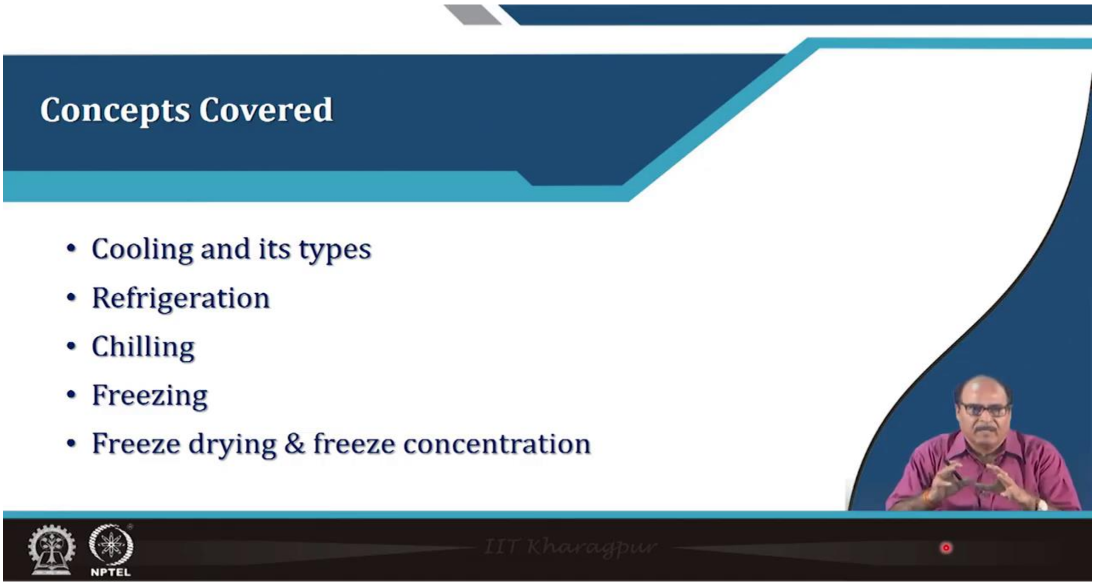
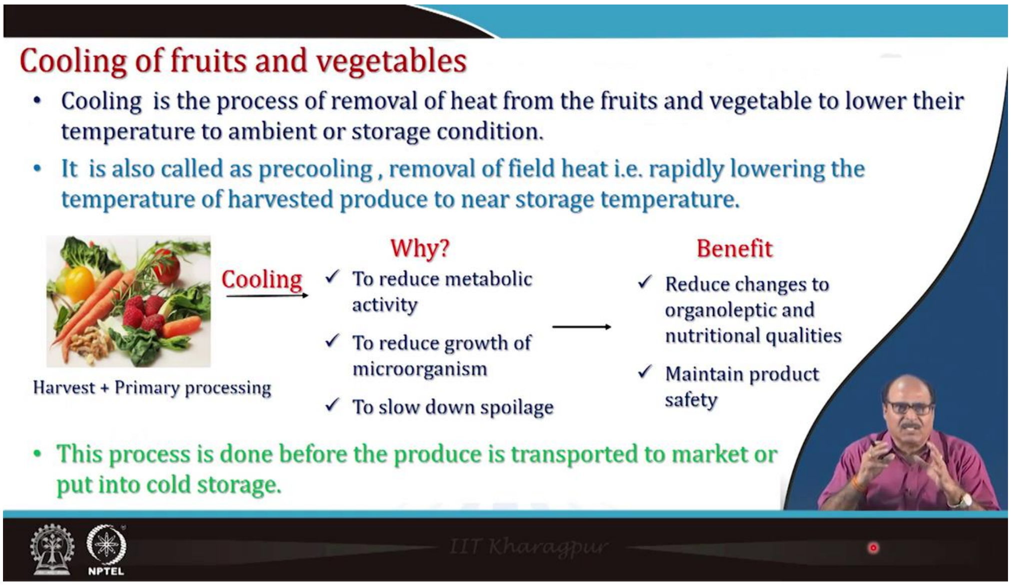
Post Harvest Operations and Processing of Fruits, Vegetables, Spices and Plantation Crop Products

Professor H.N. Mishra
Agriculture and Food Engineering Department
Indian Institute of Technology, Kharagpur

Lecture 14
Processing by Removal of Heat

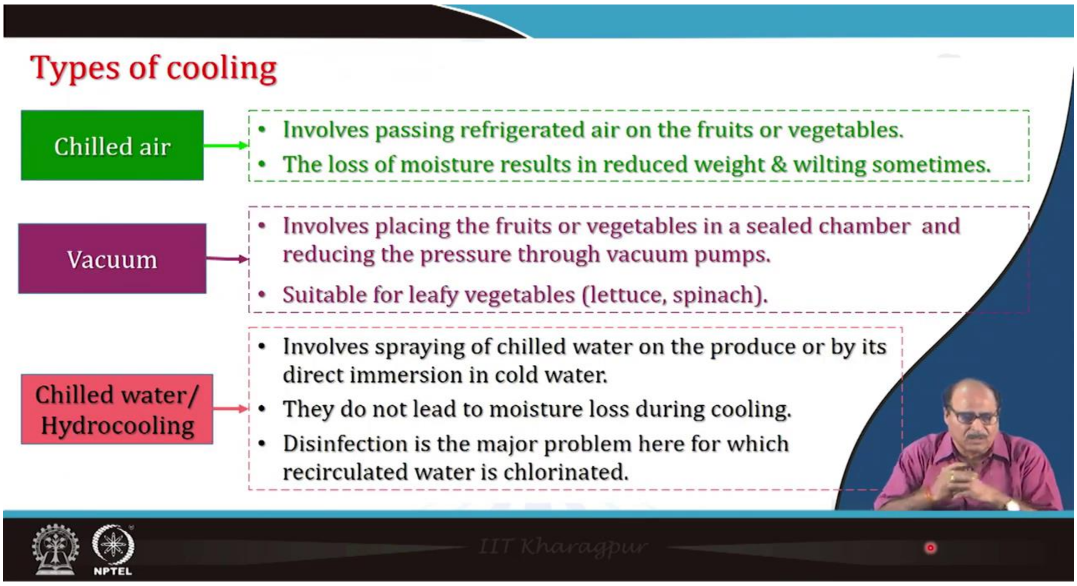


The major aspects of this lecture will be cooling and its types, refrigeration, chilling and freezing technology, freeze drying, and freeze concentration.



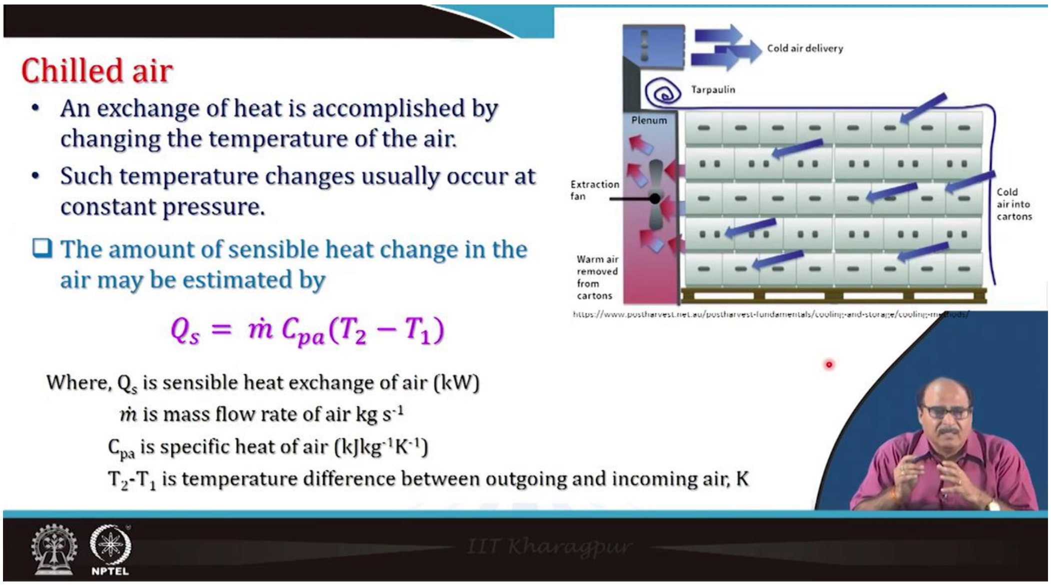
Cooling of fruits and vegetables

Cooling is the process of removal of heat from the fruits and vegetable to lower their temperature to ambient or storage condition. It is also called as precooling, removal of field heat i.e. rapidly lowering the temperature of harvested produce to near storage temperature. It is also called as pre-cooling or removal of field heat by rapidly lowering the temperature of post harvest produced to near storage temperature. The primary processing after harvesting is the cooling, which reduces the metabolic activity, growth of microorganisms, and slows down spoilage. The benefits of the process are to reduce the changes to the organoelectric and nutritional qualities of the product and maintain the product safety. This process is done before the produce is transported to market or also put into the cold storage.



Different types of cooling include chilled air cooling, vacuum cooling, and chilled water or hydro cooling. Chilled air involves passing refrigerated air on the fruits or vegetables, the loss of moisture results in reduced weight and wilting sometimes. Vacuum cooling involves placing the fruits or vegetable in a sealed chamber and reducing the pressure through the vacuum pump.

It is suitable for leafy vegetables like lettuce, spinach etc. The chilled water cooling or hydro cooling involves spraying of chilled water on the produce or by its direct immersion in the cold water. Either the chilled water can be sprayed on the produce or the produce can be directly immersed in the cold water, however, they do not lead to moisture loss during cooling but there may be some contamination, etc if the water is not of good quality. So disinfection is the major problem for which the recirculated water or the water which is used for chilled cooling or hydrocooling is chlorinated or it is sometime sanitized.



Chilled air

In chilled air cooling system, an exchange of heat is accomplished by changing the temperature of the air such temperature changes usually occur at constant pressure, the chilled air is passed inside the storage room or inside the package. The amount of sensible heat change in the air may be estimated by

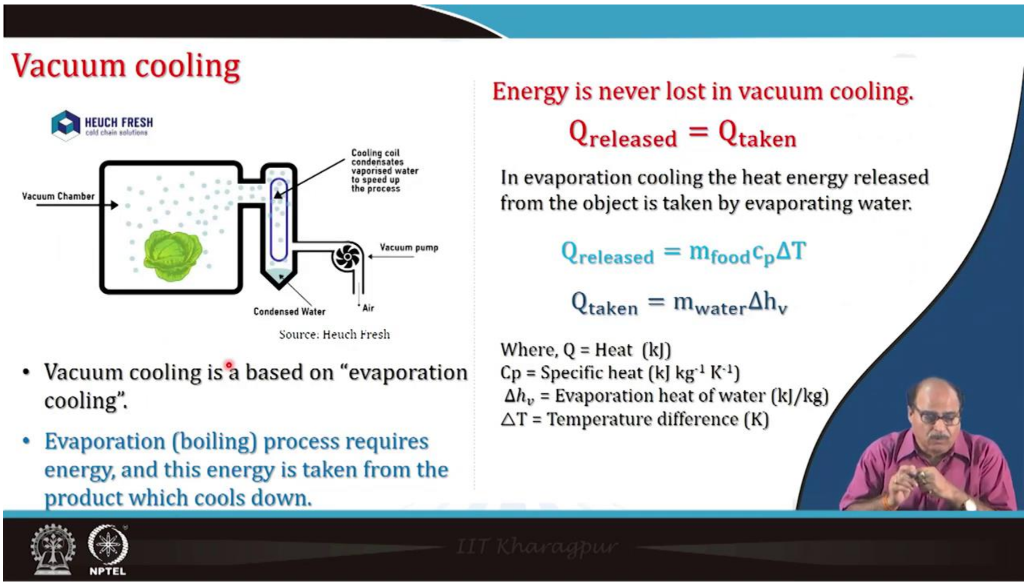
$$Q_s = \dot{m} C_{pa}(T_2 - T_1)$$

Where, Q_s is sensible heat exchange of air (kW),

$\dot{m}$ is mass flow rate of air kg s^{-1}

C_{pa} is specific heat of air ($kJkg^{-1}K^{-1}$)

T_2-T_1 is temperature difference between outgoing and incoming air, K



Vacuum cooling

Vacuum cooling is based on "evapouration cooling". Evapouration or boiling process requires energy and this energy is taken from the product which cools down. As shown in the figure, there is a vacuum chamber, which is attached with the cooling coil condensates vapourized water to separate from the vacuum where the pressure is lower than the water vapour, the condenser condenses the water, condensed water is collected and a vacuum pump is used to reduce the pressure or create the vacuum inside the chamber.

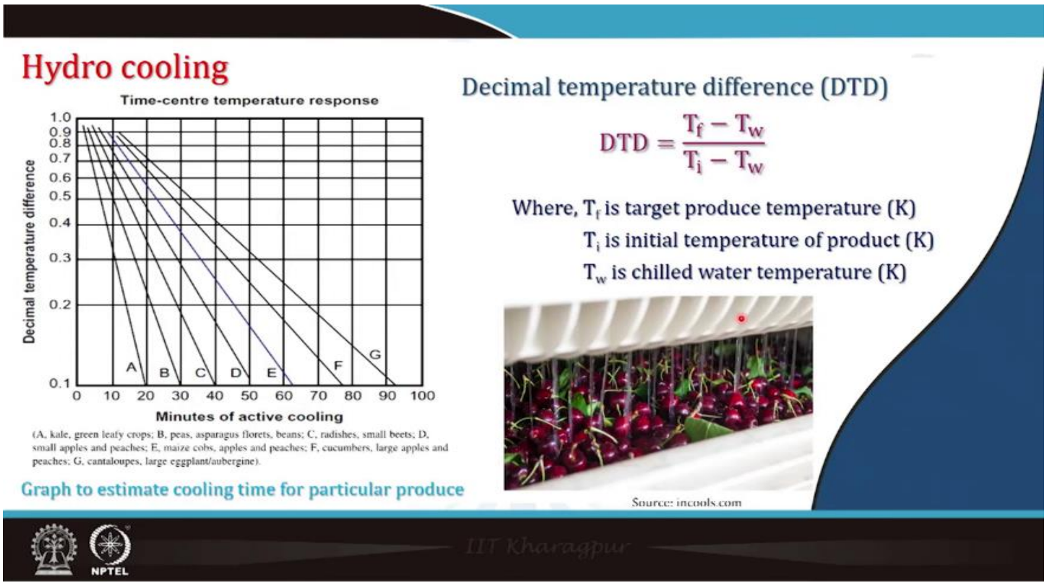
Energy is never lost in vacuum cooling. So, $Q_{released} = Q_{taken}$. In evaporation cooling the heat energy released from the object is taken by evaporating water. Hence,

$$Q_{released} = m_{food} c_p \Delta T$$
$$Q_{taken} = m_{water} \Delta h_v$$

Where, Q = Heat (kJ), C_p = Specific heat (kJ kg^{-1} K^{-1}), Δh_v = Evaporation heat of water (kJ/kg), ΔT = Temperature difference (K).

Hydro cooling

The graph shows the relationship between the decimal temperature differences (DTD), minutes of active cooling, and time center temperature response of different fruits and vegetables marked in different lines (A-G). The graph is used to estimate cooling time for a particular produce. The DTD can be calculated as



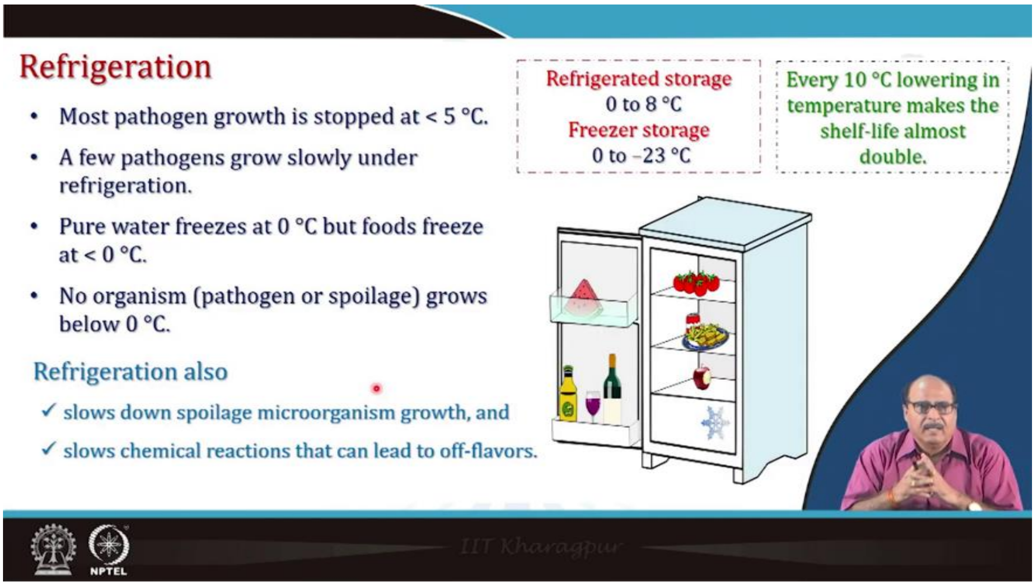
$$\mathrm{DTD} = \frac{T_f - T_w}{T_i - T_w}$$

Where, T_f is target produce temperature (K)

T_i is initial temperature of product (K)

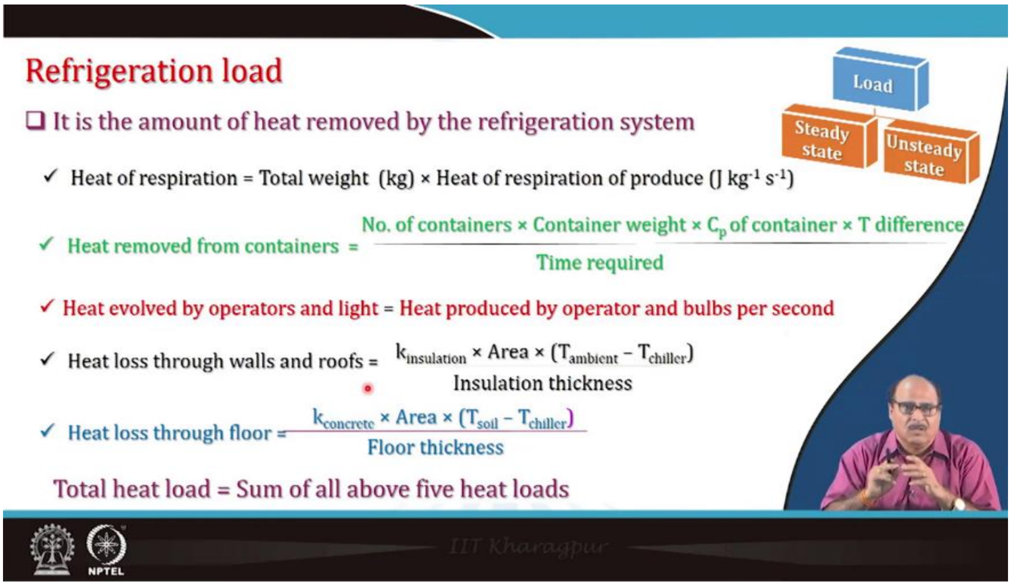
T_w is chilled water temperature (K)

From DTD, the the expected time for cooling the produce in minutes can be easily calsulated from the x-axis of the plot.



Refrigeration

Most pathogen growth is stopped at < 5 °C. A few pathogens grow slowly under refrigeration. Pure water freezes at 0 °C but foods freeze at < 0 °C because of the dissolved solutes in the food that lower down the freezing point. No organism (pathogen or spoilage) grows below 0 °C. Refrigeration also slows down spoilage microorganism growth, and slows chemical reactions that can lead to off-flavors. In household refrigerator normally the temperature may be in the range of 0 to 8 °C, whereas the temperature in frozen storage is maintained at 0 to -23 °C. So every 10 °C lowering in the temperature makes the shelf life of the commodity almost double.



Refrigeration load

It is the amount of heat removed by the refrigeration system.

Heat of respiration = Total weight (kg) × Heat of respiration of produce (J kg^{-1} s^{-1})

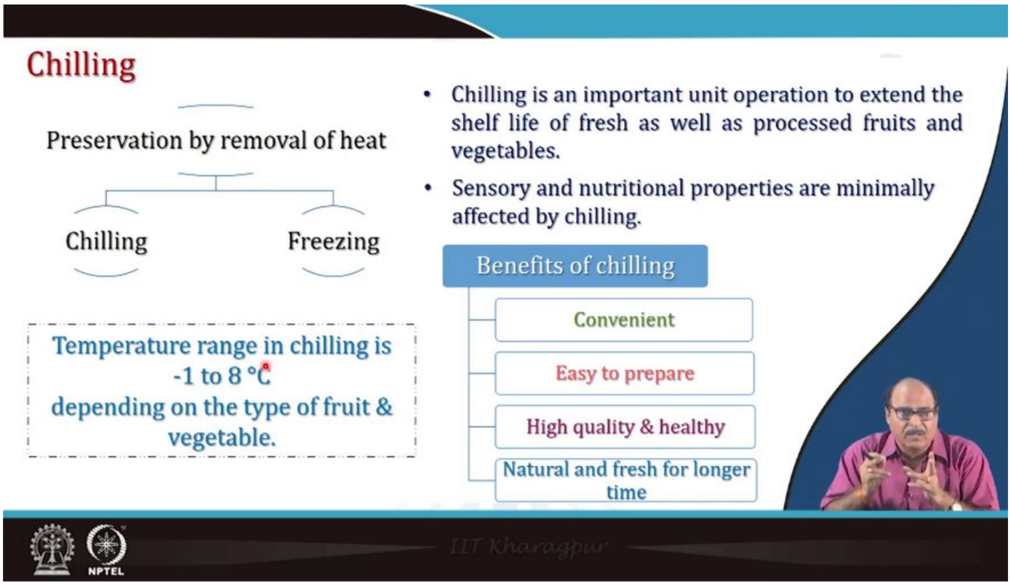
$$\text{Heat removed from containers} = \frac{\text{No. of containers} \times \text{Container weight} \times \text{Cp of container} \times \text{T difference}}{\text{Time required}}$$

Heat evolved by operators and light = Heat produced by operator and bulbs per second

$$\text{Heat loss through walls and roofs} = \frac{\text{kinsulation} \times \text{Area} \times (\text{Tambient} - \text{Tchiller})}{\text{Insulation thickness}}$$

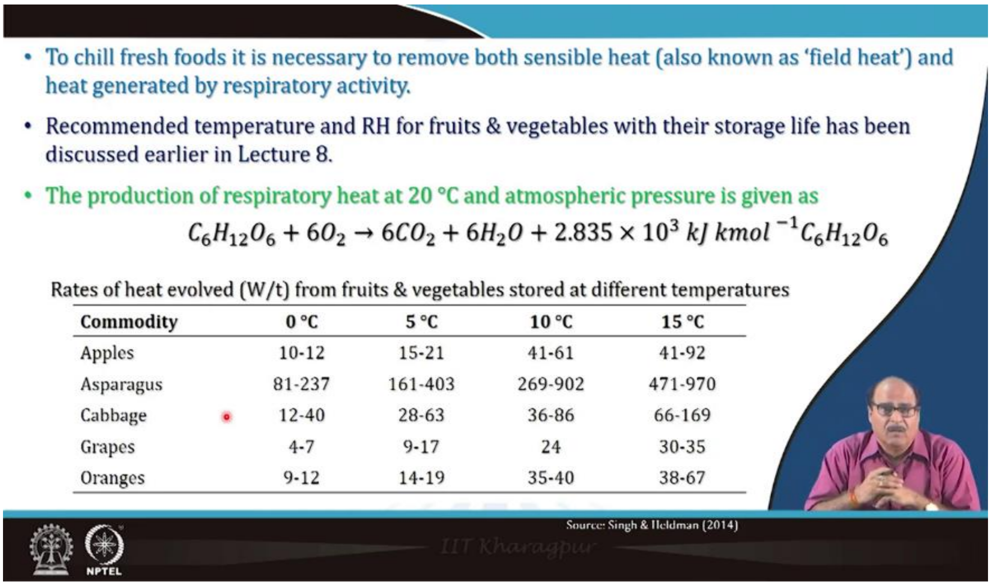
$$\text{Heat loss through floor} = \frac{\text{kconcrete} \times \text{Area} \times (\text{Tsoil} - \text{Tchiller})}{\text{Floor thickness}}$$

Total heat load = Sum of all above five heat loads



Chilling

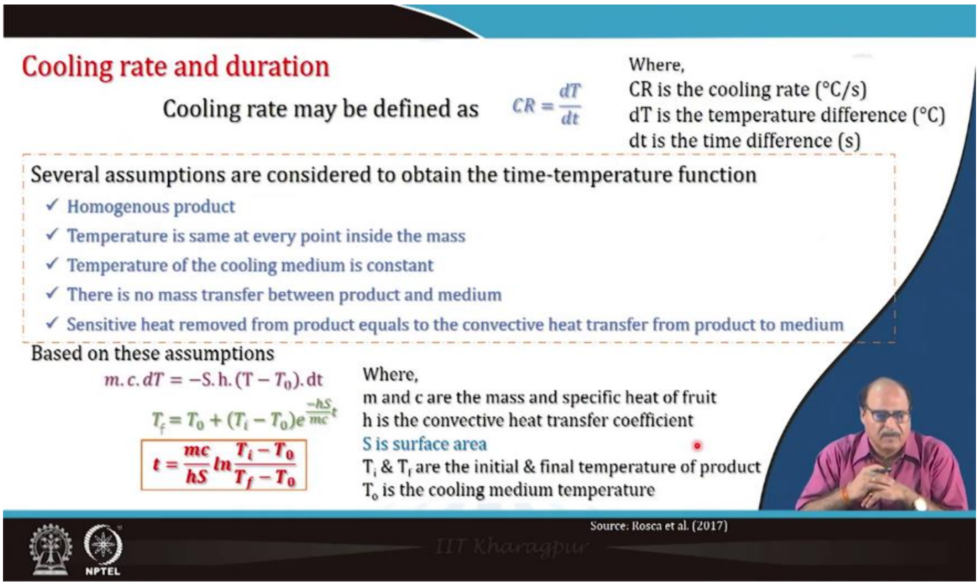
The fruits and vegetables can be preserved by removal of heat, which involves chilling and freezing process. Temperature range in chilling is -1 to 8 °C depending on the type of fruit & vegetable. Chilling is an important unit operation to extend the shelf life of fresh as well as processed fruits and vegetables. Sensory and nutritional properties are minimally affected by chilling. It is convenient, easy to prepare, high quality and healthy products can be obtained by chilling technology, and can be kept as natural and fresh for longer time by maintaining the chilling conditions inside the storage.



To chill fresh foods, it is necessary to remove both sensible heat (also known as field heat) and heat generated by the respiratory activity. The recommended temperature and RH for fruits and vegetables with their storage life we have discussed earlier in the lecture 8. The production of respiratory heat at 20 °C and atmospheric pressure is given by this equation

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 2.835 \times 10^3\ kJ\ kmol^{-1}\ C_6H_{12}O_6$$

The table represents the rate of heat evolved (W/t) from fruits and vegetables at different temperatures. It is clearly observed that the rate of heat evolution increases with increasing the temperature from 0 to 15 °C.



Cooling rate and duration

Cooling rate (CR) may be defined as

$$CR = \frac{dT}{dt}$$

Where, CR is the cooling rate (°C/s),

dT is the temperature difference (°C),

dt is the time difference (s).

So in this calculation several assumptions are considered to obtain the time temperature function like product should be homogenous, temperature is same at every point inside the mass, temperature of the cooling medium is constant, there is no mass transfer between product and medium, sensitive heat removed from product equals to the convective heat transfer from product to medium. Based on the assumptions,

$$m.c.dT = -S.h.(T - T_0).dt$$

$$T = T_0 + (T_i - T_0).e^{\frac{-h.S.t}{m.C}}$$

$$t = \frac{m.C}{h.S} \ln \frac{T_i - T_0}{T_f - T_0}$$

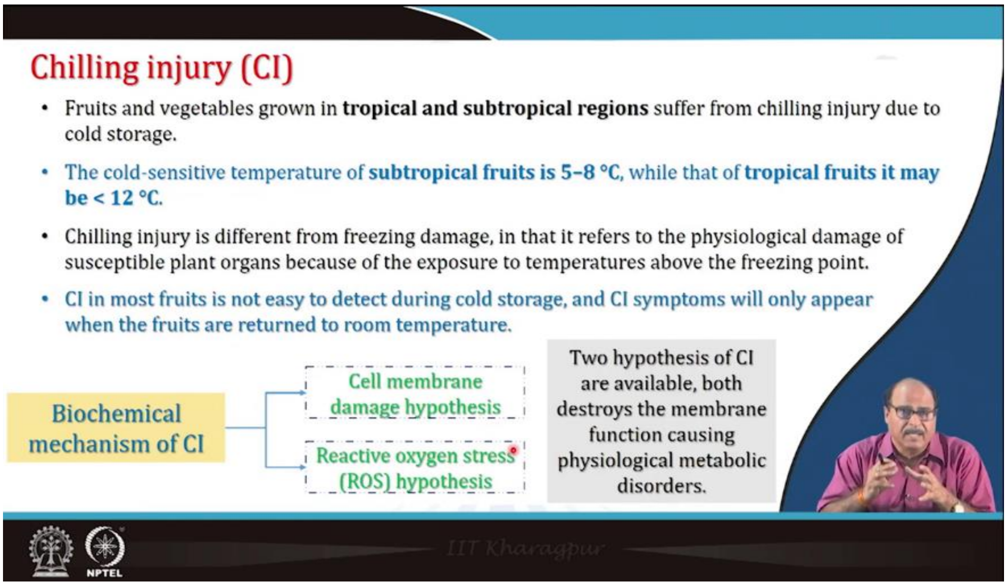
Where, m and c are the mass and specific heat of fruit,

h is the convective heat transfer coefficient,

S is surface area,

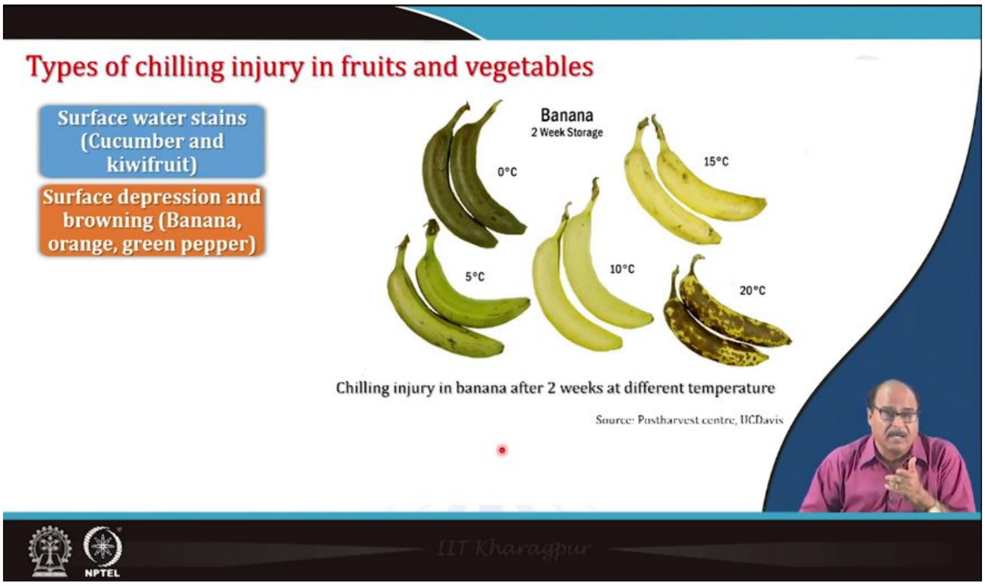
T_i & T_f are the initial & final temperature of product,

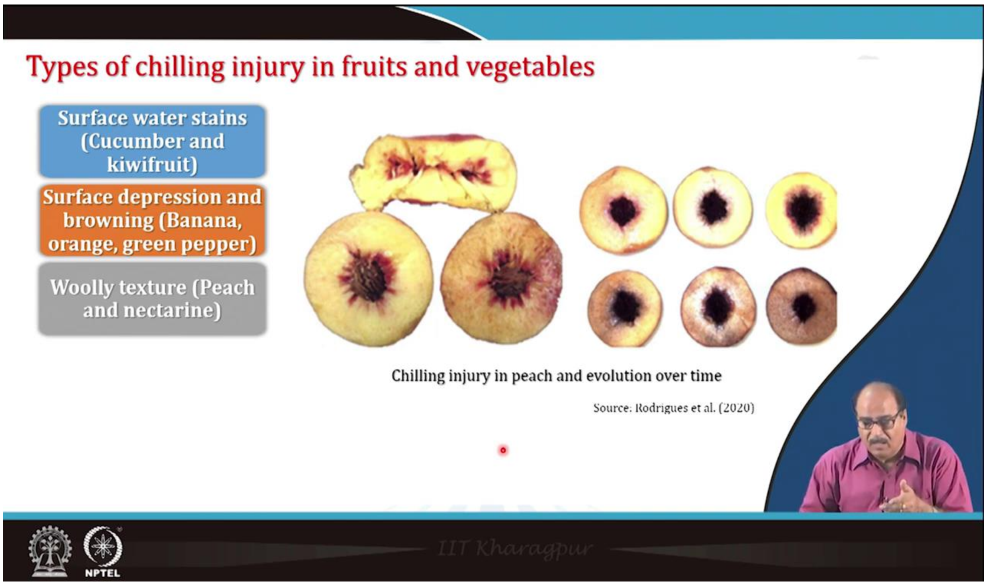
T_o is the cooling medium temperature



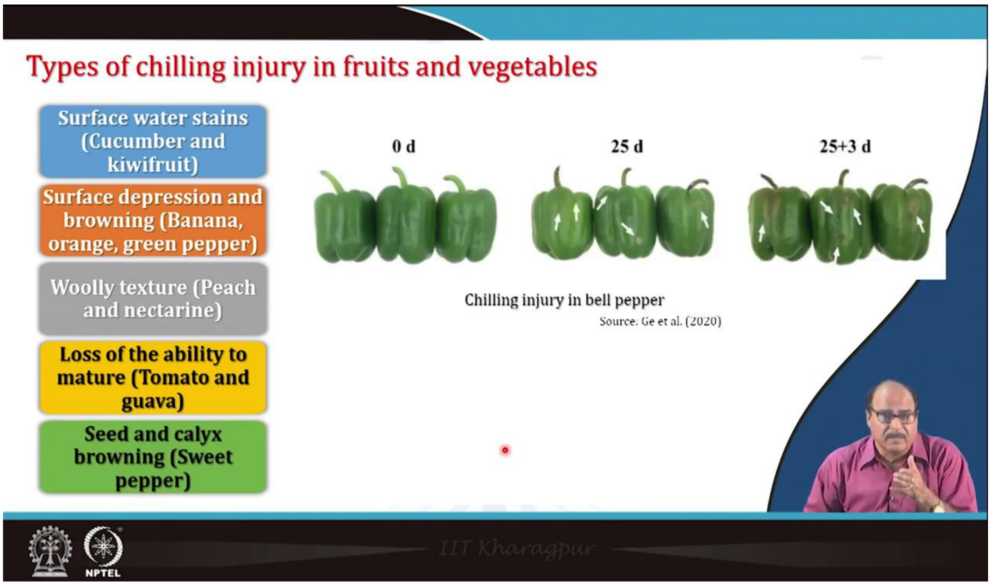
Chilling injury

Fruits and vegetables grown in tropical and subtropical regions suffer from chilling injury due to cold storage. The cold-sensitive temperature of subtropical fruits is 5–8 °C, while that of tropical fruits it may be < 12 °C. Chilling injury is different from freezing damage, in that it refers to the physiological damage of susceptible plant organs because of the exposure to temperatures above the freezing point. Chilling injury in most fruits is not easy to detect during cold storage, and its symptoms will only appear when the fruits are returned to room temperature. The biochemical mechanisms of chilling injury involve cell membrane damage hypothesis and reactive oxygen stress (ROS) hypothesis. These are the two hypothesis of chilling injury available, both destroys the memebrane function causing physiological metabolic disorders.

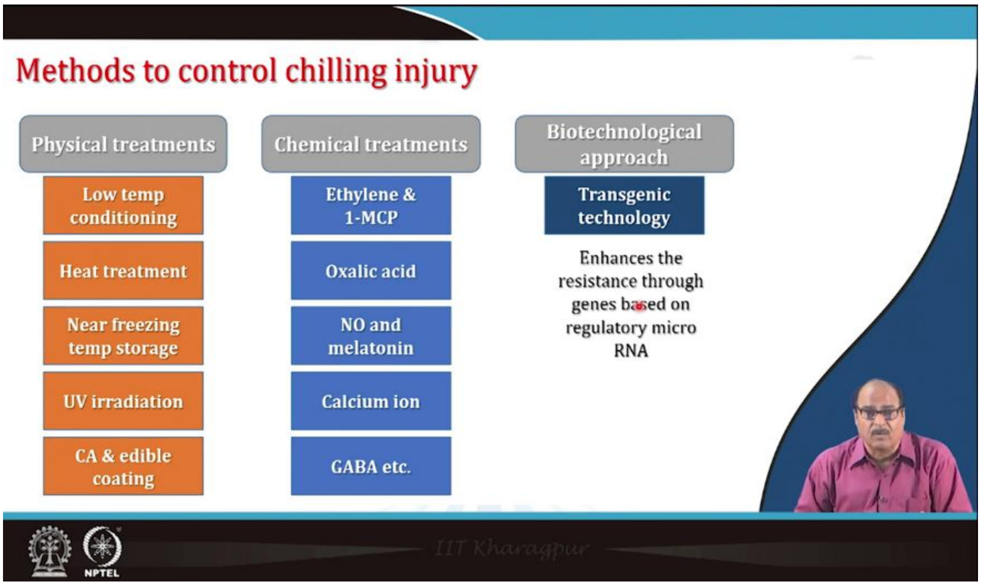

Types of chilling injury in fruits and vegetables
Surface water stains (Cucumber and kiwifruit)
Surface depression and browning (Banana, orange, green pepper)
Banana
2 Week Storage
0°C
15°C
5°C
10°C
20°C
Chilling injury in banana after 2 weeks at different temperature
Source: Postharvest centre, UCDavis
IIT Kharagpur
NPTEL


Types of chilling injury in fruits and vegetables
Surface water stains (Cucumber and kiwifruit)
Surface depression and browning (Banana, orange, green pepper)
Woolly texture (Peach and nectarine)
Chilling injury in peach and evolution over time
Source: Rodrigues et al. (2020)
IIT Kharagpur
NPTEL


Types of chilling injury in fruits and vegetables
Surface water stains (Cucumber and kiwifruit)
Surface depression and browning (Banana, orange, green pepper)
Woolly texture (Peach and nectarine)
Loss of the ability to mature (Tomato and guava)
Chilling injury in guava
Source: Postharvest centre, UCDavis
IIT Kharagpur
NPTEL



So there are different types of chilling injury in fruits and vegetables, which may be surface water stains, generally evident in cucumber, kiwi fruit etc. or it may be surface depression and browning in the case of banana, oranges, green apple, which is more common or the wooly texture in peach and nectarine or the loss of ability to mature in case of tomato and guava that is more commonly seen when the cold room temperature is not maintained to the proper recommended conditions, or seed and calyx browning, which is more common in the sweet potato.

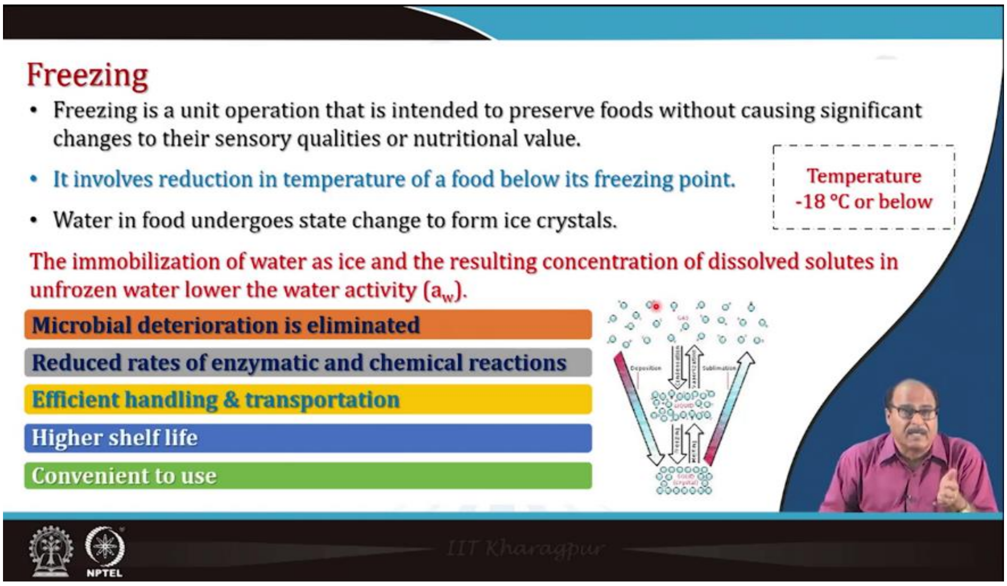


Methods to control chilling injury

Physical treatments: Low temp conditioning; Heat treatment; Near freezing temp storage; UV irradiation; CA & edible coating.

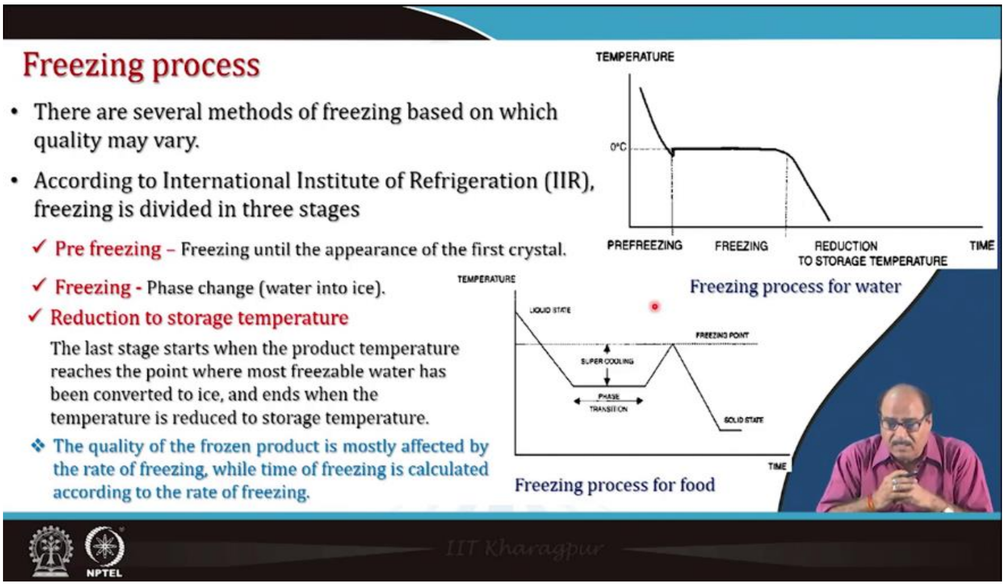
Chemical treatments: Ethylene & 1-MCP; Oxalic acid; NO and melatonin; Calcium ion; GABA etc.

Biotechnological approach: Transgenic technology which enhances the resistance through genes based on regulatory micro RNA.



Freezing

Freezing is a unit operation (temperature below -18 °C) that is intended to preserve foods without causing significant changes to their sensory qualities or nutritional value. It involves reduction in temperature of a food below its freezing point. Water in food undergoes state change to form ice crystals. The immobilization of water as ice and the resulting concentration of dissolved solutes in unfrozen water lower the water activity (a_W). It causes elimination of microbial deterioration, reduction in the rates of enzymatic and chemical reactions, improves handling and transportation of produces, increases the shelf-life, and also it is a convenient process.



Freezing process

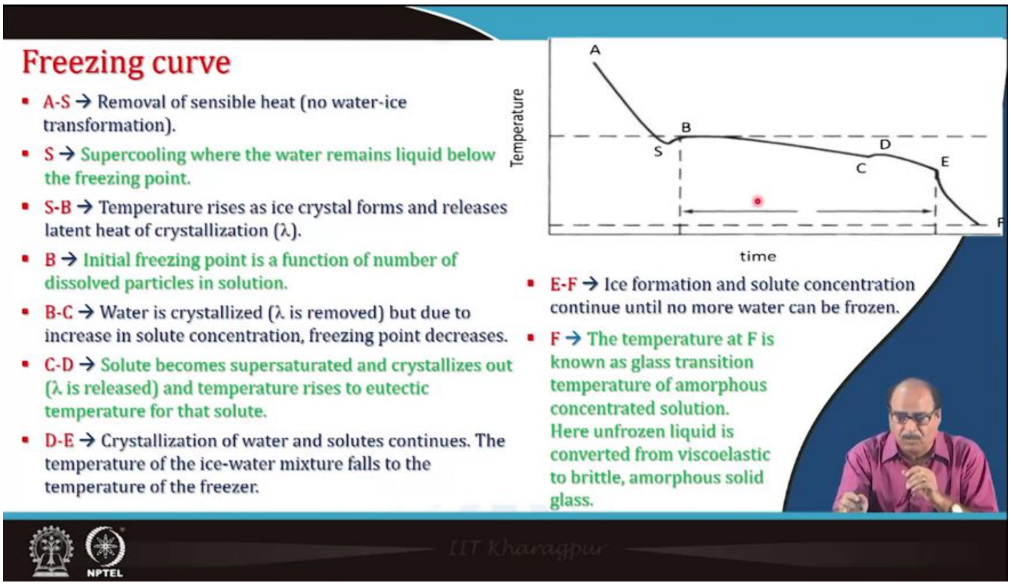
There are several methods of freezing based on which quality may vary. According to International Institute of Refrigeration (IIR), freezing is divided in three stages.

Pre freezing – Freezing until the appearance of the first crystal.

Freezing - Phase change (water into ice).

Reduction to storage temperature- The last stage starts when the product temperature reaches the point where most freezable water has been converted to ice, and ends when the temperature is reduced to storage temperature.

The quality of the frozen product is mostly affected by the rate of freezing, while time of freezing is calculated according to the rate of freezing.



Freezing curve

A-S: Removal of sensible heat (no water-ice transformation).

S: Supercooling where the water remains liquid below the freezing point.

S-B: Temperature rises as ice crystal forms and releases latent heat of crystallization (λ).

B: Initial freezing point is a function of number of dissolved particles in solution.

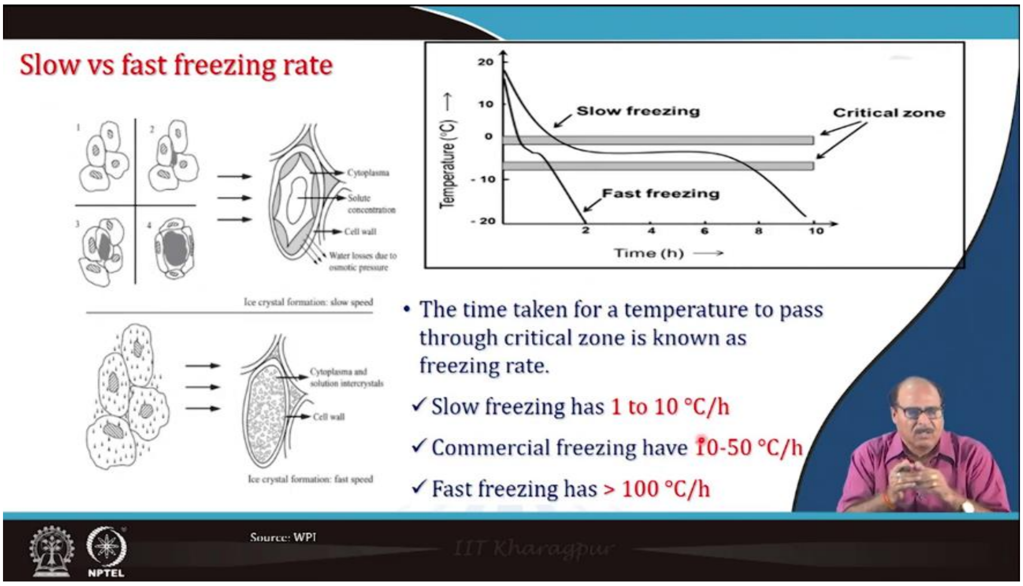
B-C: Water is crystallized (λ is removed) but due to increase in solute concentration, freezing point decreases.

C-D: Solute becomes supersaturated and crystallizes out (λ is released) and temperature rises to eutectic temperature for that solute.

D-E: Crystallization of water and solutes continues. The temperature of the ice-water mixture falls to the temperature of the freezer.

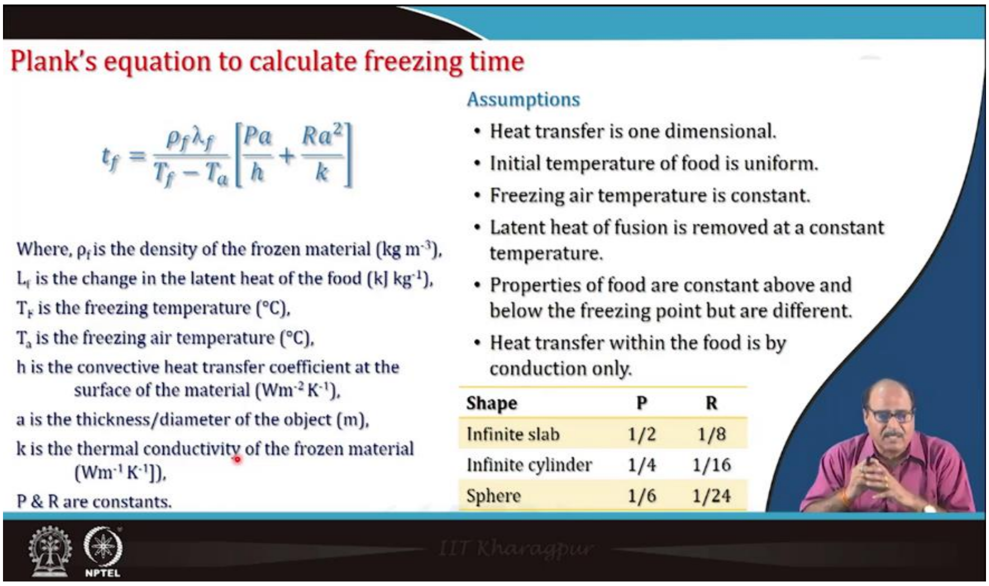
E-F: Ice formation and solute concentration continue until no more water can be frozen.

F: The temperature at F is known as glass transition temperature of amorphous concentrated solution. Here unfrozen liquid is converted from viscoelastic to brittle, amorphous solid glass.



Slow vs fast freezing rate

The time taken for a temperature to pass through critical zone is known as freezing rate. Slow freezing has 1 to 10 °C/h, commercial freezing have 10-50 °C/h, and Fast freezing has > 100 °C/h. In the slow freezing mostly small number of ice crystals of larger sizes form. So, there may be dislocation because of this large size of the ice crystal and after thawing there may be certain structural dislocation etc of the commodity whereas in the fast freezing from quality point of view it is good as there are large number of ice crystals of a smaller size form, so there is no structural or cellular dislocation inside the cytoplasma, the structure remains intact, and there is no damage, hence structural change is minimum in the case of fast freezing.



Plank's equation to calculate freezing time

Assumptions

- ✓ Heat transfer is one dimensional.
- ✓ Initial temperature of food is uniform.
- ✓ Freezing air temperature is constant.
- ✓ Latent heat of fusion is removed at a constant temperature.
- ✓ Properties of food are constant above and below the freezing point but are different.
- ✓ Heat transfer within the food is by conduction only.

$$t_f = \frac{\rho_f \lambda_f}{T_f - T_a} [\frac{Pa}{h} + \frac{Ra^2}{k}]$$

Where, ρ_f is the density of the frozen material (kg m^{-3}),

L_f is the change in the latent heat of the food (kJ kg^{-1}),

T_F is the freezing temperature (°C),

T_a is the freezing air temperature (°C),

h is the convective heat transfer coefficient at the surface of the material ($Wm^{-2} K^{-1}$),

a is the thickness/diameter of the object (m),

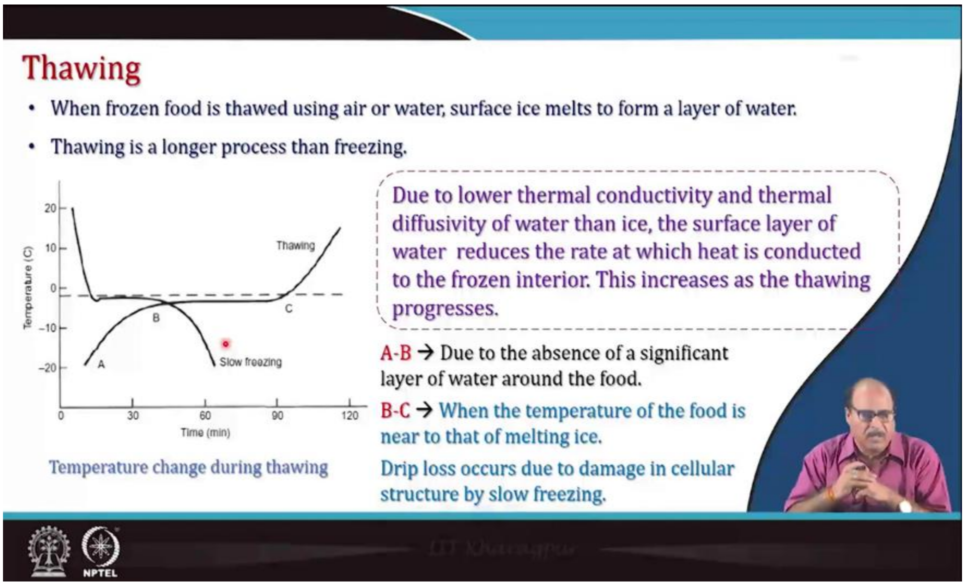
k is the thermal conductivity of the frozen material ($Wm^{-1} K^{-1}$),

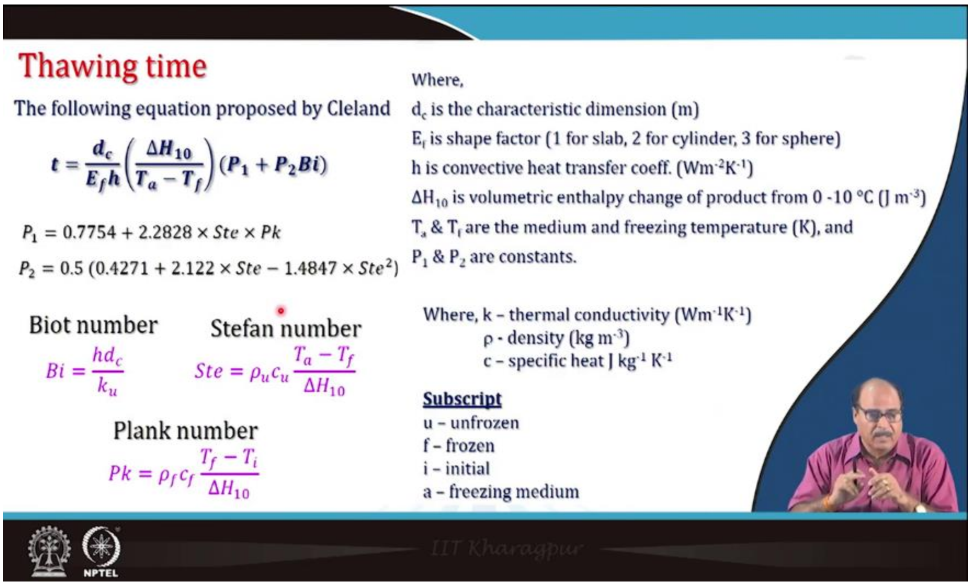
P & R are constants.

This P and R which are constants they depends upon the geometry of the material which is being frozen like for infinite slab P is 1/2 and R is 1/8, for infinite cylinder P and R are 1/ 4 and 1/16, respectively, and for sphere P is 1/6 and R is 1/24.

Thawing

When frozen food is thawed using air or water, surface ice melts to form a layer of water. Thawing is a longer process than freezing. Due to lower thermal conductivity and thermal diffusivity of water than ice, the surface layer of water reduces the rate at which heat is conducted to the frozen interior. This increases as the thawing progresses. The plot representing the temperature change during thawing, the significance of the curves as **A-B:** Due to the absence of a significant layer of water around the food, **B-C:** When the temperature of the food is near to that of melting ice. Drip loss occurs due to damage in cellular structure by slow freezing.





Thawing time

The thawing time can be calculated as per proposed by Cleland:

$$t = \frac{d_c}{E_f h}\left(\frac{\Delta H_{10}}{T_a - T_f}\right)(P_1 + P_2 Bi)$$

$$P_1 = 0.7754 + 2.2828 \times Ste \times Pk$$

$$P_2 = 0.5\ (0.4271 + 2.122 \times Ste - 1.4847 \times Ste^2)$$

$$\text{Biot number: } Bi = \frac{hd_c}{k_u}$$

$$\text{Stefan number: } Ste = \rho_u c_u \frac{T_a - T_f}{\Delta H_{10}}$$

$$\text{Plank number: } Pk = \rho_f c_f \frac{T_f - T_i}{\Delta H_{10}}$$

Where, d_c is the characteristic dimension (m),

E_f is shape factor (1 for slab, 2 for cylinder, 3 for sphere),

h is convective heat transfer coeff. ($Wm^{-2}K^{-1}$),

ΔH_{10} is volumetric enthalpy change of product from 0 -10 °C ($J\ m^{-3}$),

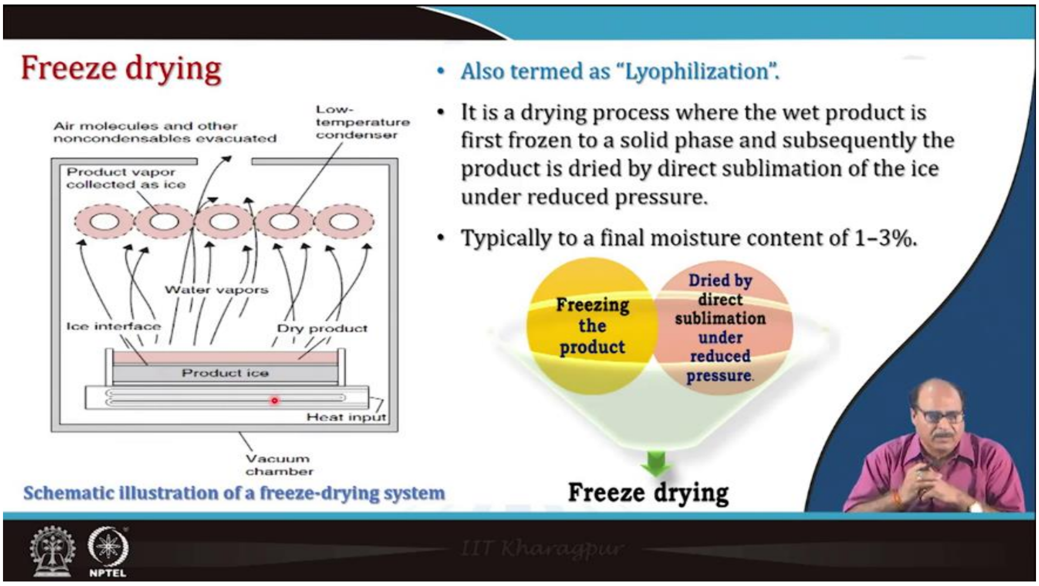
T_a & T_f are the medium and freezing temperature (K), and

P_1 & P_2 are constants.

K is the thermal conductivity ($Wm^{-1}K^{-1}$)

ρ is density ($kg\ m^{-3}$)

c is specific heat $J\ kg^{-1}\ K^{-1}$

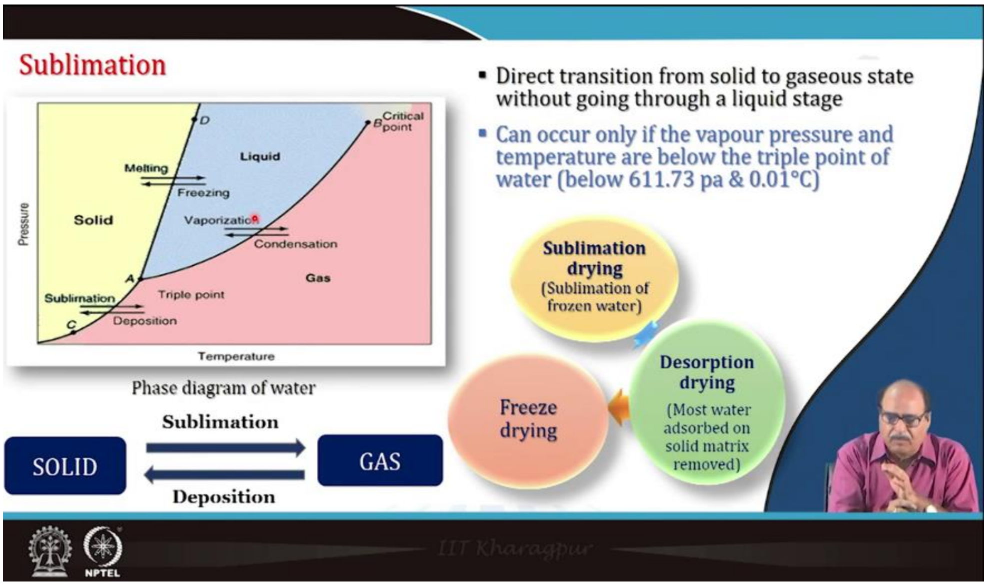


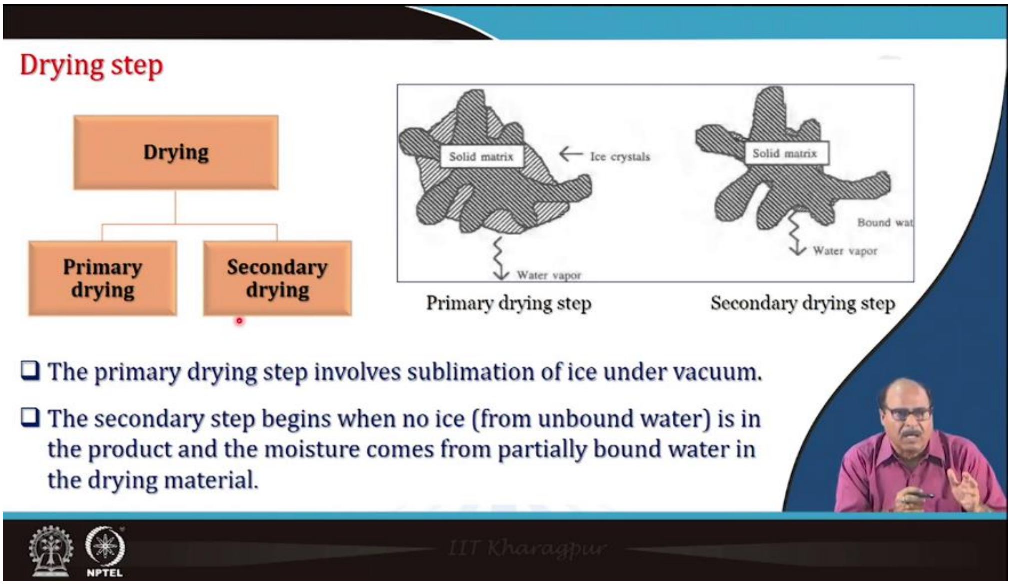
Freeze drying (Lyophilization)

It is a drying process where the wet product is first frozen to a solid phase and subsequently the product is dried by direct sublimation of the ice under reduced pressure. Typically to a final moisture content of 1–3%. It involves freezing the product followed by drying the product by direct sublimation under reduced pressure.

Sublimation

The figure shows the triple point of water, where solid, liquid, and gas phases co-exist at this particular pressure and temperature which is normally 611.73 Pa pressure and 0.01 °C. Below these conditions, there is a direct transition from solid to gaseous state without going through a liquid stage, known as sublimation process. It occurs only if the vapour pressure and temperature are below the triple point of water.





So, drying takesplace in two steps i.e. the primary and secondary drying. The primary drying step involves sublimation of ice under vacuum, whereas the secondary drying steps begins when there is no ice (from unbound water) is in the product and then moisture comes from partially bound water in the dry material.

Heat & mass transfer in freeze drying

Heat by conduction, convection and radiation from the gas phase reaches the dried surface and is transferred by conduction to the ice layer. The rate of sublimation is given by:

$$G = \frac{A\,(P_i - P_c)}{R_d + R_s + K_1^{-1}}$$

Where, G is the rate of sublimation

A is the sublimation area (ft^2)

P_i is vapour pressure of ice (torr)

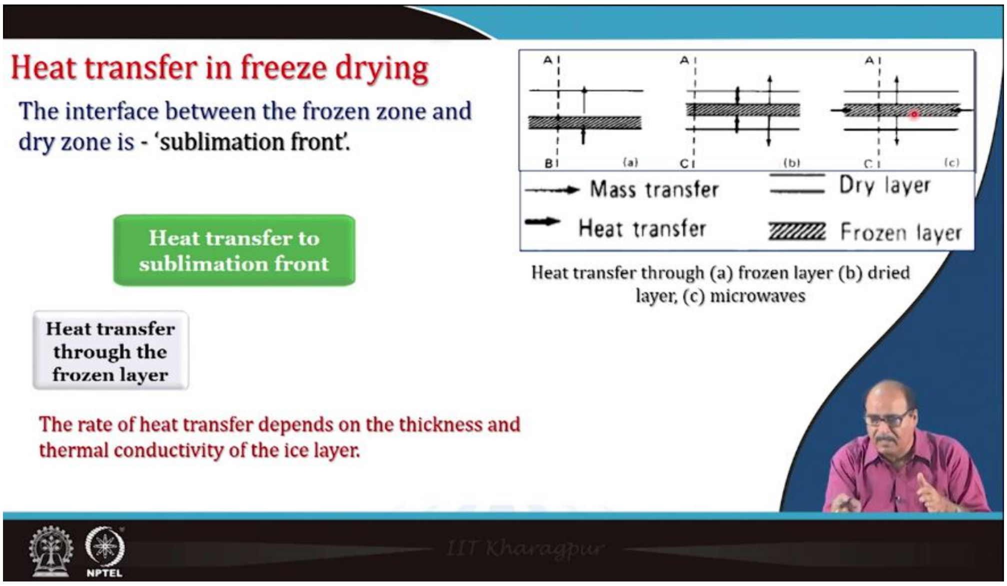
P_c is condenser vapour pressure (torr)

R_d is the resistance of dry layer in the food

R_s is the resistance of space between food and condensor

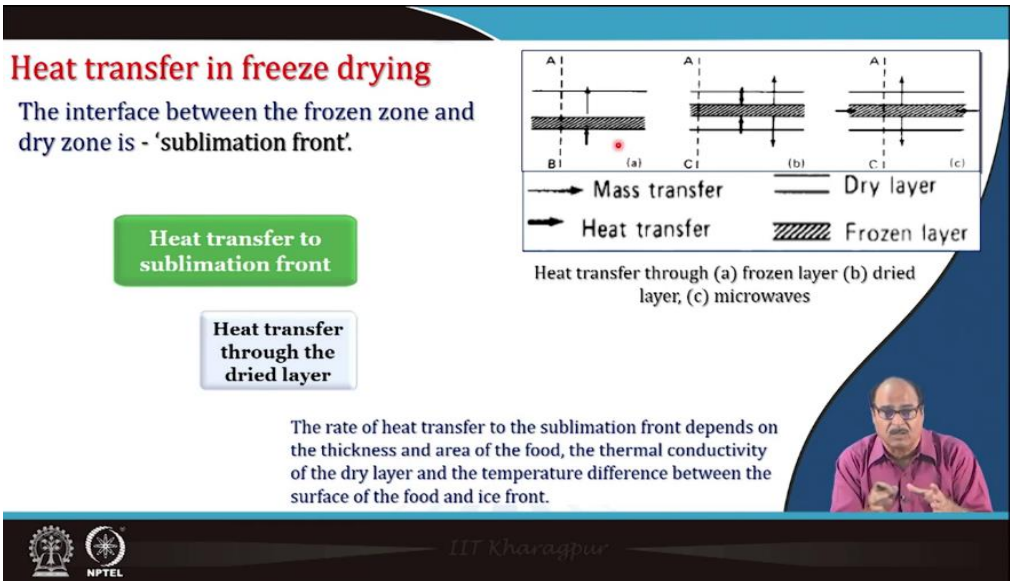
K_1 is a constant depending on the molecular weight of sublimation substance (ice)

The heat of sublimation ΔH_s must be supplied, and therefore $G = q / \Delta Hs$, Where, q is the heat flux (Btu / h).

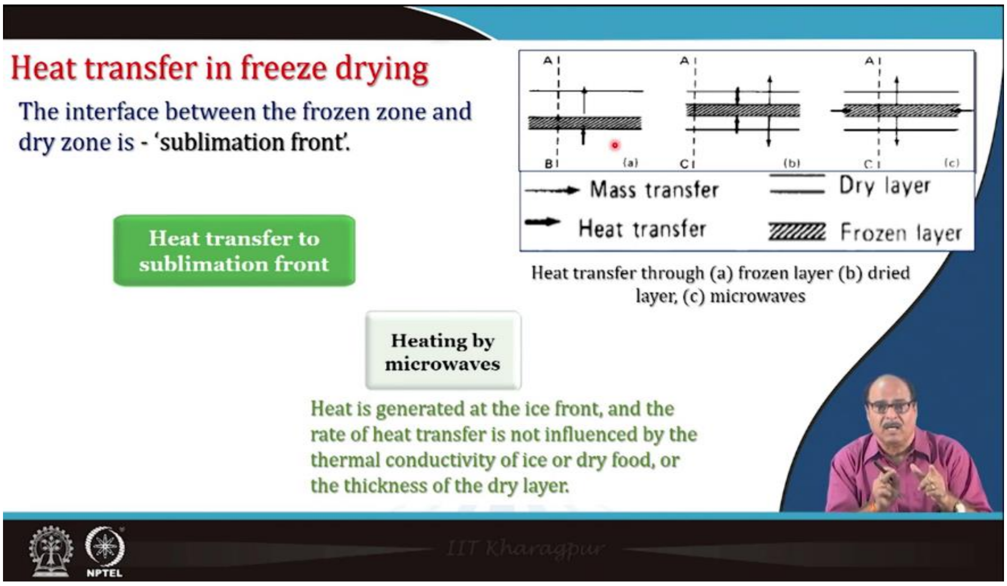


Heat transfer in freeze drying

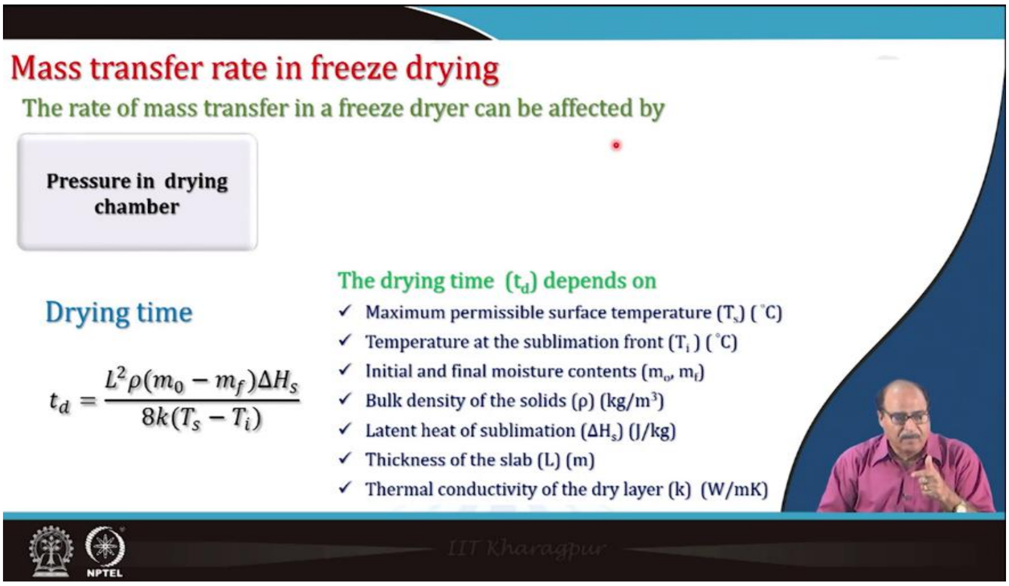
The interface between the frozen zone and dry zone is called as 'sublimation front'. So, heat transfer to the sublimation front is by through the frozen layer, the rate of heat transfer depends on the thickness and thermal conductivity of ice layer. The figure shows the heat transfer through dry and frozen layer.

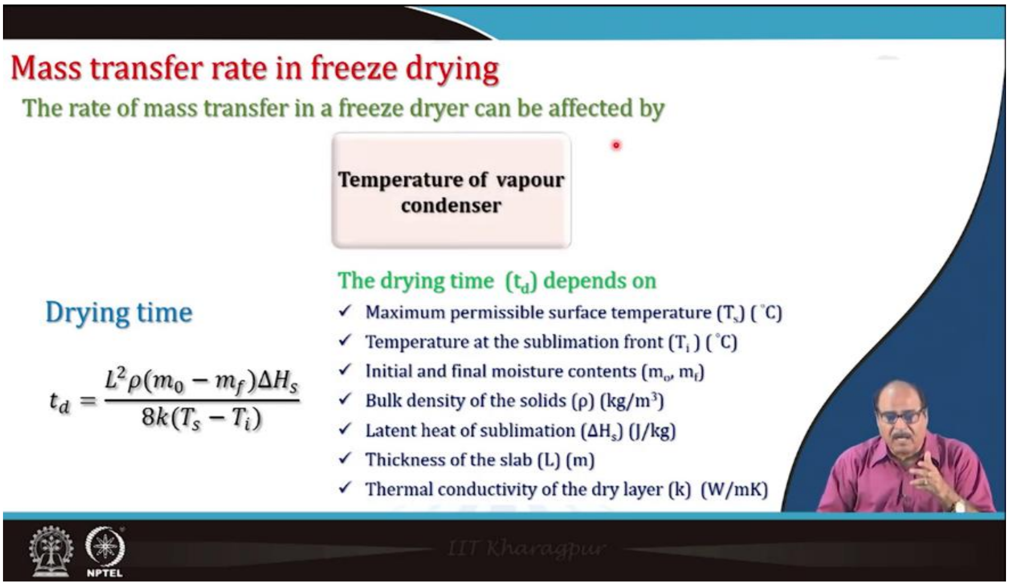


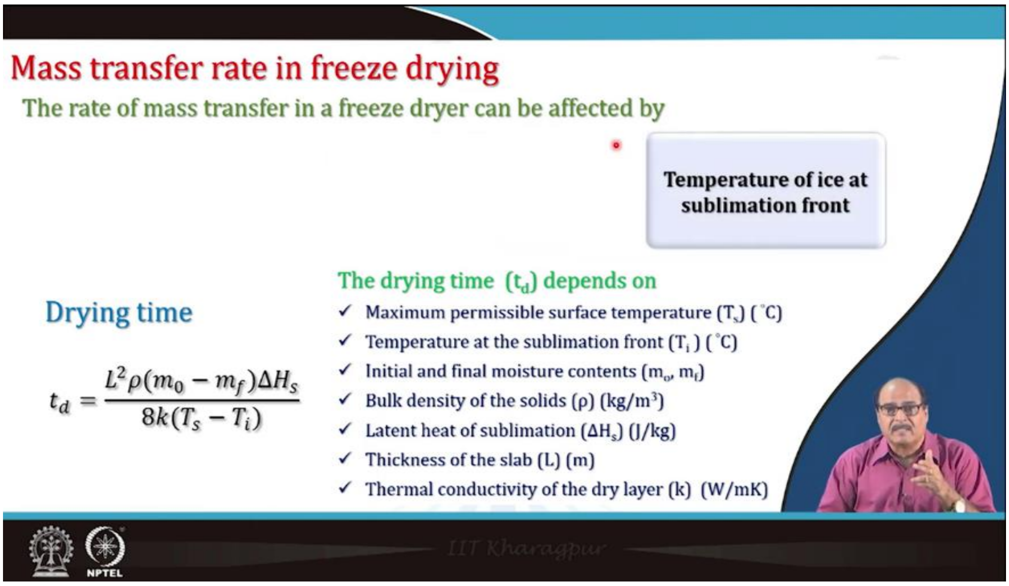
The rate of heat transfer to the sublimation front through the dried layer depends on the thickness and area of the food, the thermal conductivity of the dry layer and the temperature difference between the surface of the food and ice front.



In the third case there will be heating by microwaves that is internal heat generation, heat is generated at the ice front internally and the rate of heat transfer is not influenced by the thermal conductivity of ice or of the dry food or the thickness of the dry layer etc, because here the heat is internally generated.





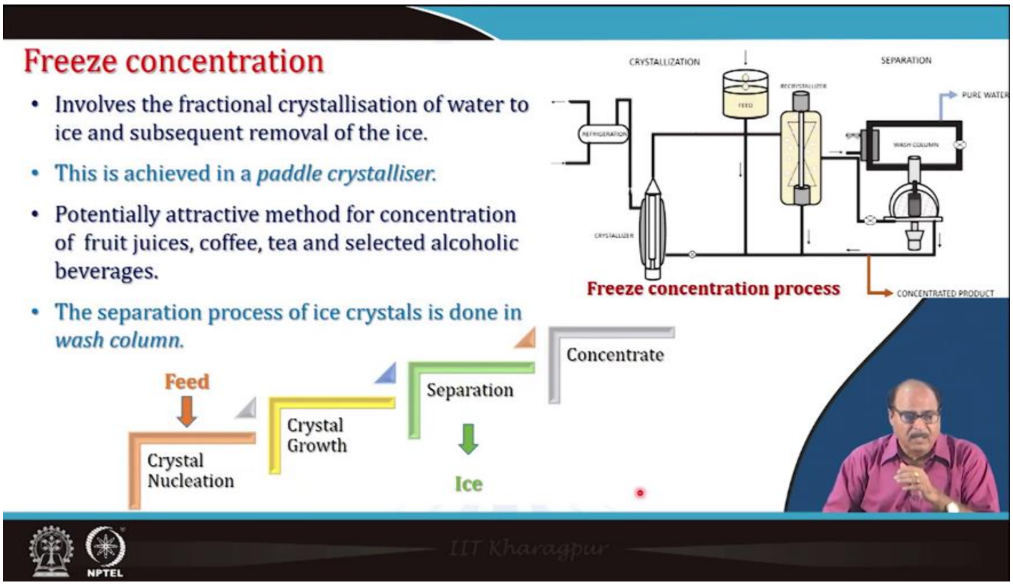


Mass transfer rate in freeze drying

The mass transfer rate in the freeze drying is affected by pressure in the drying chamber, temperature of the vapour condenser and temperature of the ice at the sublimation front. Drying time can be calculated using this equation:

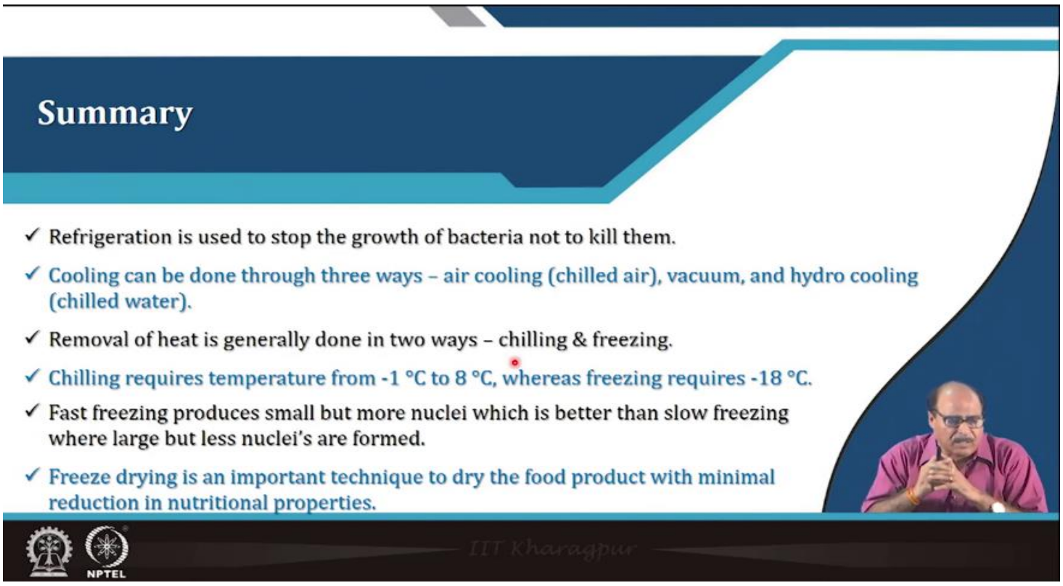
$$t_d = \frac{L^2\rho(m_0 - m_f)\Delta H_s}{8k(T_s - T_i)}$$

The drying time (t_d) depends on maximum permissible surface temperature (T_s) (°C), temperature at the sublimation front (T_i) (°C), initial and final moisture contents (m_o, m_f), bulk density of the solids (ρ) (kg/m^3), latent heat of sublimation (ΔH_s) (J/kg), thickness of the slab (L) (m), thermal conductivity of the dry layer (k) (W/mK).



Freeze concentration

It involves the fractional crystallisation of water to ice and subsequent removal of the ice. This is achieved in a paddle crystalliser. It is a potentially attractive method for concentration of fruit juices, coffee, tea and selected alcoholic beverages. The separation process of ice crystals is done in wash column. This involves crystal nucleation followed by the crystal growth, separation of ice, and finally concentration.



In summary, refrigeration is used to stop the growth of bacteria not to kill them. Cooling can be done through three ways – air cooling (chilled air), vacuum, and hydro cooling (chilled water). Removal of heat is generally done in two ways – chilling & freezing. Chilling requires temperature from -1 °C to 8 °C, whereas freezing requires -18 °C. Fast freezing produces small but more nuclei which is better than slow freezing where large but less nuclei's are formed. Freeze drying is an important technique to dry the food product with minimal reduction in nutritional properties.

These are the references for further study.