

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**Lesson 38.****Calculation of Freeze Drying Time****38.1. INTRODUCTION**

Dehydration carried out at low absolute pressures allows the vaporization of water from the solid phase. To Carry out freeze drying successfully, the absolute pressure in the drying chamber must be maintained at a minimum of 620Pa.

Figure 38.1 is a schematic diagram of a freeze drier. The absolute pressure inside the drying chamber is determined by the temperature at which the vapour trap is maintained. This pressure corresponds to the vapour pressure over ice at the vapour trap temperature. The vacuum pump is designed primarily to exhaust the vacuum chamber at the start of the operation and to remove noncondensing gases and whatever air leaked into the system. The volume of vaporized water at the low absolute pressure in freeze drying is very large; therefore, removal of the vapour by the vacuum pump alone requires a very large pump. condensing the vaporized water to ice in the vapour trap is an efficient means of reducing the volume of gases to be removed from the system by the vacuum pump.

Heat must also be supplied to the material being dried to provide the energy of vaporization. This is accomplished by the use of hollow shelves through which a heated liquid is circulated. The temperature of the shelves can be regulated by regulating either the temperature or the supply of the heat transfer medium. The material to be dried rests on top of the heated plates. Heat transfer occurs by conduction from the heated plates, by convection from the air inside the drying chamber to the exposed surfaces, and by radiation.

**38.2 DRYING TIMES FOR SYMMETRICAL DRYING**

Analysis of freeze drying is different from that of conventional drying in that drying proceeds from the exposed surfaces toward the interior. The outer layers are completely dry as the ice core recedes. Vaporization of water occurs at the surface of the ice core. Heat of sublimation is conducted to the surface of the ice core through the dried outer layer. Vaporized water diffuses through the pores of the dried outer layer before it leaves the solid and goes to the atmosphere in the drying chamber. Symmetrical drying occurs when the rate at which the ice core recedes is equal at both the top and bottom of the material. To simplify the calculations, unidirectional heat transfer is assumed.

Let  $W = \text{kg water} / \text{m}^3$  of wet material. If  $\rho$  is the density of the wet material and  $X_0$  is the initial moisture content on a dry basis,  $\text{kg water} / \text{kg dry matter}$ ,

$$W = (\rho) X_0 / 1 + X_0.$$

If drying is symmetrical, the mass of water evaporated,  $M_c$ , expressed in terms of a dried layer,  $\Delta L$ , is:

$$M_c = WA (\Delta L) \quad (2)$$

Let  $X'$  = fraction of water evaporated =  $M_c / \text{total water}$ .

$$X' = \frac{W(A)(\Delta L)(2)}{W(A)(L)} = \frac{\Delta L(2)}{L}$$

$$X' \text{ is also } \frac{X_0 - X}{X_0}$$

Where  $L$  = the thickness of the solid and  $X$  = moisture content,  $\text{kg H}_2\text{O} / \text{kg dry matter}$ .

$$\Delta L = \frac{LX'}{2}$$

The overall heat transfer coefficient calculated from the sum of the resistance to heat transfer by the dried layer and the heat transfer coefficient is:

$$\frac{1}{U} = \frac{1}{h} + \frac{\Delta L}{k} = \frac{1}{h} + \frac{LX'}{2k} \quad \dots\dots\dots(1)$$

$$U = \frac{k}{\frac{k}{h} + \frac{LX'}{2}} \quad \dots\dots\dots(2)$$

If drying is symmetrical, heat is transferred from both sides. Let  $T_a$  = Temperature of the atmosphere in the drier and let  $T_f$  temperature of the frozen core surface. The heat transferred to the ice core is

$$q = UA\Delta T = \frac{k}{\frac{k}{h} + \frac{LX'}{2}} (2A)(T_a - T_f) \dots\dots\dots(3)$$

For simultaneous heat and mass transfer, heat transferred = heat of vaporization.  $\Delta H_s$  is the heat of sublimation of ice at  $T_f$

$$\Delta H_s (W)(A)(L) \frac{dX'}{dt} = \frac{(2A)(T_a - T_f)(k)}{\frac{k}{h} + \frac{LX'}{2}} \dots\dots\dots(4)$$

Simplifying and integrating equation 4:

$$t = \frac{\Delta H_s (W)(L)}{(2k)(T_a - T_f) \left[ \frac{kX'}{h} + \frac{LX'^2}{4} \right]} \dots \dots \dots (5)$$

W in equation 5 can be expressed in terms of either the density of the wet material, p, or the density of the dried material, ρ<sub>s</sub>.

$$W = X_0 \rho_s \quad \text{or} \quad W = (\rho) \frac{(X)_0}{1+X_0}$$

$$t = \frac{\Delta H_s (X_0)(\rho_s)(L)}{(2k)(T_a - T_f) \left[ \frac{kX'}{h} + \frac{LX'^2}{4} \right]} \dots \dots \dots (6)$$

$$t = \frac{\Delta H_s (X_0)(\rho)(L)}{(2k)(1+X_0)(T_a - T_f) \left[ \frac{kX'}{h} + \frac{LX'^2}{4} \right]} \dots \dots \dots (7)$$

Either equation 6 or equation 7 can be used to calculate the time of drying, depending on whether ρ or ρ<sub>s</sub> is known.

**38.3. PREDICTION OF DRYING TIMES**

Drying of product of 2x thickness between two heating surfaces which dry it from both sides is shown in the figure.

Let φ = Porosity or original volume of ice crystal in the product.  
ρ = Density of ice.

Mass flow m<sub>v</sub> over the period dt corresponding to the retraction of ice surface by a distance dz is

$$m_v dt = dz \rho \phi \quad (m_v \text{ in kg / m}^2 \text{ s})$$

$$\{k_{dr}(\theta_o - \theta_s) / z L_s\} dt = dz \rho \phi$$

Where,

L<sub>s</sub> = Latent heat of sublimation of ice at temp. θ<sub>s</sub>

Assuming that the temperature of sublimation θ<sub>s</sub> is constant and drying process is carried out in such a way that temperature of surface of the product then θ<sub>o</sub> is constant then:

$$1/L_s k_{dr} (\theta_o - \theta_s) / z dt = dz \rho \phi$$

On integration

$$\int_0^t dt = \frac{\rho \phi L_s}{k_{dr} (\theta_o - \theta_s)} \int_0^x z dz$$

$$t = \frac{\rho \phi L_s x^2}{2 k_{dr} (\theta_o - \theta_s)}$$

**38.4 EXAMPLE:**

The density of a sample of beef is 60 lb / ft<sup>3</sup> (965 kg / m<sup>3</sup>). How long will it take to dry a 1 – in. (2.54 – cm) – thick strip of this sample from an initial moisture of 75% to a final moisture content of 4% (wet basis)? Freeze drying is carried out at an absolute pressure of 500 um of mercury. The air in the drying chamber is at 80°F (26.7°C). Assume

symmetrical drying. The thermal conductivity of the dried meat is 0.0692 W / (m. K). Estimate the heat transfer coefficient by assuming that a 3-mm-thick layer of vapour (kv of water = 0.0235 W / (m.K)] envelopes the surfaces where drying occurs and that the heat transfer coefficient is equivalent in resistance to the resistance of this vapour film.

$$h = \frac{k}{x} = \frac{0.0235}{0.003} = 7.833 \text{ w/m}^2\text{K}$$

The absolute pressure in the chamber is :

$$P = 500 * 10^{-6} \text{ m Hg} \frac{133.3 * 10^{-3} \text{ Pa}}{\text{xm Hg0}} = 66.65 \text{ Pa}$$

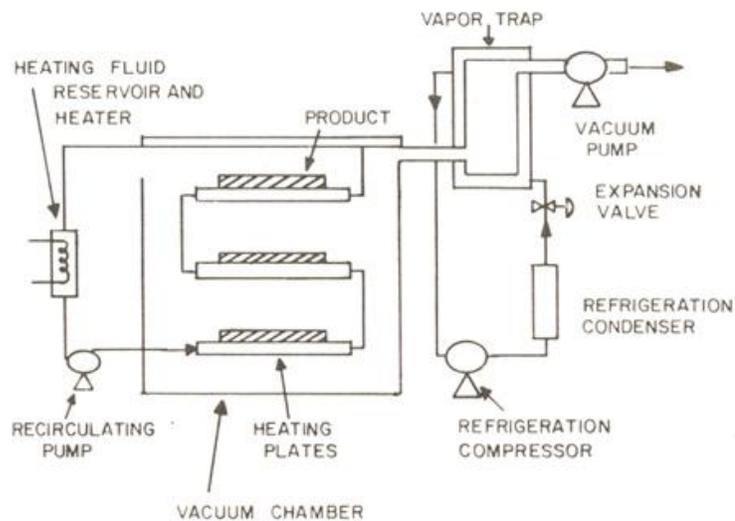
From sublimation Fig 38.2, the temperature of ice in equilibrium with a pressure of 66.65 Pa is – 24.5°C. The heat of sublimation Hs = 2.8403 MJ / kg. The final moisture content on a dry basis is : x = 0.04 / 0.96 = 0.0417 kg water / kg dry matter. The initial moisture content on a dry completion of the drying period is X' = X0 – X / X0 = 3 – 0.0417 / 3.0 = 0.986.

Substituting in equation 7:

$$t = \left[ \frac{2.8403 * 10^6 (965) * 3.00 (0.0254)}{2(0.0692)(1 + 3)(26.7 + 24.5)} \right]$$

$$t = \left[ \frac{0.0692(0.986)}{7.833} + \frac{0.0254(0.986)^2}{4} \right]$$

$$= 109,673 \text{ s} = 30.46 \text{ h}$$



**Fig. 38.1 Schematic diagram of freeze dryer**

**Lesson 39.****Equipment for pulping****39.1. INTRODUCTION**

Fruits and vegetable processing is done in a different manners as per the requirement of the type of processed end products, in some processing pulping is the major unit operation for making processed product. There are different methods of pulping of fruits and vegetables, depending on its size shape and texture. Commercial production of processed product from fruits and vegetables requires different types of pulping machines, for increased capacity as well as hygienic production of the processed foods.

**39.2. EQUIPMENT FOR PULPING**

Pulping is process that performed by the extraction or pulper equipment which crush the food products and separate the pulp, seed and skin of fruits and vegetable. Pulper may be either mechanically or electrical operated to forces the feed in the machine.

**39.2.1. Fruit crusher**

Powered machines that are used to crush pineapples or other hard fruits consist of a rotating screw inside a casing. The casing has a screen in the base. Juice/pulp drains from an outlet in the base of the casing and skin is ejected from the end of the casing down a chute. The casing should be fitted with wing nuts to remove it easily.

In operation, pineapples are cut into large pieces and fed into the hopper. Routine maintenance consists of: weekly checks on the belt tension weekly checks of electrical connections monthly greasingof bearings. A spare drive belt and fuse should be kept.



**Fig. 39.1 Fruit Crusher**

### 39.2.2. Fruit presses

Manual fruit presses have a stainless steel cage in which a press plate is raised and lowered by a screw. The screw should be made from a harder grade of steel than the bearing to prevent the more expensive screw from wearing down (the bearing can be replaced more cheaply than the screw). Layer plates made from stainless steel, nylon or painted mild steel may be needed in larger presses to promote efficient pressing. In operation a muslin or cotton bag is placed in the cage and pulp is poured in. The bag is closed and the press plate is lowered. After a few minutes, additional turns of the screw increase the pressure further. Juice is collected via a pipe. The screw is then raised and the bag is removed.



Fig. 39.2 a Fruit press

Important innovations are

#### 1. Low water-use pulpers

Pulping systems that accept mixtures of green and ripe cherry and separate the 'greens' without crushing



Fig. 39. 2 b Fruit press

### 39.2.3. Fruit & Vegetable Pulper

The leading manufacturer of fruit & vegetable pulp based products. These fruit and vegetable pulper are used for the extraction of pulp from vegetables and fruits like mango, litchi, guava, pear, tomato, passion fruit, grape ad so on. The working capacity of these machines depend upon the size, type and quality of the product to be pulped. Our range of fruit & vegetable pulper machines are available from 80 kg/hr to 3 t/hr capacity also are also found in the followng capacities



Fig. 39.3 Fruit and vegetable pulper

### 39.2.4. Twin pulper

A wide range of Fruit and Vegetable Pulper which can be used to extract pulps from fruits and vegetables. These pulpers are highly effective and also high on performance. These Fruit an Vegetable Pulpers are used various purposes like skin removal, destoning, pulping and finishing of pulps from fruits and vegetables like mangoes, litchi, tomatoes, carrot, pineapple and many more. The fruit and vegetable pulper is furnished with parts like scraper rotors, spiral scraper and brushes which rotates at a very high speed thus separating the stone, skin and the pulp. The secondary stage id used for receiving the refined pulp from the primary stage and are available in the wide range of capacity:



Fig.39.4 Twin Pulper

### 39.2.5. Fruit mill

Manufacturer of fruit mill crusher enabled with sturdy fixture mounted on MS steel band. The product is used for crushing hard seedless fruits for pulping or juice extraction. The machine is fed into a hopper which is then crushed by SS rotor against the SS blades driven by a powerful motor. All the parts of the fruit mill crusher are made up of food grade stainless steel.



Fig.39.5 Fruit Mill

### 39.2.6. Motorized hydraulic fruit press

A comprehensive range of Hydraulic Juice Press (Motorised) manufactured with high quality material. The Hydraulic Juice Press (Motorised) is used for the extraction of juice from crushed fruits like pineapple, grapes, orange, apple and so on. The product is also endowed with features like efficient durability and high tensile strength. The motorized Hydraulic Juice Press having stainless steel tray with proper depth which prevents the juice from spilling out from the filter cloth and wooden racks thereby retaining the nutrients left in the pulp from other juices.



Fig.39.6 Motorized hydraulic fruit press

### 39.2.7. Fruit juicer

The product is used for the extraction of juice from peeled fruits and is fabricated with an all sturdy aluminum body with stainless steel strainer. The Hand Operated Fruit Juicer is suitable for continuous operation and is easy to clean and maintain. These machines also easy to use, and do not require any power or electricity as it works on the similar principle of pressing the machine. The product is available in a variety of designs and models .



Fig.39.7 Fruit Juicer

### 39.2.8. Stainless steel pulper

These Stainless Steel 304 fruit and vegetable pulper are used for the extraction of pulp from vegetables and fruits like mango, litchi, guava, pear, tomato, passion fruit, grape ad so on. The working capacity of these machines depend upon the size, type and quality of the product to be pulped. Our range of fruit & vegetable pulper machines are available from 500 kg/hr to 3 t/hr capacity also are also found in the different capacities.



Fig. 39.8 Stainless Steel Pulper

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**Lesson 40.****Fruit Juice Extraction****40.1. INTRODUCTION**

Juice extraction—the elimination of the juice from fibrous, solid particles—is a basic technological step of fruit juice production. The fruit has to be prepared prior to juice extraction, which is then followed by juice clarification and drink completion. Subsequently, the finished drink is packed and preserved.

Diffusion-based liquid extraction requires chopping to minimize the thickness of the slices and strips. In addition the size of these pieces should form channels to ensure the flow of the extraction liquid. There are different devices for the crushing of fruits. These can be specialized for a given fruit (e.g., apple crusher) or generally used as hammer- and roller based machines. Their common feature is the rotating system and the pressing, shearing, pulling, and striking forces applied.

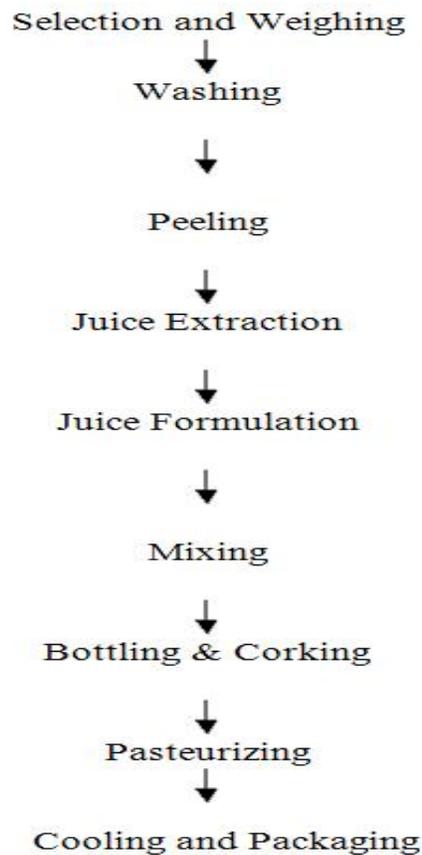
**40.2. FRUIT JUICE PRODUCTION**

Fig-36.1: Flow chart of fruit extraction

## Operation in Juice Extraction:

This operation can be divided into two steps: fruit chopping and preparation and the separation from solid fruit particles.

### 40.2.1. Chopping

The aim of this step is to smash, cut the fruit, increase its surface, and launch cell-fluid elimination. However, this can lead to enzymatic reactions damaging valuable components. Therefore, the fruit has to be processed immediately after chopping. If this step is done appropriately, the fruit is not pulpy but consists of homogenous, irregular-shaped, few-millimeter-sized particles, which tend to form channels to drain the liquid when pressed .

### 40.2.2. Chopped Fruit Preparation

Procedures designed to prepare chopped fruits are to increase juice yield and prevent undesirable changes (chemical, biological, mechanical, etc.) to achieve better aroma, flavor, and color properties. The type of preparation will depend largely on the type of fruit and production technology. There are several methods for this operation, such as mechanical, freezing, enzymatic, vibration, ultrasonic, electro-plasmolytic, ion-radiation procedures, and heat treatment. In practice, mechanical operations, heat treatments, and enzymatic solutions are widely used .

Mechanical preparation is used to chop fruit flesh, smash the tissues, and increase the surface. Stiff raw materials (e.g., apple) are usually crushed; meanwhile, soft ones (e.g., red currant) are only cracked. Crushing opens up the tissues, damaging some of the cells as well, and the draining of cell-fluid begins.

The degree of chopping is determined by the method of juice extraction. If pressing is applied, the chopped fruit releases the juice under a relatively small amount of pressure. Appropriately prepared chopped fruits contain particles of nearly identical size, enabling channels to form for the liquid to drain. If the fruit is chopped into very fine pieces, it spreads easily, expands under pressure and does not tend to form channels to drain the juice.

### 40.2.3. Methods of Extraction

In recent years there has been considerable interest in using extraction instead of expression for recovering juices from fruits and vegetables. Countercurrent screw extractors, some operated intermittently, have been used to extract juice with water. In some cases this results in higher yields of good quality compared to that obtained by expression.

Centrifugation may be used for a variety of tasks in fruit juice processing. Self opening centrifuges are used to remove pulp and control the level of pulp remaining in pineapple and citrus juices. Centrifuged apple juice is cloudy but free from visible pulp particles. Tubular bowl centrifuges were originally used to clarify apple juice but more recently nozzle and self-opening machine are used. The use of hermetically sealed centrifuges prevents excessive aeration of the juice. In the production of oils from citrus fruits centrifugation is applied in two stages. The product from the extractor contains an emulsion of 0.5–3.0% oil. This is concentrated up to 50–70% oil in a nozzle or self-opening centrifuge. The concentrated emulsion is then separated in a second centrifuge to produce the citrus oil.

There are many other applications for centrifugation in food processing, e.g. tubular bowl machines for clarifying cider and sugar syrups , nozzle and self-opening machines for dewatering starches and decanting centrifuges for

recovering animal and vegetable protein, separating fat from comminuted meat and separating coffee and tea slurries.

Preparation with heat treatment is mainly used prior to the pressing of berries, since it can increase juice yield by 5–10%.

#### 40.2.4. Process Description

In this process, the liquid phase of fruits is detached from solid particles. There are different methods for this separation: pressing, diffusion, centrifugal procedures, and reverse-osmosis. The type of equipment applied depends on the fruit species, production line, and economical background. The most widely used solution is pressing. Pressing separates a food system into two phases. In this case, fruit tissues mean the solid phase, while the liquid between the particles is the liquid phase. Pressing needs outside forces to create tension in the system, drain liquid, resulting in shape modification. The equipment hinders the disposal of the solid phase and the liquid gathers in a vessel. The remaining material, with low liquid content, is called marc. The most important parameter of pressing is the liquid yield, which means the percentage of juice extracted, compared to the raw material at the beginning of the process. Juice yield is basically determined by the type of the pressing device, and the quality and preparation of the raw material.

Fruit processing industry applies continuous—such as belt- and screw-based—and intermittent—like the package and basket type—pressing machines. In addition, decanters are based on centrifugal forces.

The juice of fruits can also be detached with extraction. It means that semi permeable cell walls are made permeable following a heat treatment and the cell fluid is then dissolved with water. This process is featured by the degree of extraction, expressing the amount of extracted valuable substances, compared to the total valuable matter content of the fruit.

The amount of substances diffused is in direct proportion with the diffusion coefficient, the active surface, and the concentration gradient.

In order to increase the diffusion coefficient and the permeability of the cell walls, diffusion fluid extraction is performed at 50–70°C. Active surface can be increased by proper chopping. The concentration gradient is determined by the stream conditions and the solvent–cell fluid ratio. However, the amount of solvent applied is limited by the concentration decrease of the liquid extracted. Diffusion juice extraction is usually carried out in double-screw extractor devices.

#### 40.2.5. Energy optimizing

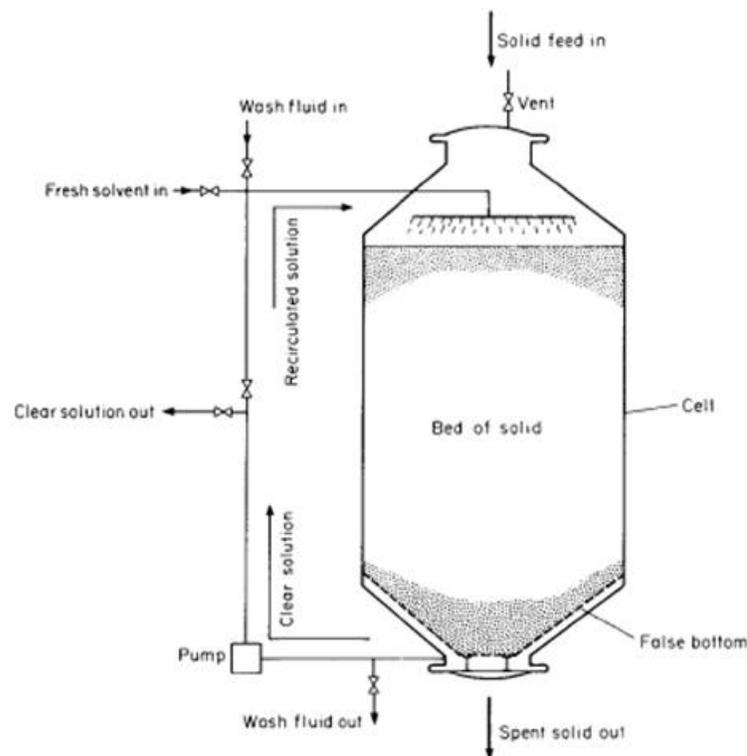
Proper juice extraction is important to optimize the efficiency of the juice production process as well as the quality of the finished drink. The latter is true because oranges have thick peels, which contain bitter resins that must be carefully separated to avoid tainting the sweeter juice. There are two automated extraction methods commonly used by the industry. In the first place the fruit between two metal cups with sharpened metal tubes at their base. The upper cup descends and the fingers on each cup mesh to express the juice as the tubes cut holes in the top and bottom of the fruit. The fruit solids are compressed into the bottom tube between the two plugs of peel while the juice is forced out through perforations in the tube wall. At the same time, a water spray washes away the oil from the peel. This oil is reclaimed for later use.

The second type of extraction has the oranges cut in half before the juice is removed. The fruits are sliced as they pass by a stationary knife and the halves are then picked up by rubber suction cups and moved against plastic serrated reamers. The rotating reamers express the juice as the orange halves travel around the conveyor line. Some of the peel oil may be removed prior to extraction by needles which prick the skin, thereby releasing the oil which is washed away. Modern extraction equipment of this type can slice, ream, and eject a peel in about 3 seconds.

#### 40.2.6. Extraction Equipment

In the food industry solid - liquid extraction is mainly applied to relatively coarse, particulate materials, usually greater than 200 mesh in size. In many cases, the solid has a cellular structure. The equipment used includes single and multistage static tanks and continuous moving bed extractors. Vigorous movement of the solid is seldom desirable.

##### a) Single Stage Extractors



**Fig- 40.2(a): Single stage, enclosed extractor cell**

The simplest form of extractor consists of an open tank, fitted with a false bottom which supports a bed of the solid to be extracted. The solvent is distributed over the surface of the bed of solid, percolates down beneath the false bottom. In the food applications, extraction is often carried out at high temperatures and pressures. In the case of oil extraction the solvent is relatively volatile. For these reasons and also for hygienic considerations, vessels are usually totally enclosed and capable of with-standing the required pressure.

Provision may be made for re-circulating the outflow. A heater may be incorporated in the feed line and/or re-circulation line to enable the temperature of the solution to be maintained at the desired value. Some units are jacketed for this purpose. Such cells may be filled manually or with the aid of a conveyor or some other mechanical device. The solid residue is removed manually or dumped through an outlet in the base of the cell. Where volatile

solvents are being used, it is possible to incorporate a solvent recovery and recycling system in such units. This enables a relatively concentrated overflow to be obtained.

Single stage units are used for pilot plant and small-scale commercial operations for the extraction of oil from seeds, beans and nuts, coffee solubles from ground & roasted beans and tea from dried leaves.

Many materials - fruits, vegetables and seeds contain valuable liquid constituents within the cell structure composing them. Groundnuts, coconuts, soybeans, sunflower seeds and olives for example, yield edible oils and fats, while juices from a variety of fruits are used in the manufacture of various soft drinks and wines. The cell walls normally require disruption before this liquid constituent can be separated and some form of pre-treatment such as pulping or heating is often required.

Traditionally, separation is accomplished by either solvent extraction - as in the recovery of fats from animal and vegetable materials - or by mechanical expression. Expression, the unit operation considered here, is the separation of liquids from solids by the application of compressive forces and is often used in the food and beverage industries.

The methods of expressing the liquid from the solid - liquid matrix are :

(i) Hydraulic pressing

(ii) Roller pressing

(iii) Screw pressing

Hydraulic presses are widely used in fruit juice processing whereas roller presses have not really been accepted. Roller presses are universally used in expressing juices from sugar cane.

Screw presses are being used in fruit juice expression but here they tend to be used as 'finisher' following a prior pulp thickening process using other thickening techniques. A recent process uses a basket centrifuge for pre-thickening before expression. Both hydraulic and screw presses are used in the extraction of oils and during oil milling, the oil being expressed from cleaned oil bearing seeds after cooking and conditioning in steam cookers. In general, hydraulic presses are used for batch type operations while roller and screw presses find their main application in continuous processing.

The efficiency of an expression process depends on several factors including :

(I) The yield stress of the solid phase (i.e. its resistance to deformation).

(ii) The porosity of the cake formed.

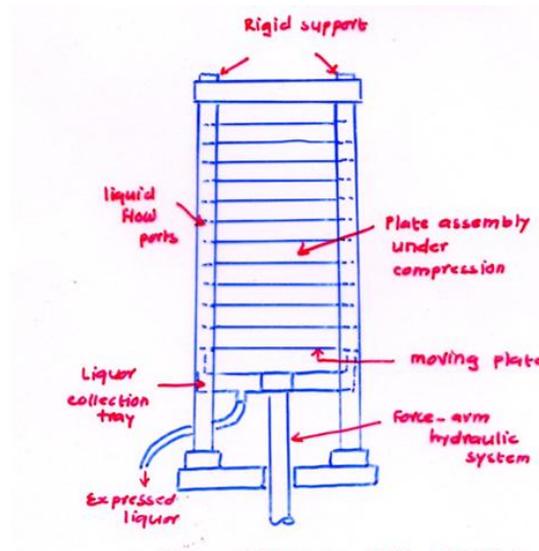
(iii) The viscosity of the liquid extracted (expressed).

(iv) The compressive force applied.

The rate of flow of liquid through the interstices of the cake of 'pomace' will depend on the thickness of the cake and on its porosity, both quantities which can vary with the degree of compressed applied.

The nature of the pulp itself depends on its type and previous history. Fruit pulp, for example, varies with the particular variety of a fruit, with the climatic and soil conditions under which it was grown, its maturity at picking and any metabolic changes occurring during the interval between picking and processing.

b) Hydraulic Pressing



c) Fig. 40.3 Hydraulic Press Extractor

Two types of hydraulic press are in common use—

1) Plate Press : The Pulp to be expressed is placed in heavy cotton filter bags or cloths, which are placed between grooved pressure plates arranged in a vertical stack. Hydraulic pressure is applied across the ends of the stack, a pressure of 31-62 MN/m (2-4 ton/in<sup>2</sup> ) being developed. The pulp, in the form of relatively thin layers, experiences a compressive force. Keeping the layers thin permits reasonably rapid draining of liquor through the cake interstices and across the grooved plate faces to common receivers.

Filling, pressing, opening and cleaning of these batch units requires a high labour usage. In an attempt to achieve extraction more economically, presses capable of exerting increasing pressure in several stages have been developed. In these units the assembly of plates moves beneath a series of pressure heads each exerting a higher pressure than the preceding head. The pressure should be increased gradually, since rapid changes can lead to sharp decreases in bed voidage with a consequent drop in drainage rate.

c) Continuous press : To reduce the high labour requirements associated with hydraulic expression, continuous presses have been developed.

i) Roller Press

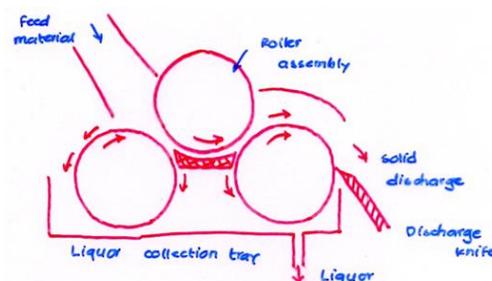


Fig-40.4: Roller Extractor

In this type of unit, a compressive force is applied by pressing the pulp between heavy rollers. Modifications of this method have been developed to improve the separation of liquid from solid. For instance, simple crushing rolls of the type used for expressing juice from the sugar cane have drainage grooves (Menchaeerts groves) on the roller surfaces. These grooves direct the liquors away from the compressed cake thus reducing re-wetting. Pulp is fed between the rollers as shown liquid is expressed from the pulp and flows to a collection launder, solids pass to the third delivery roller where it is removed by a 'doctor knife'. In other types of roller presses, drums similar in design to those used in drum filtration are used. The face of the drum is perforated and covered by a filter cloth. De-watering rollers bear against the face of the drum. Pressing takes place between the drum and rollers, liquid is drawn through the filter cloth and into the perforated drum, the interior of which may be maintained under reduced pressure to aid flow. The cake is removed by 'doctor knife' or 'string discharge'.

## ii) Screw Press

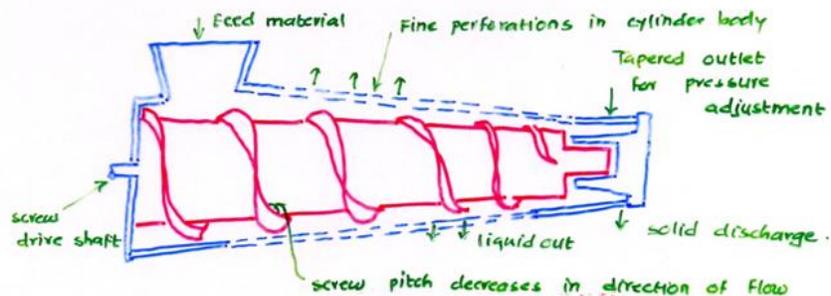


Fig-40.5: Screw Extractor

In this unit, known in the oil milling industry as an expeller, fruit pulps or oil seed meals are fed to a thick walled cylinder containing a rotating polished screw having a gradually decreasing pit. Material trapped between the screw and the inside of the cylinder barrel passes through a gradually reducing flow area, experiencing an increasing compressive force. The walls of the cylinder contain fine perforations or lots covered by adjustable screens, through which expressed liquor drains from the cake. The expressed cake leaves the unit through an adjustable discharge port. Power consumption in this unit is high. Power is dissipated in friction and may raise the temperature appreciably. The risk of thermal degradation of heat sensitive materials can be reduced by the use of hollow water-cooled screws. The degree of compression achieved can be varied by adjusting the area of the discharge port and by varying the speed of rotation of the worm. Shaft speed falls in the range of 5-500 rev/min depending on application and barrel pressures of 138-276 MN/m<sup>2</sup> (20,000-40,000 psi) are achieved. Good separations at through inputs of up to 8500 kg/h are reported with the residual cake containing 4.5 % liquid. With certain fruits, passage of fine particles with the liquid can present problems. In such cases subsequent clarification by centrifugation may be required.



## Lesson 41

### Blanching

#### 41.1. INTRODUCTION

Blanching is used to destroy enzymatic activity in vegetable and some fruits prior to other processing like freezing or dehydration or canning or thermal processing. It is a pretreatment by mild heat for a specific time followed by rapid cooling or passing immediately to the next processing stage. The time and temperature combination varies from product to product, the condition and size of product. Generally the temperature varies from 88 to 99 ° C. In some of the fruits and vegetables poly phenol oxydase enzyme is responsible for discoloration in presence of oxygen, hence it needs to be inactivated by blanching pretreatment, before futher processing of fruits and vegetables to maintain its original colour after processing.

#### 41.2. MECHANISM OF BLANCHING

Plant cells are discrete membrane-bound structures contained within semirigid cell walls. The outer or cytoplasmic membrane acts as a skin, maintaining turgor pressure within the cell. Loss of turgor pressure leads to softening of the tissue. Within the cell are a number of organelles, including the nucleus, vacuole, chloroplasts, chromoplasts and mitochondria. This compartmentalisation is essential to the various biochemical and physical functions.

Blanching causes cell death and physical and metabolic chaos within the cells. The heating effect leads to enzyme destruction as well as damage to the cytoplasmic and other membranes, which become permeable to water and solutes. An immediate effect is the loss of turgor pressure. Water and solutes may pass into and out of the cells, a major consequence being nutrient loss from the tissue. Also cell constituents, which had previously been compartmentalized in sub cellular organelles, become free to move and interact within the cell.

The following f actors are affecting blanching time:

The type of fruit or vegetable.

The size of the pieces of food.

The blanching temperature and

The method of heating

#### 41.3. PURPOSE AND OBJECTIVE OF BALANCING

The purpose of blanching is to achieve several objectives.

To soften the tissue to facilitate packaging.

To avoid damage to the product.

To eliminate air form the product.

To preserve the natural colour.

To destroy or retard certain undesirable enzymes.

To help preserve natural flavour.

The major purpose of blanching is frequently to inactivate enzymes, which would otherwise lead to quality reduction in the processed product. For example, with frozen foods, deterioration could take place during any delay prior to processing, during freezing, during frozen storage or during subsequent thawing. Similar considerations apply to the processing, storage and rehydration of dehydrated foods. Enzyme inactivation prior to heat sterilization is less important as the severe processing will destroy any enzyme activity, but there may be an appreciable time before the food is heated to sufficient temperature, so quality may be better maintained if enzymes are destroyed prior to heat sterilisation processes such as canning.

It is important to inactivate quality-changing enzymes, that is enzymes which will give rise to loss of colour or texture, production of off odours and flavours or breakdown of nutrients. Many such enzymes have been studied, including a range of peroxidases, catalases and lipoxygenases. Peroxidase and to a lesser extent catalase are frequently used as indicator enzymes to determine the effectiveness of blanching. Although other enzymes may be more important in terms of their quality-changing effect, peroxidase is chosen because it is extremely easy to measure and it is the most heat resistant of the enzymes in question. More recent work indicates that complete inactivation of peroxidase may not be necessary and retention of a small percentage of the enzyme following blanching of some vegetables may be acceptable.

Blanching causes the removal of gases from plant tissues, especially intercellular gas. This is especially useful prior to canning where blanching helps achieve vacuum in the containers, preventing expansion of air during processing and hence reducing strain on the containers and the risk of misshapen cans and/or faulty seams. In addition, removing oxygen is useful in avoiding oxidation of the product and corrosion of the can. Removal of gases, along with the removal of surface dust, has a further effect in brightening the colour of some products, especially green vegetables.

Shrinking and softening of the tissue is a further consequence of blanching. This is of benefit in terms of achieving filled weight into containers, so for example it may be possible to reduce the tin plate requirement in canning. It may also facilitate the filling of containers. It is important to control the time/temperature conditions to avoid overprocessing, leading to excessive loss of texture in some processed products. Calcium chloride addition to blanching water helps to maintain the texture of plant tissue through the formation of calcium pectate complexes. Some weight loss from the tissue is inevitable as both water and solutes are lost from the cells.

A further benefit is that blanching acts as a final cleaning and decontamination process. It also removes pesticide residues or radionuclides from the surface of vegetables, while toxic constituents naturally present (such as nitrites, nitrates and oxalate) are reduced by leaching. Very significant reductions in microorganism content can be achieved, which is useful in frozen or dried foods where surviving organisms can multiply on thawing or rehydration. It is also useful before heat sterilization if large numbers of microorganisms are present before processing.

#### 41.4. PRINCIPLES OF BLANCHING

Blanching is achieved in hot water for a short period of time or in an atmosphere of steam. In water blanching, the product is moved through water usually maintained at a temperature between 88 and 99 °C. In steam blanching the product is carried on a belt through a steam chamber into which live steam is constantly injected. The steam chamber is hooded and equipped with exhaust and also a drain for the condensate. The time temperatures are regulated for each specific product to achieve the desired enzyme inactivation, colour preservation and other characteristics. As a guide, the operator utilizes either the catalase or the peroxidase tests to determine the adequacy of blanching. Currently the peroxide test is commonly used in industry. For the most part, a negative peroxidase test is necessary to prevent the development of undesirable characteristics in the finished product. Immediately after blanching, vegetables are quickly cooled, usually in cold water, which often serves as means to convey the product to the next operation. A rod type cylindrical reel connected to the discharge of blancher and equipped with water sprays also serves as an excellent cooling system.

#### 41.5. PROCESSING CONDITIONS FOR BLANCHING

It is essential to control the processing conditions accurately to avoid loss of texture, weight, colour and nutrients. All water-soluble materials, including minerals, sugars, proteins and vitamins, can leach out of the tissue, leading to nutrient loss. In addition, some nutrient loss (especially ascorbic acid) occurs through thermal lability and, to a lesser extent, oxidation.

Ascorbic acid is the most commonly measured nutrient with respect to blanching, as it covers all eventualities, being water soluble and hence prone to leaching from cells, thermally labile, as well as being subject to enzymic breakdown by ascorbic acid oxidase during storage. Wide ranges of vitamin C breakdown are observed, depending on the raw material and the method and precise conditions of processing.

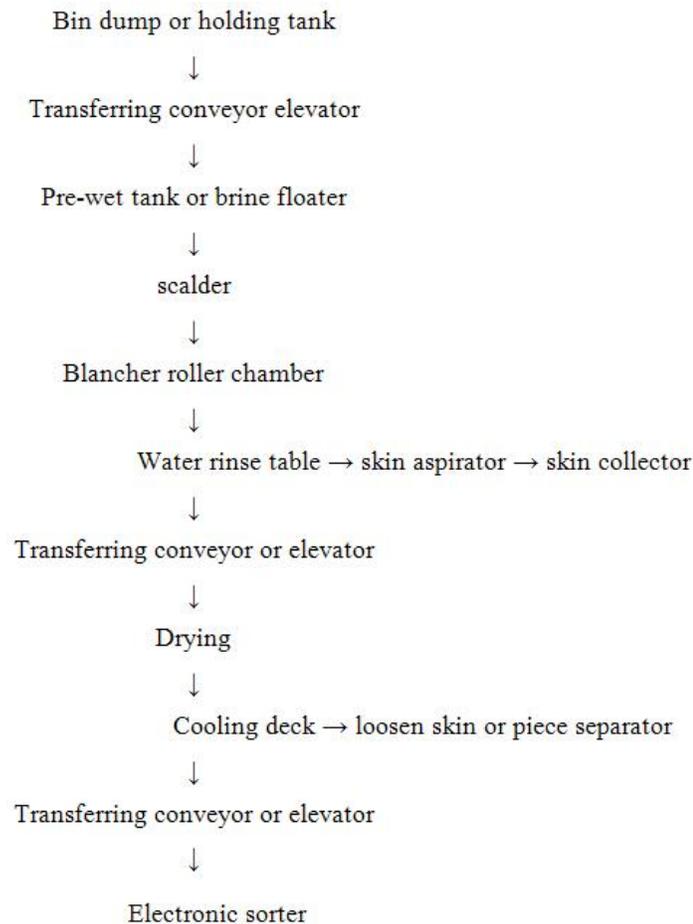
The aim is to minimize leaching and thermal breakdown while completely eliminating ascorbic acid oxidase activity, such that vitamin C losses in the product are restricted to a few percent. Generally steam blanching systems give rise to lower losses of nutrients than immersion systems, presumably because leaching effects are less important.

Blanching is an example of unsteady state heat transfer involving convective heat transfer from the blanching medium and conduction within the food piece. Mass transfer of material into and out of the tissue is also important. The precise blanching conditions (time and temperature) must be evaluated for the raw material and usually represent a balance between retaining the quality characteristics of the raw material and avoiding over-processing.

The following factors must be considered for deciding processing conditions of blanching:

1. Fruit or vegetable properties, especially thermal conductivity, which will be determined by type, cultivar, degree of maturity etc
2. Overall blanching effect required for the processed product, which could be expressed in many ways including: achieving a specified central temperature, achieving a specified level of peroxidase inactivation, retaining a specified proportion of vitamin C.
3. Size and shape of food pieces
4. Method of heating and temperature of blanching medium

Time/temperature combinations vary very widely for different foods and different processes and must be determined specifically for any situation. Holding times of 1–15 minutes at 70–100 °C are normal.



**Fig-41.1: Flow Chart for Blanching**

#### 41.6. METHODS OF BLANCHING

The two most widespread commercial methods of blanching involve passing food through an atmosphere of saturated steam or a bath of hot water. Both types of equipment are relatively simple and inexpensive. Microwave blanching is not yet used commercially on a large scale. There have been substantial developments to blanchers in recent years to reduce the energy consumption and also to reduce the loss of soluble components of foods, which reduces the volume and polluting potential of effluents and increases the yield of product.

Conventional steam blanching consists of conveying the material through an atmosphere of steam in a tunnel on a mesh belt. Uniformity of heating is often poor where food is unevenly distributed; and the cleaning effect on the food is limited.

However, the volumes of waste water are much lower than for water blanching. Fluidised bed designs and 'individual quick blanching' (a three-stage process in which vegetable pieces are heated rapidly in thin layers by steam), held in a deep bed to allow temperature equilibration, (followed by cooling in chilled air) may overcome the problems of nonuniform heating and lead to more efficient systems.

The two main conventional designs of hot water blancher are reel and pipe designs. In reel blanchers, the food enters a slowly rotating mesh drum which is partly submerged in hot water. The heating time is determined by the speed of rotation. In pipe blanchers, the food is in contact with hot water recirculating through a pipe. The residence time is determined by the length of the pipe and the velocity of the water. There is much scope for improving energy efficiency and recycling water in either steam or hot water systems. Blanching may be combined with peeling and cleaning operations to reduce costs.

Following the microwave heating, the vegetable material is subjected to blanching comprising heat treating in a current of hot air at temperature 100 to 150°C. The heating is conducted in an environment which prevents loss of water from the vegetable material and this may readily achieved by introducing steam in to the oven.

#### 41.7 EQUIPMENT FOR BLANCHING

##### a) Steam Blanchers

At its simplest a steam blancher consists of a mesh conveyor belt that carries food through a steam atmosphere as shown in the figure 41.2. The residence time of the food is controlled by the speed of the conveyor. In conventional steam blanching, there is often poor uniformity of heating in the multiple layers of food. To overcome this Individual Quick Blanching (IQB) was introduced which involves blanching in two stages. In the first stage food is heated in single layer to a sufficiently high temperature. In the second stage a deep bed of food is held for sufficient time to allow the temperature at the center of each piece to increase to that needed for enzyme inactivation.

##### b) Hot Water Blanchers

There are a number of different designs of blanchers each of which retains the food in hot water at 70 – 100 oC for a specific time and thus removes it to a dewatering-cooling section. A blancher cooler is shown in the figure 41.3. It has three sections: a pre-heating stage, a launching stage and a cooling stage. The food is preheated with water that is circulated through a heat exchanger. After blanching a second re-circulation system cools the food. The two systems pass water through the heat exchanger and this heats the pre-heat water and simultaneously cools the cooling water. A re-circulated water-steam mixture is used to blanch the food and final cooling is done by cold air. A counter-current water blancher is shown in the Fig.41.3.

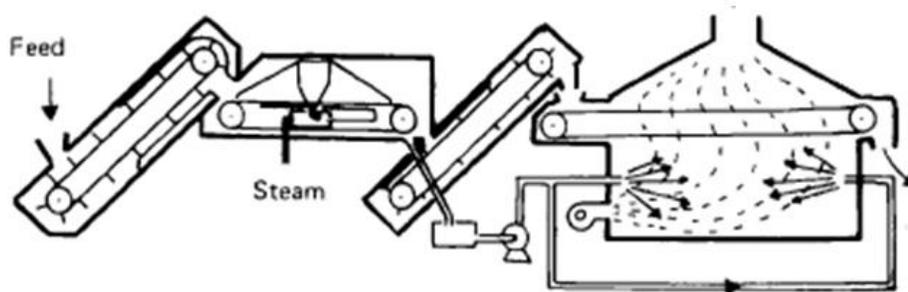


Fig-41.2: IQB Steam Blancher

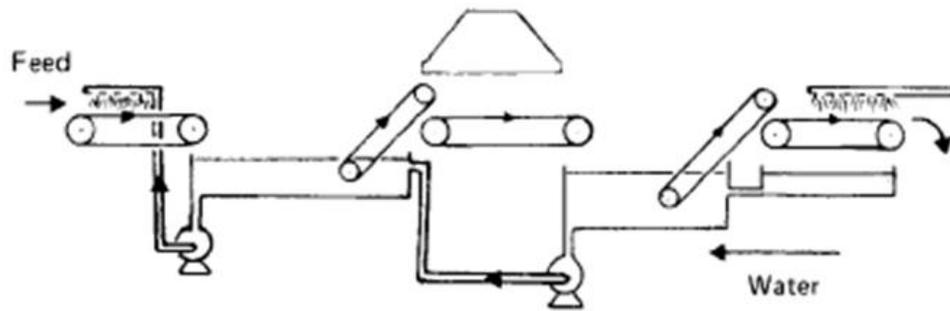


Fig-41.3: Co-current Blancher

Table-41.1: The advantages and limitations of convectional steam and hot water blancher

Equipment	Advantages	Limitations
Conventional steam blanchers	Smaller loss of water-soluble components. Smaller volumes of waste and lower disposal charges than water blanchers, particularly with air-cooling instead of water. Easy to clean and sterilize.	Limited cleaning of the food, washers also required. Higher capital costs than water blanchers. Uneven blanching if the food is piled too high on the conveyor belt. Some mass loss in food, poorer energy efficiency than water blanchers.
Convectional hot-water blanchers.	Lower capital cost and better energy efficiency than steam blanchers.	Large losses of water soluble components, including vitamins, minerals and sugars. Higher costs in purchase of water; big charges for treatment of large volumes of dilute effluent. Risk of contamination by thermophilic bacteria.

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## Lesson 42

### Dehulling

#### 42.1. INTRODUCTION

The purpose of hulling machine is to remove husk from any grain or seeds with minimum damage to the bran layer and as far as possible not to break the grains. Due to surface characteristics of different types of grains it is necessary to apply friction to the grain to remove the husk. Therefore, during hulling, certain percentage of broken cannot be avoided. In this respect the construction of machine, it's precision adjustment and the operation govern the optimum performance and the efficiency of the machine and best quality of grain production.

#### 42.2. SELECTION OF A HULLER

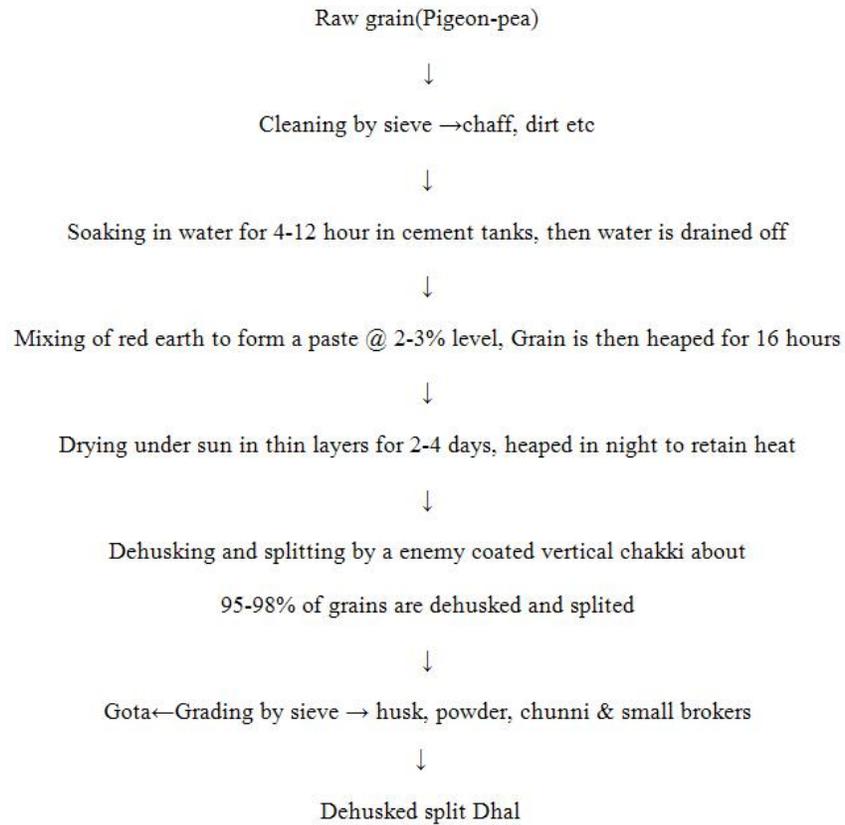
Factors to be considered in the selection of a huller are

- Capacity
- Energy requirement
- Efficiency of husk removal
- Extent of physical damage to beans
- Separation of loose husk
- Durability
- Ease of maintenance

#### 42.3. METHOD OF MILLING/ DEHUSKING

##### (1) Wet milling method

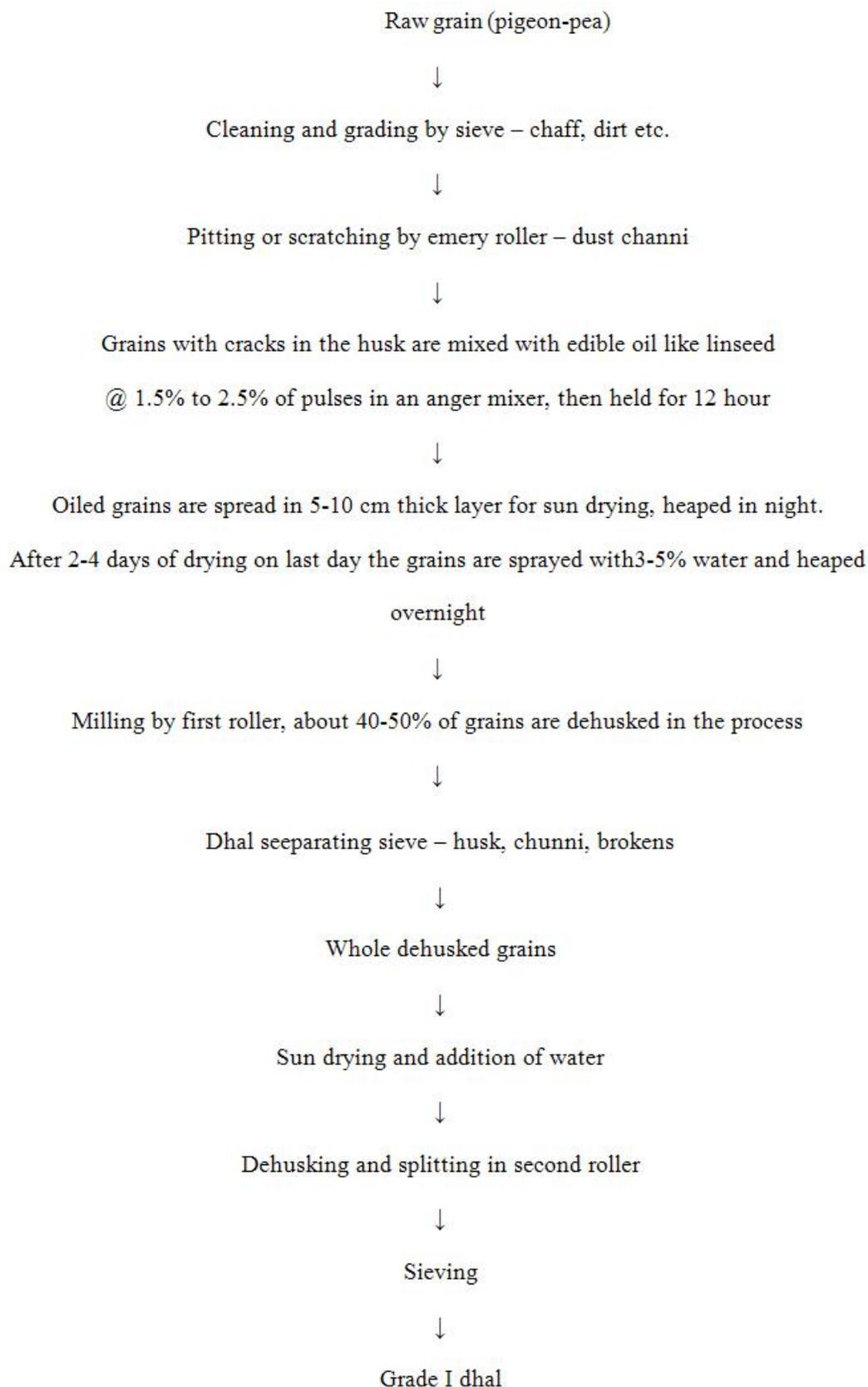
This method of processing is being adopted by comparatively smaller units. This method is practiced in southern india. The milling quality of this method was found to be good and on an average 72% recovery of grains



**Fig-42.1: Flowchart for wet milling method**

### (1) Dry milling method

This method of milling of pulses is mostly adopted in the northern and central India. It varies widely from region to region. Dhal from dry milling method is said to have better cooking quality a wet milling.



**Fig-42.2: Flowchart for dry milling method**

#### 42.4. EQUIPMENT FOR DEHULLING

##### a) Engle berg Huller

The most common machine used for paddy hulling in India is “Engle berg” huller. The working element of this machine is ribbed cast iron roller. The roller rotates on axis inside a large concentric cylinder. On the inner cast iron roller, spiral ribbed strip are mounted to  $\frac{1}{4}$  part of the length and on remaining  $\frac{3}{4}$  part 4 to 6 straight ribbed strips are mounted. The roller is rotated at 600 to 900 rpm. Paddy is fed into the hopper and due to rotational direction of flutes, it is moved around the cylinder and finally towards the outlet. Friction between the grain and the steel parts of the huller causes the husk and bran to be scraped off. The huller does the job of husking and bran removal simultaneously.

##### b) Under Runner Disc Huller

The Under Runner disk huller consist of two horizontal cast iron disks partly covered with an abrasive layer preferably of energy. The top disk is fixed with the body of machines, while the bottom disk rotates. The rotating disk is vertically adjustable by which clearance between the two disks is adjusted. As per the variety and the condition of grains, the clearance is decided. The condition of abrasive coating on the disks also affect the clearance. During hulling there is wear of abrasive coating and is not uniform over the entire surface of coating. Hulling is mainly concentrated at the center, therefore, after some time a ridge is formed at the outer ring of coating.

##### c) Rubber–Roll Sheller

Rubber-roll sheller consists of two rubber rolls rotating in opposite direction at different speed. A feeder feeds uniformly to the machine. Feed is fed in thin layer between the rotating roll by the feeder. One of the roll is fixed while the other is adjustable to obtain desirable clearance between them. Speed of the rolls develop a shearing force on grain surface resulting in the opening and breaking of husk.

##### d) Husk Separator

This machine is required to blow away husk from the mixture of shelled grains, husk and unshelled grain obtained from huller/sheller. In the first stage the husk, brokens, germ and bran must be separated which is accomplished by the husk separator. It is a simple machine having a fan and an arrangement to distribute the product of sheller uniformly on an oscillating sieve with fine perforation. This is done to ensure that air flows across uniformly and blow away the husk, the broken, germs and bran are separated through perforation while the immature grains are also blown away by fan.

##### e) Popular Industrialised Dehulling System

###### i) Hot Dehulling

The most popular dehulling system to meet today’s high protein/low fiber meal market is Crown’s Hot Dehulling System. This system will produce the meal quality for 12 months of the year, even with hard to dehull new crop beans while maintaining hull fats of less than 1%. When processing high moisture beans, up to 13.5% moisture, directly from the field or within a couple of weeks of harvest, the Crown Hot Dehulling system will produce the high protein/low fiber meal as per the market requirements. With the Hot Dehulling system there is no need to install expensive, high maintenance Grain Dryers, Tempering Silo’s, or Rotary Conditioners. In a standard conventional

dehulling system the beans are heated twice, but in the Hot Dehulling system the beans are heated only once. A Vertical Seed Conditioner - 'VSC' is used to slowly heat the beans to 140°F [60°C] and dry the beans upto more than 2% moisture level. This heating and drying process results in very consistent conditioned beans in only 30 minutes. The patented Jet Dryer is then used for the final heating and drying.

### ii) Warm Dehulling

The Warm Dehulling System is designed for areas of the world where imported beans are processed. With imported beans, the beans are harvested two to three months prior to processing and are naturally conditioned during the shipping process. There are only two changes from Hot Dehulling system to Crown's Warm Dehulling System. One is a slightly larger Crown VSC installed to heat the beans to proper flaking temperatures, 155°F [70°C] along with drying more than 2%. The other change is the Jet Dryer is no longer required, reducing installation costs. The remainder of the dehulling system is very similar to the Hot Dehulling system. The low fiber/high protein meal is still accomplished while maintaining hull fats close to 1%. The warm system is designed so the customer can upgrade to a complete hot Dehulling system in the future.

### iii) Cold Dehulling

A Cold Dehulling System if plants have an existing preparation system that includes grain dryers and conditioners and want to add dehulling to produce a lower fiber meal. The cold system utilizes existing drying and conditioning equipment and installs the very efficient, patented Aspirators to separate the free hulls and meats after the cracker and conditioner. Again, we design this system so it can easily be upgraded to a complete Hot Dehulling system in the future. With any of the systems you choose, Crown's experienced technical expertise will provide you with the best solution for your plant layout.



Fig.42.3 Dehulling Machine



Fig.42.4 Dehulling-Shelling-Cleaning Machine Machine

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## Lesson 43

### Size reduction

#### 43.1. INTRODUCTION

Size reduction of solids involves creating smaller mass units from larger mass units of the same material. To bring this about, the larger mass units need to be subjected to stress by the application of force. Three types of force may be applied, i.e. compression, impact and shear. Compressive forces are generally used for the coarse crushing of hard materials. Careful application of compressive forces enables control to be exercised over the breakdown of the material, e.g. to crack open grains of wheat to facilitate separation of the endosperm from the Bran. Impact forces are used to mill a wide variety of materials, including fibrous foods. Shear forces are best applied to relatively soft materials, again including fibrous foods. All three types of force are generated in most types of mill, but generally one predominates. For example, in most roller mills compression is the dominant force, impact forces feature strongly in hammer mills and shear forces are dominant in disc attrition

The extent of the breakdown of a material may be expressed by the reduction ratio, which is the average size of the feed particles divided by the average size of the products particles. In this context, the term average size depends on the method of measurement. In the food industry, screening or sieving is widely used to determine particle size distribution in granular materials and powders. In this case, the average diameter of the particles is related to the aperture sizes of the screens used. Size reduction ratios vary from below 8:1 in coarse crushing to more than 100:1 in fine grinding.

#### 43.2. OBJECTIVE

The breakdown of solid material through the application of mechanical forces is a frequent requirement in many food-processing operations. The reasons for size reduction are varied.

Size reduction may aid the extraction of a desired constituent from a composite structure, e.g. flour from wheat grains or juice from sugar cane.

Reduction to a definite size range may be a specific product requirement; e.g. as in the manufacture of icing sugar, in the preparation of spices and in chocolate refining.

A decrease in particle size of a given mass of material leads to an increase in surface of the solid. This increase in surface is of assistance in many rate process, e.g.

The drying time for moist solids is much reduced by increasing the surface area of the solid.

The rate of extraction of a desired solute is increased by increasing the contact area between solid and solvent.

Process time required for certain operation such as cooking, blanching, etc.-can be reduced by cutting, shredding or dicing the process material.

Intimate mixing or blending is usually easier with small size ranges of particles, an important consideration in the production of formulated packaged soups, cake mixes, etc.

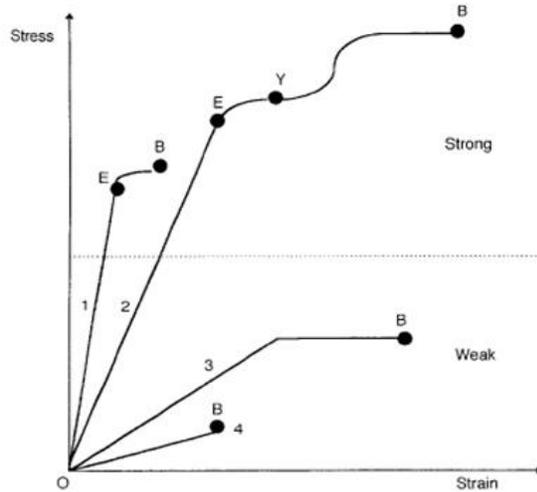
The objective in many size reduction operations is to produce particles within a specified size range. Consequently, it is common practice to classify the particles coming from a mill into different size ranges. Again, screening is the technique most widely used for this purpose. To achieve a specified reduction ratio, it may be necessary to carry out the size reduction in a number of stages. A different type of mill may be used in each stage and screens employed between stages.

### 43.3. PROCESS DESCRIPTION

When a solid material is subjected to a force, its behaviour may be represented by a plot of stress versus strain, Some materials exhibit elastic deformation when the force is first applied. The strain is linearly related to stress (see curve 2 in Fig.43.1). If the force is removed the solid object returns to its original shape. Elastic deformations are valueless in size re-duction. Energy is used up but no breakdown occurs. Point E is known as the elastic limit.

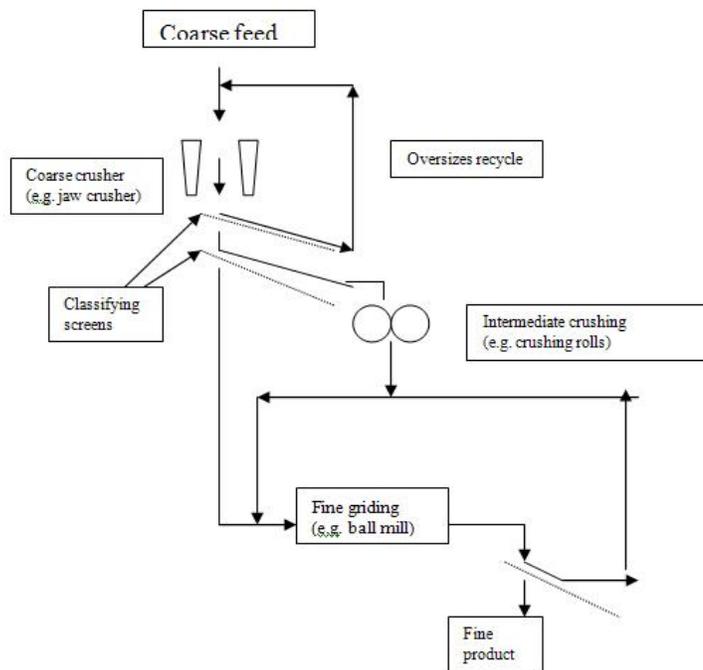
Beyond this point, the material undergoes permanent deformation until it reaches its yield point Y. Brittle materials will rupture at this point. Ductile materials will continue to deform, or flow, beyond point Y until they reach the break point B, when they rupture. The behaviour of different types of material is depicted by the five curves in Fig 43.1. and explained in the legend on the figure. The breakdown of friable materials may occur in two stages. Initial fracture may occur along existing fissures or cleavage planes in the body of the material. In the second stage new fissures or crack tips are formed and fracture occurs along these fissures. Larger particles will contain more fissures than smaller ones and hence will fracture more easily. In the case of small particles, new crack tips may need to be created during the milling operation. Thus, the breaking strength of smaller particles is higher than the larger ones. The energy required for particle breakdown increases with decrease in the size of the particles.

In the limit of very fine particles, only intermolecular forces must be overcome and further size reduction is very difficult to achieve. However, such very fine grinding is seldom required in food applications. Only a very small proportion of the energy supplied to a size reduction plant is used in creating new surfaces. Literature values range from 2.0% down to less than 0.1%. Most of the energy is used up by elastic and inelastic deformation of the particles, elastic distortion of the equipment, friction between particles and between particles and the equipment, friction losses in the equipment and the heat, noise and vibration generated by the equipment.



**Fig- 43.1: Stress-strain diagram for various foods**

(E, elastic limit; Y, yield point; B, breaking point; O-E, elastic region; E-Y, inelastic deformation; Y-B, region of ductility. 1. Hard, strong, brittle material. 2. Hard strong ductile material. 3. Soft, weak, ductile material. 4. Soft, weak, brittle material.)



**Fig-43.2: Flow sheet for typical size reduction plant with three reduction stages**

#### 43.4. ENERGY ANALYSIS

Mathematical models are available to estimate the energy required to bring about a specified reduction in particle size. These are based on the assumption that the energy  $dE$  required to produce a small change  $dx$  in the size of a unit mass of material can be expressed as a power function of the size of the material. Thus:

$$dE/dx = - K/x^n \dots\dots\dots 1$$

Rittinger's Law is based on the assumption that the energy required should be proportional to the new surface area produced, i.e.  $n=2$ . So:

$$dE/dx = - K/x^2 \dots\dots\dots 2$$

or, integrating

$$E = K[1/x_2 - 1/x_1] \dots\dots\dots 3$$

Where  $x_1$  is the average initial size of the feed particles,  $x_2$  is the average size of the product particles,  $E$  is the energy per unit mass required to produce this increase in surface area and  $K$  is a constant, known as Rittinger's constant. Rittinger's law has been found to hold better for fine grinding.

Kick's Law is based on the assumption that the energy required should be proportional to the size reduction ratio, i.e.  $n = 1$ . So:

$$dE/dx = - K/x \dots\dots\dots 4$$

or, integrating

$$E = - \ln[x_1/x_2] \dots\dots\dots 5$$

Where  $n$  is the size reduction ratio (see above). Kick's law has been found to apply best to coarse crushing.

In Bond's Law,  $n$  is given the value  $3/2$ . So:

$$dE/dx = K/x^{3/2} \dots\dots\dots 6$$

or, integrating :

$$E = 2 K [ 1/ (x_2)^{1/2} - 1/ (x_1)^{1/2} ] \dots\dots\dots 7$$

Bond's law has been found to apply well to a variety of materials undergoing coarse, intermediate and fine grinding.

**43.5. SIZE-REDUCTION EQUIPMENT**

a) Roller mill

A common type of roller mill consists of two cylindrical steel rolls, mounted on horizontal axes and rotating towards each other. The particles of feed are directed between the rollers from above. They are nipped and pulled through the rolls where they are subjected to compressive forces, which bring about their breakdown. If the rolls turn at different speeds shear forces may be generated which will also contribute to the breakdown of the feed particles .

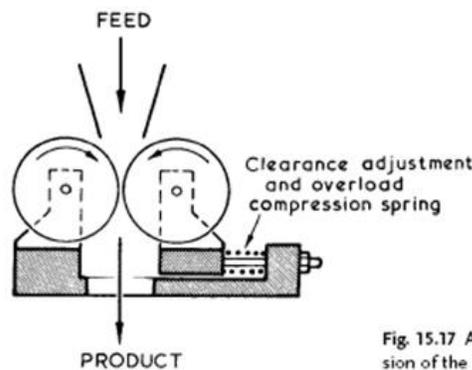


Fig. 15.17 A roller mill; from [6] with permission of the authors.

**Fig: 43.3-A roller mill**

b) Ball Mills

In the ball mill both shearing and impact forces are utilized in the size reduction. The unit consists of a horizontal, slow speed-rotating cylinder containing a charge of steel balls or flint stones. As the cylinder rotates balls are lifted up the sides of the cylinder and drop on to the material being comminuted, which fills the void spaces between the balls. The balls also tumble over each other, exerting a shearing action on the feed material. This combination of impact and shearing forces brings about a very effective size reduction. Ball sizes are usually in the range 1 – 6

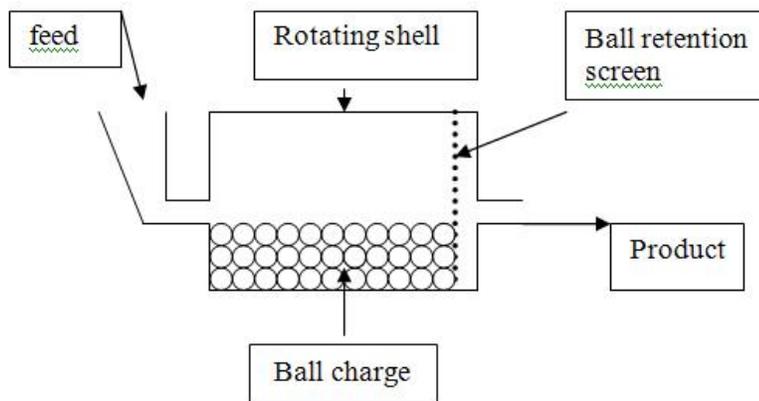
inches. Small balls give more point contacts but larger balls give greater impact. As with all grinding mills, working surfaces gradually wear, so product contamination must be guarded against.

At low speeds of rotation the balls are not lifted very far up the walls of the cylinder. The balls tumble over each other and shear forces predominate. At faster speeds the balls are lifted further and the impact forces increase. Attrition and impact forces play a part in reduction. At high speeds the balls can be carried round at the wall of the mill under the influence of centrifugal force. Under these conditions grinding ceases. For efficient milling the critical speed should not be exceeded. This is defined as the speed at which a small sphere inside the mill just begins to centrifuge. It can be shown that the critical speed  $N_c$  in r.p.m., is given by:

$$N_c = 41.98 / \sqrt{2R}$$

Where,  $R$  is the radius of the mill, in m

In practice, the optimum operating speed is about 75% of the critical speed and should be determined under the plant operating conditions.



**Fig-43.4: A ball mill**

#### c) Impact Percussion Mill

When two bodies collide, i.e. impact, they compress each other until they have the same velocity and remain in this state until restitution of the compression begins. Then the bodies push each other apart and separate. If one of the bodies is held in position, the other body has to conform with this position for a short interval of time. During the very short time it takes for restitution of compression to occur, a body possesses strain energy which can lead to fracture. The faster the bodies move away from each other the more energy is available to bring about fracture.

#### d) Beater Bar mill

In this type of mill, the hammers are replaced by bars in the form of a cross. The tips of the bars pass within a small clearance of the casing. Beater bars are mainly used in small machines.

#### e) Comminuting Mill

Knives replace the hammers or bars in this type of mill. They may be hinged to the shaft so that they swing out as it rotates. Alternatively, they may be rigidly fixed to the shaft. Such mills are used for comminuting relatively soft materials, such as fruit and vegetable matter. In some designs, the knives are sharp on one edge and blunt on the other. When the shaft rotates in one direction the machine has a cutting action. When the direction of rotation of the shaft is reversed, the blunt edges of the knives act as beater bars.

#### f) Pin (Pin-Disc) Mill

In one type of pin mill a stationary disc and rotating disc are located facing each other, separated by a small clearance. Both discs have concentric rows of pins, pegs or teeth. The rows of one disc fit alternately into the rows of the other disc. The pins may be of different shapes; round, square or in the form of blades. The feed in

introduced through the centre of the stationary disc and passes radially outwards through the mill where it is subjected

to impact and shear forces between the stationary and rotating pins. The mill may be operated in a choke feed mode by having a screen fitted over the whole or part of the periphery.

#### g) Fluid Energy Jet Mill

In this type of mill, the solid particles to be comminuted are suspended in a gas stream travelling at high velocity into a grinding chamber. Breakdown occurs through the impact between individual particles and with the wall of the chamber. The gases used are compressed air or superheated steam, which are admitted to the chamber at a pressure of the order of 700 kPa. An air-solids separation system, usually a cyclone, is used to recover the product. Particles up to 10 mm can be handled in these mills but usually the feed consists of particles less than 150  $\mu$ m. The product has a relatively narrow size range. Since there are no moving parts or grinding media involved, product contamination and maintenance costs are relatively low. However, the energy efficiency of such mills is relatively low.

#### h) Attrition Mills

The principle of attrition mills is that the material is rubbed between two surfaces. Both pressure and frictional forces are generated. The extent to which either of these forces predominates depends on the pressure with which both surfaces are held together and the difference in the speed of rotation of the surfaces.

#### i) Rod Mill

Grinding rods, usually made of high carbon steel, are used instead of balls in rod mills. They are 25–125 mm in diameter and may be circular, square or hexagonal in cross-section. They extend to almost the full length of the shell and occupy about 35% of the shell volume. In such mills, attrition forces predominate but impacts also play a part in size reduction. They are classed as intermediate grinders and are more useful than ball mills for milling sticky materials.

### 43.6. Selection Criteria for Size-reduction Equipment

#### a) Mechanical Properties of the Feed

Friable and crystalline materials may fracture easily along cleavage planes. Larger particles will break down more readily than smaller ones. Roller mills are usually employed for such materials. Hard materials, with high moduli of elasticity, may be brittle and fracture rapidly above the elastic limit. Alternatively, they may be ductile and deform extensively before breakdown. Generally, the harder the material, the more difficult it is to break down and the more energy is required. For very hard materials, the dwell time in the action zone must be extended, which may mean a lower throughput or the use of a relatively large mill. Hard materials are usually abrasive and so the working surfaces should be made of hard wearing material, such as manganese steel, and should be easy to remove and replace.

#### b) Moisture Content of the Feed

The moisture content of the feed can be of importance in milling. If it is too high, the efficiency and throughput of a mill and the free flowing characteristics of the product may be adversely affected. In some cases, if the feed material is too dry, it may not breakdown in an appropriate way. For example, if the moisture content of wheat grains are too high, they may deform rather than crack open to release the endosperm. Or, if they are too dry, the bran may break up into fine particles which may not be separated by the screens and may contaminate the white flour. Each type of grain will have an optimum moisture content for milling. Wheat is usually 'conditioned' to the optimum moisture content before milling.

Another problem in milling very dry materials is the formation of dust, which can cause respiratory problems and fire and explosion hazard. In wet milling, the feed materials is carried through the action zone of the mill in a stream of water.

### c) Temperature Sensitivity of the Feed

A considerable amount of heat may be generated in a mill, particularly if it operates at high speed. This arises from friction and particles being stressed within their elastic limits. This heat can cause the temperature of the feed to rise significantly and a loss in quality could result. If the softening or melting temperatures of the materials are exceeded the performance of the mill may be impaired. Some mills are equipped with cooling jackets to reduce these effects. Cryogenic milling involves mixing solid carbon dioxide or liquid nitrogen with the feed. This reduces undesirable heating effects. It can also facilitate the milling of fibrous materials, such as meats, into fine particles.



## Lesson 44 Distillation

### 44.1. INTRODUCTION

Distillation is a separation process, separating components in a mixture by making use of the fact that some components vaporize more readily than others. When vapours are produced from a mixture, they contain the components of the original mixture, but in proportions which are determined by the relative volatilities of these components. The vapour is richer in some components, those that are more volatile, and so a separation occurs.

In fractional distillation, the vapour is condensed and then re-evaporated when a further separation occurs. It is difficult and sometimes impossible to prepare pure components in this way, but a degree of separation can easily be attained if the volatilities are reasonably different. Where great purity is required, successive distillations may be used. The following types of distillation processes are in use

### 44.2. STEAM DISTILLATION

In some circumstances in the food industry, distillation would appear to be a good separation method but it cannot be employed directly as the distilling temperatures would lead to breakdown of the materials. In cases in which volatile materials have to be removed from relatively non-volatile materials, steam distillation may sometimes be used to effect the separation at safe temperatures.

A liquid boils when the total vapour pressure of the liquid is equal or more than the external pressure on the system. Therefore, boiling temperatures can be reduced by reducing the pressure on the system; for example by boiling under a vacuum, or by adding an inert vapour which by contributing to the vapour pressure, allows the liquid to boil at a lower temperature. Such an addition must be easily removed from the distillate, if it is unwanted in the product, and it must not react with any of the components that are required as products. The vapour that is added is generally steam and the distillation is then spoken of as steam distillation.

If the vapour pressure of the introduced steam is  $p_s$  and the total pressure is  $P$ , then the mixture will boil when the vapour pressure of the volatile component reaches a pressure of  $(P - p_s)$ , compared with the necessary pressure of  $P$  if there were no steam present. The distribution of steam and the volatile component being distilled, in the vapour, can be calculated. The ratio of the number of molecules of the steam to those of the volatile component, will be equal to the ratio of their partial pressures -

$$p_A/p_s = (P - p_s)/p_s = (w_A/M_A)/(w_s/M_s)$$

and so the weight ratios can be written:

$$w_A/w_s = (P - p_s)/p_s \times (M_A/M_s)$$

where  $p_A$  is the partial pressure of the volatile component,  $p_s$  is the partial pressure of the steam,  $P$  is the total pressure on the system,  $w_A$  is the weight of component A in the vapour,  $w_s$  is the weight of steam in the vapour,  $M_A$  is the molecular weight of the volatile component and  $M_s$  is the molecular weight of steam.

Very often the molecular weight of the volatile component that is being distilled is much greater than that of the steam, so that the vapour may contain quite large proportions of the volatile component. Steam distillation is used in the food industry in the preparation of some volatile oils and in the removal of some taints and flavours, from edible fats and oils.

#### 44.3. BATCH DISTILLATION

Batch distillation is the term applied to equipment into which the raw liquid mixture is admitted and then boiled for a time. The vapours are condensed. At the end of the distillation time, the liquid remaining in the still is withdrawn as the residue. In some cases the distillation is continued until the boiling point reaches some predetermined level, thus separating a volatile component from a less volatile residue. In other cases, two or more fractions can be withdrawn at different times and these will be of decreasing volatility. During batch distillation, the concentrations change both in the liquid and in the vapour.

Let  $L$  be the mols of material in the still and  $x$  be the concentration of the volatile component. Suppose an amount  $dL$  is vaporized, containing a fraction  $y$  of the volatile component.

Then writing a material balance on component A, the volatile component:

$$y \Delta L = \Delta(Lx) = L\Delta x + x\Delta L$$

$$y \Delta L - x\Delta L = L\Delta x$$

$$(y - x)\Delta L = L\Delta x$$

$$\Delta L/L = \Delta x/(y - x)$$

and this is to be integrated from  $L_0$  moles of material of concentration  $x_0$  up to  $L$  moles at concentration  $x$ .

To evaluate this integral, the relationship between  $x$  and  $y$ , that is the equilibrium conditions, must be known.

If the equilibrium relationship is a straight line,  $y = mx + c$ , then the integral can be evaluated:

$$\text{Log}L/L_0 = 1/\text{Log}e (m - 1)x + c$$

$$(m - 1) (m - 1)x_0 + c$$

or

$$L/L_0 = [(y - x)/(y_0 - x_0)]^{1/(m-1)}$$

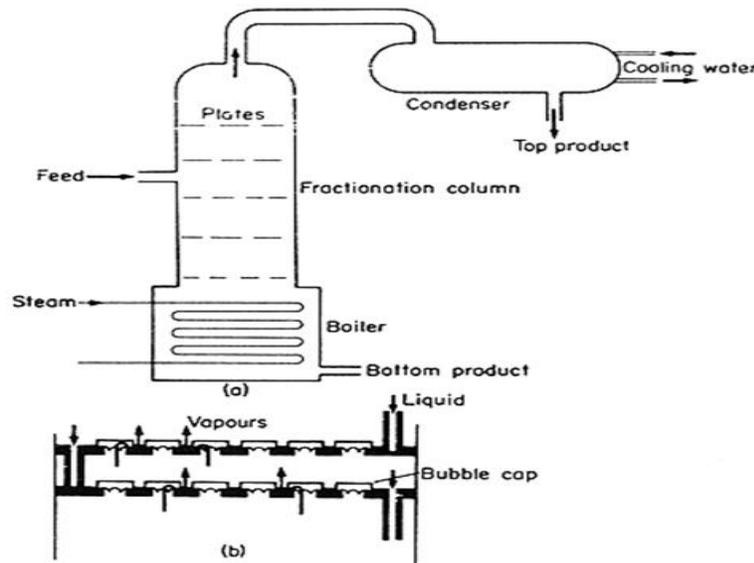
In general, the equilibrium relationship is not a straight line, and the integration has to be carried out graphically. A graph is plotted of  $x$  against  $1/(y - x)$ , and the area under the curve between values of  $x_0$  and  $x$  is measured.

#### 44.4. VACUUM DISTILLATION

Reduction of the total pressure in the distillation column provides another means of distilling at lower temperatures. When the vapour pressure of the volatile substance reaches the system pressure, distillation occurs. With modern efficient vacuum-producing equipment, vacuum distillation is tending to supplant steam distillation. In some instances, the two methods are combined in vacuum steam distillation.

#### 44.5. DISTILLATION EQUIPMENTS

The conventional distillation equipment for the continuous fractionation of liquids consists of three main items: a boiler in which the necessary heat to vaporize the liquid is supplied, a column in which the actual contact stages for the distillation separation are provided, and a condenser for condensation of the final top product. A typical column is illustrated in Figure 44.1 .



**Fig- 44.1: Distillation column (a) assembly, (b) bubble-cap trays**

The condenser and the boiler are straightforward. The fractionation column is more complicated as it has to provide a series of contact stages for contacting the liquid and the vapour. The conventional arrangement is in the form of "bubble-cap" trays, which are shown in Fig. 44.1 (b). The vapours rise through the bubble caps. The liquid flows across the trays past the bubble caps where it contacts the vapour and then over a weir and down to the next tray. Each tray represents a contact stage, or approximates to one as full equilibrium is not necessarily attained, and a sufficient number of stages must be provided to reach the desired separation of the components.

In steam distillation, the steam is bubbled through the liquid and the vapours containing the volatile component and the steam are passed to the condenser. Heat may be provided by the condensation of the steam, or independently. In some cases the steam and the condensed volatile component are immiscible, so that separation in the condenser is simple.

#### 44.6. APPLICATION

##### a) Manufacture of Whisky

Whisky is a spirit produced by the distillation of a mash of cereals, which may include barley, corn, rye and wheat, and is matured in wooden casks. There are three types of Scotch and Irish whisky: malt whisky produced from 100% malted (germinated) barley, grain whisky produced from unmalted cereal grains and blended whisky which contains 60– 70% grain whisky and 30–40% malt whisky.

##### b) Manufacture of Neutral Spirit

A multicolun distillation plant is used for producing neutral spirits from fermented mash. A typical system would be comprised of five columns: a whisky-separating column, an aldehyde column, a product-concentrating column, an aldehyde-concentrating column and a fusel oils concentrating column. The whisky-separating column is fitted with sieve plates, with some bubble cap plates near the top of the column. The other four columns are fitted with bubble cap plates. The fermented mash containing 7% (v/v) of alcohol is fed to near the top of the whisky-separating column. The overhead distillate from this column is fed to the aldehyde column. The bottom product from this column is pumped to the middle of the product-concentrating column. The end product, neutral spirit, is withdrawn from near the top of this column.

c) Recovery of solvents from oil after extraction

Most of the solvent can be recovered by evaporation using a film evaporator. However, when the solution becomes very concentrated, its temperature rises and the oil may be heat-damaged. The last traces of solvent in the oil may be removed by steam distillation or stripping with nitrogen.

d) Concentration of Aroma Compounds from Juices and Extracts

By evaporating 10–30% of the juice in a vacuum evaporator, most of the volatile aroma compounds leave in the vapour. This vapour can be fed to a distillation column. The bottom product from the column is almost pure water and the aroma concentrate leaves from the top of the column. This is condensed and may be added back to the juice or extract prior to drying. Fruit juices and extract of coffee may be treated in this way.

e) Extraction of Essential Oils from Leaves, Seeds, etc.

This may be achieved by steam distillation. The material in a suitable state of subdivision is placed on a grid or perforated plate above heated water. In some cases the material is in direct contact with the water or superheated steam may be used. If the oil is very heat sensitive distillation may be carried out under vacuum.



**Lesson 45****Microwave Processing****45.1. INTRODUCTION**

Microwaves are part of electromagnetic spectrum in the frequency range falling between radio and infrared region. Two frequencies have been set aside for exclusive use of microwave heating application namely 915 MHz and 2450 MHz.

Microwave heating is a method that offers technique of heating requiring neither conduction nor convection. Microwave generates heat within the food rapidly raising the temperature to the desired extent. Special oscillator tubes called magnetrons and klystrons, which generate the microwaves are used. These devices convert low frequency electrical energy into hundreds and thousands of megacycles. The electromagnetic energy at microwave frequency is conducted through a coaxial tube or wave-guide at a point of usage. The microwaves are channeled along a wave guide, then a stirrer or paddle distributes them evenly into cavity. Once they are inside the cavity, three things can happen to the microwaves, i.e. reflection, transmission and absorption.

The microbial inactivation kinetics for microwaves are essentially the same as the inactivation kinetics of conventional thermal processing. Although as many as four separate effects have been proposed -selective heating of micro-organisms, electroporation, cell membrane rupture and cell lyses due to electromagnetic energy coupling are the significant ones. It has also been suggested that microorganism load can be reduced to a greater extent by microwave treatment.

**45.2. Mechanism of Microwave Heating:**

Heating with microwave frequency involves primarily two mechanisms dielectric and ionic. Water in the food is often the primary component responsible for dielectric heating. Due to their dipolar nature, water molecules try to follow the electric field associated with electromagnetic radiation as it oscillates at the very high frequency. Such oscillation of trip molecules produces heat. The second major mechanism of heating with microwave frequency is through the oscillatory migration of ions in the food that generate heat under the influence of the oscillating electric field. Kinetic energy is actually imparted to the ions by the electric field so that the field is alternating rapidly heat.

Microwaves penetrate materials and release their energy in the form of heat as the polar molecules (ones with positively and negatively charged ends - such as water) vibrate at high frequency to align themselves with the frequency of the microwave field. The microwaves interact directly with the object being heated. The interaction is related to the chemical properties of the object and it is possible to apply heat in ways that cannot be achieved by conventional means: convection heating, conductive heating or radiant heating.

### 45.2.1. Microwave Generation

The microwaves are generated by special oscillator tubes called "Magnetrons and Kystron". These are devices that convert low frequency electrical energy into hundreds and thousands of megacycles. The electromagnetic energy, at microwave frequency is conducted through a coaxial tube or wave guide at a point of usage. Both Magnetron and Kystron are electron tubes which generate microwaves.

1. Magnetron : It is a cylindrical diode with a ring of resonant cavities that acts as a anode structure. The cavity is the space in the tube which becomes excited in a way that makes at a source for the oscillation of microwave energy . The Magnetron is a vacuum valve in which the electron, emitted by the cathode, turn around under the action of a continuous electric field produced by the power supply and of a continuous magnetic field. The movement produces the electro-magnetic radiation.

2 Keltron: It is a vacuum tube in which the oscillation are generated by alternatively slowing down and speeding upon electron beam. This results in periodic bunching of electrons. Keltron uses the transit time between two given points to produce this modulated electron stream which then delivers pulsating energy to a cavity resonator and sustain oscillation within the cavity.

#### Advantages of Microwave Processing:

The main advantage of a microwave oven over the conventional oven (electric and gas oven) is its high thermal efficiency in converting the energy in electricity into heat in the food. Other advantages are:

Speedy: microwave cookers heat food more quickly than any other conventional oven (shortening of processing time often by 70-85% and more).

Clean: with microwave cooking there is no risk of the food burning onto the cooker walls or they do not become hot in the way that the surfaces of conventional oven do. In addition, most foods are cooked covered and so remain in their containers (higher quality of product).

Smell free: because food is contained within the cooker cavity (and usually also in a covered dish), smells are kept to a minimum.

Less washing up: it is often possible to microwave food in serving containers or on the plate from which it is to be eaten. This is reducing the kind of washing up required when saucepans and metal oven dishes are used.

Thawing: thawing can be done quickly in a microwave cooker, saving hours in the fridge or kitchen and removing, the need for too much forward planning.

Nutritionally sound: many foods retain more nutrients than when cooked conventionally, as cooking time is so short, and there is little or no added water, particular examples are fish, vegetable.

Easy to use: once controls and cooking techniques are mastered, microwave cookers are extremely easy to use.

Cool: unlike conventional ovens, microwave cookers do not produce external heat and so can be used anywhere that is convenient such as a dining room.

Higher capacity: due to shorter residence time

Less space requirement by up to 50-90% against other methods

Better hygiene of working environment

Easier and faster maintenance

Savings of electric energy in comparison with conventional methods are frequently within the range of 25-50%.

Waste elimination and lower consumption of fossil fuels, causing lowering of environmental stress.

### **Disadvantages of Microwave processing**

Because of speed, and the way in which microwave energy cooks, food cooked in a microwave oven will not be brown, so no crust formation or browning in case of bread or meat (in such cases microwave with grilling can be used).

High initial cost.

Short cooking time does not allow flavors to develop and this makes food unacceptable.

### **Application of Microwave in dairy and Food Processing**

**Baking:** for internal heating microwave, for external heating hot air (electric coil) or infrared for crust formation.

**Concentrating:** concentration of heat sensitive fluids and slurries at relatively low temperature in relatively short time.

**Cooking:** it cooks relatively larger pieces without high temperature gradients between surface and interior (for continuous cooking of meals).

**Curing:** effective for glue-line curing of laminates (as in package) without direct heating of the laminate themselves.

**Drying:** microwave selectively heats water with little direct heating of most solids. Drying is uniform throughout the product, drying at relatively low temperature.

**Enzyme inactivation (blanching):** rapid and uniform heating inactivates enzymes, so it is adapted for blanching of fruits and vegetables without leaching losses associated with hot water or steam and it does not overcook the outside before core enzymes are inactivated.

**Finish drying:** when most of the water has been removed by conventional drying, microwaves remove the last traces of moisture from the interior of the product quickly, and without overheating the already dried material.

**Freeze drying:** the ability of the microwave energy to selectively heat ice crystals in matter makes it attractive for accelerating the final stages of freeze drying.

**Heating:** almost any heat transfer problem can benefit from the use of microwaves because of their ability to heat in depth without high temperature gradient.

**Pasteurizing:** microwaves heat the product rapidly and uniformly without the overheating associated with conventional methods.

**Precooking:** it is well suited for precooking 'heat and serve' because there is no overcooking and no cooking losses.

**Puffing and foaming:** rapid internal heating by microwave causes puffing and foaming when the rate of heat transfer is made greater than the rate of vapor transfer out of the product interior. May be applied to puffing of snack foods and other materials.

**Solvent removal:** many solvents other than water are efficiently vaporized by microwave, permitting solvent removal at relatively low temperature.

**Sterilizing:** where adequate temperature may be reached (acid foods), quick, uniform come up time may permit HTST sterilization. Selective heating of moisture containing microorganisms makes possible the sterilization of such materials as glass, and plastic films, which are not themselves heated appreciably by microwaves (it will not destroy bacterial spores)

**Tempering:** microwave heating is roughly proportional to moisture content, so it can equalize the moisture in a product that came from the process of non uniform condition.

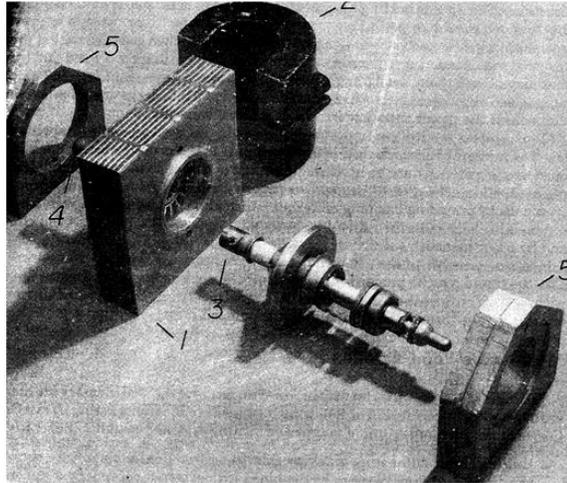
**Thawing:** controlled, rapid thawing of bulk items is possible due to substantial penetration of microwaves into frozen materials.

Microwave processing technique has attracted considerable attention in the dairy and food processing area. However, its application in the dairy industry has not aroused as much interest. Some of the applications of microwave in dairy industry include -inactivation of bacteriophage in cheese whey, production of anhydrous milk fat, heat treatment of whey protein concentrates, mass crystallization of lactose in sweetened condensed milk, sterilization of milk, pasteurization of milk (HTST method), in packaging sterilization of yoghurt and tempering of frozen butter. The process can also be used for cooking of cut curd cubes during cheese making, and plasticizing of Provolone and Mozzarella cheese.

Microwave energy is unique energy sources that may allow shorten processing time, saving in energy, labor and space and often better quality products. Advances in technology concentrating, focusing and controlling microwave energy has increased the feasibility of developing microwave processing for the food and dairy industry.

Microwave processing is expected to grow beyond our expectation due to increasing consumers demands for newer type of convenience foods having more nutritional value and better sensory quality in the recent years. There is a great potential for the combination ovens because they are more effective than either oven alone in the manufacture of shelf stable packed foods. Advances in microwave oven design and narrowing gap in cost between microwave and thermal processing will provide and incentive for the development of newer microwave processes.

Microwave food processing design development will require additional research on mechanisms of microwave heating of foods, particularly in the areas of energy coupling and propagation modes, and further development of quantitative electro physical and electrochemical models as an aid to microwave process design.



1. Anode with multicavity, 2. permanent magnet, 3. cathode assembly, 4. antenna radiating element, 5. mounting block

Fig. 45.1 Magnetron

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## Lesson 46

### Irradiation, Pulsed Electric Field, Ultrasound Processing, Nano technology

#### 46.1. INTRODUCTION

Food radiation has many advantages in food processing like (i) it can extend shelf life of many fresh foods., by preventing sprouting, deactivating moulds and killing spoilage bacteria. (ii) It can improve world food supplies by reducing postharvest losses. (iii) it could replace fumigants and other pesticides, resulting in a reduction of chemical residues in food (iv) It improves food safety by destroying the microorganisms that cause foodborne illness and parasites that cause diseases.

#### 46.2 FOOD IRRADIATION

Food irradiation is the process of exposing food to controlled levels of ionized radiation to kill harmful bacteria, pests, or parasites, or to preserve its freshness.

The process of food irradiation is often called cold pasteurization , because it kills harmful bacteria without heat. The process of radiation is carried out by Gamma Rays or Electron Beams or X-rays.

The amount of radiation used to expose food is controlled by the intensity of the radiation and the length of exposure. The dose permitted for use in food varies according to the type of food and the desired action. Treatment levels have been approved by FDA and adopted by Codex General Standards for irradiated foods are as follows:

“Low” doses, < 1 kGy

1. Control insects in grains and fruits.
2. Inhibit sprouting in tubers.
3. Delay the ripening of some fruits/vegetables.
4. Reduce the problems of parasites in products of animal origin, (e.g., trichinella spiralis in pork).

“Medium” doses, (1-10 kGy)

1. Control Salmonella, Shigella, Campylobacter, Yersinia, Listeria and E. coli in meat, poultry, and fish.
2. Delay mold growth on strawberries and other fruits.

“High” doses, (> than 10 kGy)

1. Kill microorganisms and insects in spices.
2. Commercially sterilize foods, destroying all microorganisms of public health concern (i.e., special diets for people with weakened immune systems) .

It is reported that all the fresh produce is not suitable for irradiation and some radiation treated foods may taste slightly different but nutritional value of food is virtually unchanged.

#### 42.2.1. Infra Red Treatment

Infrared rays belong to one type of electromagnetic waves, and any object with its temperature above absolute zero degree (- 273 ° C.) radiates infrared rays. The wavelength of infrared rays is about between 1 and 1,000 microns. Infrared rays can be classified into near infrared rays (between 1 and 1.5 microns), middle infrared rays (between 1.5 and 5.6 microns), and far infrared rays (between 5.6 and 1,000 microns) according to their energies carried.

Generally, infrared rays radiated from heaters, firebrands, or electric cookers almost belong to near infrared rays which produce a large quantity of thermal effects for short wavelength. Whereas with near infrared rays, far infrared rays will not result thermal effect due to their long wavelengths and relative low energy. Far infrared rays also differ from electromagnetic waves of low frequency (60 Hz) as they have a strong penetrability and change the characteristics of product. Thus they are highly suspected as a serious factor to cancer. The case of far infrared rays is different. In fact, human bodies themselves radiate far infrared rays (9 microns). External far infrared rays only penetrate into skin to 0.1-0.1 centimeter.

In recent years, far infrared ray technologies have been used in military industries, household appliances, food processing and preservation and biochemistry industry, and have achieved quite good effects. Far infrared products not only have multiple functions, but also have small space occupied and low cost.

In future, technology will be advanced that process food will not deteriorate its quality till it reaches to the hands of consumer. This is possible with the help of Nanotechnology and Encapsulation of Food.

Nutrient deficiency and malnutrition are basically as a result of mismatch of production and requirement. Therefore, there will be a need to find out alternate sources of the nutrients. These nutrients, must be having biological origin, may be plant or animal. Extraction of the nutrient in pure form, dilution / conversion in the digestible form and fortification or encapsulation will be the one in future food.

#### 46.3. PULSED ELECTRIC FIELD

It is a technique in which a food is placed between two electrodes and exposed to a pulsed high voltage field (typically 20–80 kV cm<sup>-1</sup>). PEF uses strong electric field processing to deactivate microbial cells, effectively preserving foods with little or no actual heat. For food quality attributes, PEF technology is superior to traditional heat treatment of foods because it avoids or greatly reduces the detrimental changes to the sensory and physical properties of foods. One drawback is that only pumpable fluids can be treated. Flavour freshness, low energy utilization, and extended shelf life, are some of the virtues attributed to PEF treatment. A number of studies have demonstrated effectiveness of pulsed electric field process.

#### 46.4 ULTRASOUND PROCESSING

When ultrasound passes through a liquid medium, Cavitation occurs, causing alternate rarefactions and compressions and is responsible for cellular disruption. The mechanisms involved in cellular disruption are multifactorial and may include shear forces generated during movement (subcellular turbulence) of the bubbles or sudden localised temperature and pressure changes caused by bubble collapse

## 46.5 NANO TECHNOLOGY

Nanotechnology exhibits great potential for the food industry. New methods for processing nanostructures are being developed having novel properties that were not previously possible. Parallel to the development of nanostructure fabrication techniques, nanoscale analysing methods are being developed, which can provide new knowledge and explanations to previously empirically gained knowledge.

### 46.5.1 Nano Technology in Food Packaging and Safety:

Nanotechnology offers many possibilities here. Hollow nanofibres and silicate nanoparticles or metallic/ceramic nanoparticles (carbon nanofibres) combine light weight and strength. These new materials are currently routinely produced in laboratories and can be used for both equipment and structures.

Another promising application in food packaging is Gas-barrier structures with low permeability. Nanoparticles embedded in plastics may be used to retard the diffusion of gases such as oxygen or water vapour by creating tortuous paths. Such products are already in the market.

Encoding or decoding individual surfaces, counterfeit protection using nanotagants, nanocrystalline indicators to sense and signal modified atmosphere environments within packages, light-activated oxygen sensing links, food deterioration sensors and power for smart packagings, such as radiofrequency identification (RFID) are also possible application. Nanotubes may be filled with materials such as antimicrobials to disperse in the plastic matrix.

Materials that could improve bioactivity and thereby biodegradability of polyesters like PLA are boon to environmental control. Surfaces can be nanostructured in order to influence their adhesiveness to products or dirt and there by their susceptibility to fouling, which is important in food processing and food packaging.

### 46.5.2 Nano Technology in Food Processing:

Principal applications are on demand preservatives and interactive foods. Nanocapsules can be incorporated into food to deliver nutrients. Addition of nanoparticles to existing food can enable increased absorption of nutrients. Applications that are already being tested in new products to enter the market. Another key application is additives which could easily be absorbed by the body and could increase product shelf life. Nanosized dispersions, emulsions and filled micelles have the advantage that they are not subjected to sedimentation which gives better product life span and storage. As their size is much smaller than the wavelength of light, they can be incorporated in clear and transparent foods without causing muddiness. Substances difficult to dissolve can more easily be absorbed by the body if they are of nanoscale size due to their large surface area. If the active substance is to be protected during storage or passage through the intestines the existing nanotechnology can produce perfect protective layers. It is also possible to tailor protective layers to release active substances in an “intelligent” way, e.g. caused by a change of pH-value.



## Lesson 47

### High pressure processing

#### 47.1. INTRODUCTION

High hydrostatic pressure processing (HPP), a relatively new technology to the food industry inactivates microorganisms without causing significant flavour and nutritional changes to foods. On the other hand, the effectiveness of thermal processing technologies explains why it remains as the prevailing method to achieve microbial safety and the inactivation of enzymes and microorganisms responsible for food spoilage. However, the high temperatures used in these processes cause significant chemical changes in foods. Particularly important are thermal degradation reactions leading to off-flavours, destruction of nutrients and other product quality losses.

For example, high-temperature short-time (HTST) pasteurization treatments (72°C for 15 s) impart a slight cooked, sulphurous note that has become acceptable to milk consumers but its refrigerated shelf life is only approximately 20 days. Ultra pasteurization (UP), a process similar to HTST pasteurization using more severe treatments (e.g. 1 s at 89 °C, 0.1 s at 96 °C or 0.01 s at 100 °C) lowers flavour quality and causes more nutrient damage but yields milk with a refrigerated shelf life of approximately 30 days. Pressure treatments of 400 MPa for 15 min or 500 MPa for 3 min at room temperature achieves microbiological reductions similar to thermal pasteurization but it is not used commercially because long pressure processing times are not financially viable. HPP treatments (586 MPa for 3 and 5 min) at moderate temperature (55°C) extend the refrigerated shelf life of milk to over 45 days while retaining milk volatile profiles similar to those observed after conventional HTST treatments. Finally, ultra high temperature (UHT) processing (135–150°C for 3–5 s) yields milk that is stable at room temperature for 6 months; however, this process induces strong 'cooked' off-flavour notes thus limiting its consumer acceptance in important markets.

Future advances are expected from the synergistic effects of using high pressure and high temperature combinations in the rapidly evolving pressure-assisted thermal processing technology (PATP). PATP is not yet a commercial application and will require more complex safety validation procedures than HPP, particularly for the case of low-acid foods (pH under 4.5). PATP conditions are sufficiently severe to achieve the inactivation of bacterial spores and recent studies suggest that pressure can lower the degradation rate of product quality caused by high temperature treatments.

High pressure processing at refrigeration, ambient or moderate heating temperature allows inactivation of pathogenic and spoilage microorganisms in foods with fewer changes in food quality as compared to conventional technologies. Pressure acts by disrupting mainly hydrogen bonds without affecting covalent bonds. Therefore, high pressure processing (HPP) treatments at low (approximately 0–30°C) and moderate (approximately 30–50°C) temperature cause minimum losses in quality factors associated with small molecules such as vitamins, pigments and volatile flavours. Research has confirmed that the sensory characteristics of HPP products make them often indistinguishable from untreated controls. Five decimal reductions in pathogens including *Salmonella typhimurium*, *S. enteritidis*, *Listeria monocytogenes*, *Staphylococcus aureus* and *Vibrio parahemolyticus* can be achieved by HPP.

## 47.2. Principle

The high pressure technique is essentially additive-free, mostly non-thermal or involves reduced heat treatments. Based on the pascal or isostatic principle, the hydrostatic pressure at a given point is the same in all directions and pressure is transmitted uniformly and immediately through the pressure transferring medium. Thus, the effects of pressure are independent on product size and geometry. It is often stated that HP processing is a uniform way of processing foods.

The effectiveness of a high pressure treatment is influenced by various intrinsic and extrinsic factors. Treatment time, pressurization or decompression rate, temperature and the number of pulses are critical to the effectiveness of the process. Moreover, the factors which include the effect of pressure on water, adiabatic heating and heat dissipation, food composition and the physiological states of microorganisms to be inactivated must be taken into account when optimising pressure treatments for the production of safe, quality foods.

### 47.2.1. Effects of HPP

- Microorganism inactivation
- Modification of biopolymers including enzyme activation and inactivation, protein denaturation and gel formation.
- Quality retention (colour, flavour, nutritional value)
- Modification of physiochemical properties of water

#### General Description of HP Equipment For Food Industry

The main components of an HP system are a pressure vessel, a pressure generation system, a temperature control device and a material handling system. Most pressure vessels are made from a high tensile steel alloy 'monoblocs' (forged from a single piece of material), which can withstand pressure of 400-600 MPa. For high pressures, pre-stressed multilayer or wire-wound vessels are used. In operation, after all air has been removed, a pressure-transmitting medium (either water or oil) is pumped from a reservoir into the pressure vessel using a pressure intensifier until the desired pressure is reached. Temperature control in commercial operations can be achieved by pumping a heating/cooling medium through a jacket that surrounds the pressure vessel. This is satisfactory in most applications as a constant temperature is required but if it is necessary to change the temperature regularly, an internal heat exchanger is fitted.

There are two methods of processing foods in high pressure vessels: in-container processing and bulk processing. Since foods reduce in volume at the very high pressure used during processing, there is considerable stress and distortion to the package selection is an important issue in using this method. Materials handling for in-container processing is achieved using equipment similar to that used to load/unload batch retorts. Bulk handling of liquids is simpler, requiring only pumps, pipes and valves.

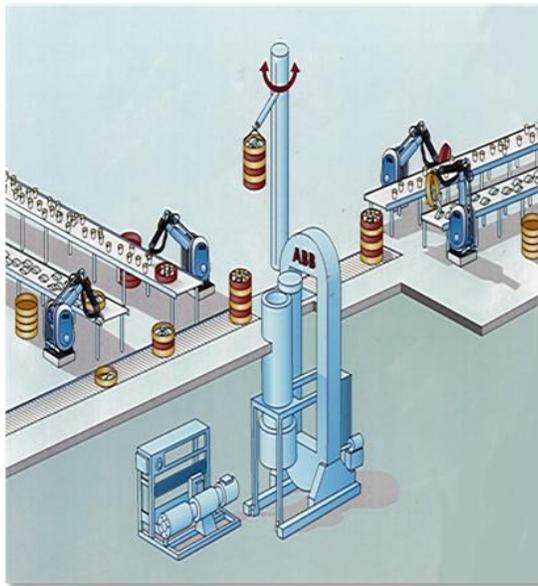
There are two main types of High pressure equipments:

1. Batch type: A batch press can be used for any kinds of food in flexible packages, such as pouches, cups, or bulk bags. With the food already packed in the final consumer package at the processing stage, the risk of contamination is eliminated. The food packaged, are placed in the pressure vessel where they are isostatically compressed.

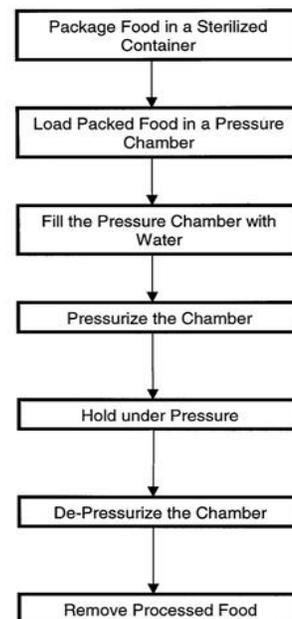
2. Continuous type: Continuous systems can be used for pumpable food. The system is installed with other equipment, and in the end the liquid food reaches an aseptic or clean filler. Thus any kind of consumer package can be used. Top of-the-line, high quality juice may be perceived as more valuable if sold in glass bottles, rather than PET or other plastic that would require for batch cycling.

The volume in a pressure vessel for continuous use is better utilized than in a batch press, where there is dead space between the food packages. Thus the output volume is large despite the fairly small dimensions of the vessels used.

The principle of the continuous system is comparable to a four stroke engine. A valve is opened at the top of the press cylinder to let the product in and then closed. A floating piston inside the cylinder acts as a movable divider, and separates the water from the product. The pressure is the same on both the sides of the floating piston. When full pressure has been reached, it is held for a short period of time. After the hold time is over, the water is released through the bottom of the vessel and thus the vessel is decompressed. Another valve is then opened at the top, and the product leaves the cylinder when water is pumped in at the vessel filling, one for holding, and one for emptying the product. As the vessels take turns delivering the high pressure cycled product. There is an almost continuous output of product. With a balance tank in line with the system, the output will be continuous.



**Fig- 47.1: High Pressure Processing**



### 47. 3 Advantages of HPP

- Retention of flavour and texture of the product
- Increase in Microbiological safety and shelf-life
- Low energy consumption
- Minimal heat input
- Minimal effluent and losses

- Uniform isostatic pressure & adiabatic temperature distribution
- Combination with heat gives better effects

#### 47.4 Applications of HPP

Milk treated at pressures of upto 500 MPa for few minutes has been shown to have a shelf-life at least equivalent to HTST pasteurized milk. Most vegetative cells, including non-sporeforming thermotolerant, can be eliminated.

HPP treatment (200 MPa, 10 min) after acidification (rise of acidity after acidification) in yogurt, increases the water binding capacity of whey proteins.

The cheese yield is not influenced when milk treated at pressure  $\leq 250$  MPa, but at 600-800 MPa, it gets increased by up to 25% with increase in moisture content in curd and decrease in protein content in whey.

Cheese Ripening can be accelerated by using the High Pressure treatment, which avoids the usage of elevated temperatures, addition of cheese slurries or exogenous enzymes or by the use of adjunct starters.

Cheddar cheese, when exposed to HP from 5 to 300 MPa for 3 days at 25°C, shows free amino acid levels of 26.5 mg/g at 50 MPa compared to 21.3 mg/g in the 6-month old cheese (which had not been HP treated). The taste of both the cheese were described as “excellent”. This shows a considerable reduction in the ripening times of the cheese, attained through the application of HPP.

**Table-47.1: Processing parameters of foods by HPP**

PRODUCT	PROCESSING CONDITIONS	PACKAGE
Jams, Fruits dressings, sauces, jellies, Yoghurt	400 MPa, 20°C, 10-30 mins	Plastic cup (100-125 g)
Grape Fruit juice	120-400 MPa, 20°C, 2-20 min	Glass Bottle (200-800 g)
Sugar impregnated tropical fruits for sherbets and ice-creams	50-200 MPa	Paper cups (130 g)
Beef Tenderisation	100-250 MPa, 20°C, 30 mins – 3 hrs	-

High pressure sterilization is possible by starting at elevated temp. e.g. 60–90°C, & using the adiabatic compression for rapid heating to higher temperatures. High pressure sterilisation is a combined process where both pressure and temperature contribute to sterilisation by the inactivation of spores and enzymes. The result is a shelf stable product, and in many cases a higher general quality than those products obtained using conventional processing.



## Lesson 48

### Microfluidization

#### 48.1. INTRODUCTION

Micro fluidization technology is a very unique type of high pressure homogenization in order to produce spherical particles that can act as fat substitute. Micro fluidization homogenization results in fat globules with a narrow size distribution and smaller average fat globules sizes than are usually found using traditional valve homogenizers. Micro fluidization is a new type of homogenization process, which gives fat globules with a diameter of 0.1-5.0  $\mu\text{m}$  (av. 0.35  $\mu\text{m}$ ), i.e. about half the diameter obtained with conventional homogenization. It works by passing the milk through micro channels into an interaction chamber to produce two fine jets that are directed against each other at right angle at high pressures up to 20,000 psi.. As the two microstreams collide, there is a sudden pressure drop and emulsification occurs as a result of turbulence, cavitation and shear effects that occur on impact. An increase in number of passes through the microfluidizer reduces the mean particle size, but there is little to be gained by having more than three passes.

Micro fluidization can produce of fine emulsion, spherically shaped particles from completed aggregated protein dispersion which will have mimic fat and functionality of fat to produce fat substitute. It is a new alternative to produce fat-substitute, which gives spherically shaped particles from a completed aggregated protein (whey proteins or total milk proteins) dispersion into small spherical shaped to mimic the ball bearing effect of fat particles in food. Micro fluidization can be used to extend shelf-life of products such as cream liqueurs and infant formulae by producing fine emulsions (particle size approx. 0.1  $\mu\text{m}$ ). Compared with the high-pressure valve homogenizer, the micro fluidizer produced smaller particles with a narrow size distribution, but the rheological properties of the acid gels were similar to that of produced by high pressure valve homogenization. Micro fluidization in place of homogenization is used as a new technologies for the ice-cream industry and it allows optimal emulsifier concentration around 1% and pressure of 1200 bar. Diameter of the fat globules was changed by varying the micro fluidization pressure from 14 to 35 MPa and the number of passes (2- to 5-times). A decrease in the average hydrodynamic diameter of the fat globules from 390 to 313 nm decreased the rennet coagulation time and the curd firming rate. Consumption of foods containing phytosterols provides health benefits. These nutraceutical compounds have been known to reduce serum total and LDL cholesterol by lowering intestinal cholesterol absorption. However, phytosterols are not suitable in aqueous solution, but micro fluidization process is used as a means of incorporation of phytosterols into fluid milk. Understanding the impact of new micro fluidization processing techniques on the final texture of a cheese helps the food scientist to develop new cheeses like low-fat cheeses with desired texture. Micro fluidization of milk is useful for making cheeses with no or low melting ability or with a crumbly texture. Micro fluidization can cause low-fat and nonfat milk and dairy products, including frozen dairy desserts, to have a body and texture and mouth feel more closely resembling their full-fat counterparts. Micro fluidization produces nonfat and low-fat ice creams that usually had a slower meltdown without affecting sensory properties.

## 48.2 Operational Principle

Micro fluidics homogenizers contain air-powered intensifier pumps designed to supply the desired pressure at a constant rate to the product stream. As the pump travels through its pressure stroke, it drives the product at constant pressure through precisely defined fixed-geometry microchannels within the interaction chamber.

As a result, the product stream accelerates to high velocities creating shear rates within the product stream that are orders of magnitude greater than any other conventional means. All of the product experiences identical processing conditions, producing the desired results, including: uniform particle and droplet size reduction (often submicron), deagglomeration and high yield cell disruption.

## 48.3 Technology Overview

The basic principle behind particle-collision technology is the bombardment of a colloid system or fluid stream against itself inside an interaction chamber of fixed geometry and at very high energy. The energy results in the breakup and dispersion of the slurry. None of the energy is wasted. All product components experience the same high force in the same small area, resulting in extremely small particle sizes and a narrow particle size distribution. With particle-collision technology, no grinding media, mixing blade, or homogenizer valve is required because size is reduced by:

- \* Crushing forces of the particles hitting themselves;
- \* Shear forces on the particles within the interaction chamber;
- \* Cavitation forces due to extreme velocity changes in the material stream.

Particle-collision technology pressurizes a fluid stream, develops high-velocity stream(s), and then smashes these against each other within the interaction chamber. The energy applied to the product can be changed by changing the pressure on the fluid stream - to accommodate more viscous liquids, perhaps, or to create a more intense mixing or dispersing action.

The geometry of the jet paths within the interaction chamber remains constant. Therefore, all particles experience the same forces, and the smallest size and the most uniform size distribution of any of the high-performance mixing processes are achieved. Besides the fixed geometry of the interaction chamber, another factor that ensures uniform particle size is the type of pump used, which is called an "intensifier pump." This pump can be driven by air or hydraulic fluid. The intensifier pump's advantage is that it can pump the product, even viscous systems, through the fixed geometry interaction chamber at constant pressure.

The pressure can be incrementally and accurately increased or decreased over a wide range simply by adding or subtracting pneumatic or hydraulic power. Yet, even though intensifier pumps can be set to a broader range of pressures than conventional pumps, once set their pressures stay constant over the entire process stroke.

Another factor that contributes to the range of particle-collision technology is the overall architecture of the process itself. Breaking the stream in two and redirecting the streams to impinge upon themselves doubles the relative velocity with which particles impact each other. Added to the force of this impact are the cavitation forces created by the sudden increase in velocity within the interaction chamber. This sudden increase in velocity results in a sudden decrease of pressure in the channels, creating bubbles that collapse on themselves. This is cavitation. There are also shear forces acting within the passages at very high speeds.

**48.3.1 Characteristics of particle-collision technology include:**

- \* Smaller particle and droplet sizes;
- \* More uniform particle size distribution;
- \* Faster processing times (greater than two orders of magnitude in some applications);
- \* Better control of the amount of energy applied;
- \* Much higher energy (up to 40,000 psi sustained);
- \* Scalability from small batches to continuous production;
- \* No moving parts in the patented interaction chamber;
- \* Little or no contamination of product being produced;
- \* Uniform dispersions and emulsions;
- \* Highly repeatable process from run to run.

**Table-48.1: Dairy & Food Applications of microfluidization**

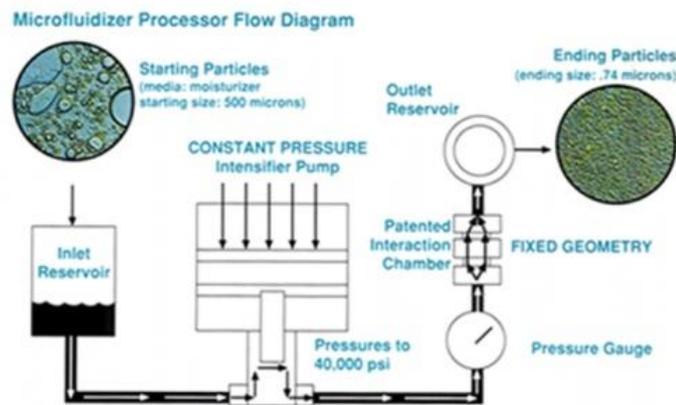
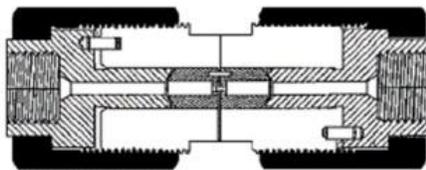
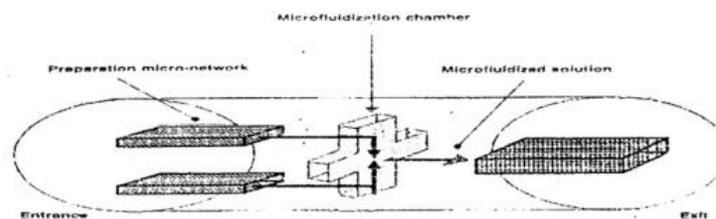
<b>DAIRY APPLICATIONS</b>			
<b>Sample description</b>	<b>Pressure (psi)</b>	<b># passes</b>	<b>Results and comments</b>
Dairy based Emulsion	10,000	3	Heated to 60 °C for processing then was cooled to 45 °C on outlet. Particle size reduced from 0.91μ to 0.13μ Viscosity decrease. Perceived as successful test. Survived canning (post-sterilization) step
vitamins Filtered whey protein	5,000	1&3	Particle size reduced to 10μ in 1 pass and between 2 to 5μ in 3 passes
Cheese slurry, 10% solids	10,000	1-3	Particle size reduced from 100μ down to 30μ Particle size reduced to 10μ with large quantity of back round smaller particles
<b>FOOD APPLICATIONS</b>			
Peanut Butter	3,000	3	Heated sample to 29-32 °F. Particle size reduced from 5-50μ to a good distribution at 20μ Smooth creamy product resulted.
Non-dairy chocolate base	5,000	1 to 3	Heated sample to 52-66 °F. Sample did not separate on standing. Sample was also noticeably thicker. Desired stability and viscosity achieved
Non-fat ice cream Proprietary formulation	18,200	1	Particle size data:-Start: 0.42μ+/- 47%-1 pass: 0.23μ+/- 27%Mouthfeel was noticeable smoother and creamier.
Starch powder in water	7,000	1	Material started as grainy dispersion and became smooth and semi-translucent after one pass. Marked viscosity increase from starting mat'l being like a thin batter and the processed mat'l similar to toothpaste in consistency.
Orange oil in gum arabic for spray drying	11,000	1	Starting particle size: 3.87μ Processed particle size: 0.90μ. 100% retention of feed oil as opposed to 95 % retention for all other competitive equipment. Smaller particles yielded dried powders with less extractable surface oil. Increase stability.
Ketchup	2,000	1	Improved tomato cell rupture resulted in smoother, more homogenous ketchup. Small, experimental batches for R&D work are now possible

e

**Table-48.2: Results of Microfluidizer**

Sample	psi	# Passes	Results & comments
Tomato Sauce	2000	1	Increased viscosity. Smoother, more homogenous sauce with improved mouth feel.
Dairy fillings	3000	1	Superior emulsion. Replaced hand homogenizer.
Soya Milk	4000	1	Particle size reduced from 0.76 to 0.4 microns
Mustard	8000	1	Very smooth results with brighter color and higher sheen.

Micro fluidization results fat of globule particle size about 25% smaller than that found with conventional homogenization and there is no major change in fat-globule size over the storage period. Micro fluidization has little effect on the formation of fat-cluster in milk. Micro fluidization can be used for fat substitute production. Micro fluidization can offer better tasting low-fat ingredients since finer emulsions closely imitate the mouth feel of full-fat products.

**FIG: 48.1 MICROFLUIDIZATION PROCESSOR FLOW DIAGRAM****FIG: 48.2 Schematic cross-section through the dispersion zone of the Microfluidizer, the so-called interaction chamber****FIG: 48.3 Enlarged view of the liquid jet flow through the dissipation zone in the centre area of the interaction chamber**

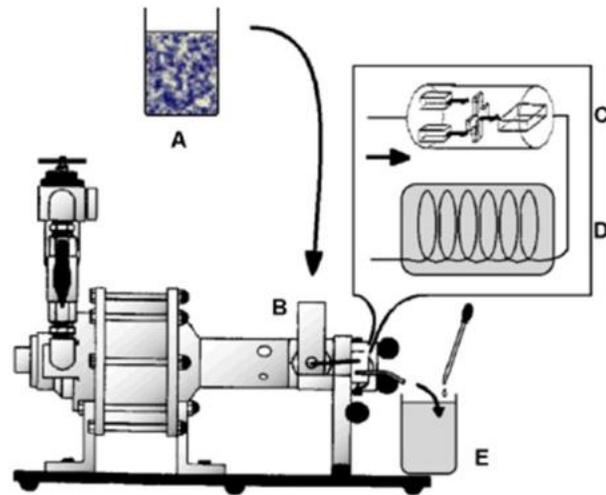


FIG: 48.4 Schematic drawing of the homogenisation process using the Microfluidizer

[A]: Crude dispersions, [B]: Reservoir, [C]: Dissipation zone, [D]: Heat exchanger, [E]: Outlet

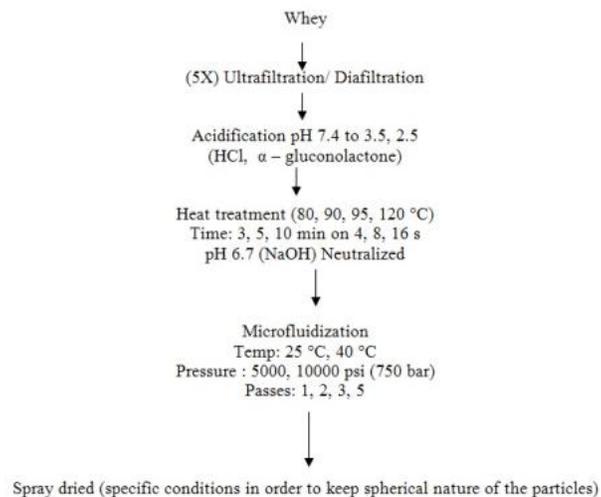


FIG: 48.5 Fat substitute production

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