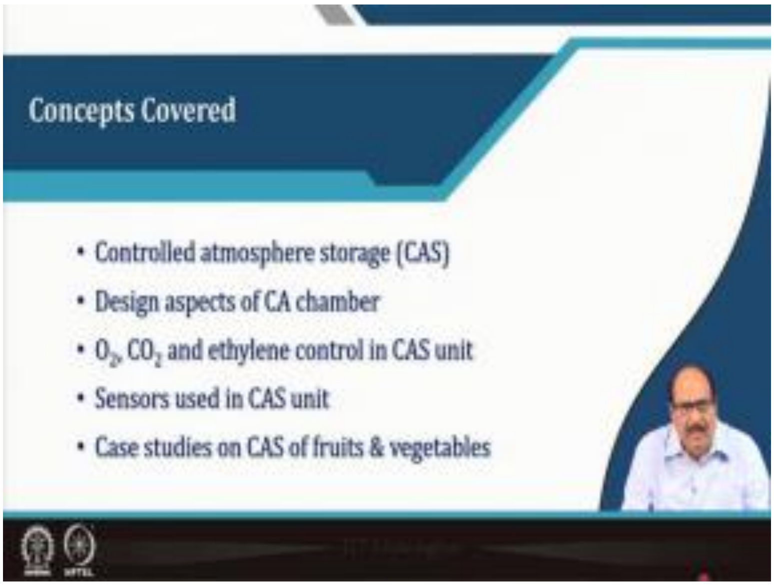
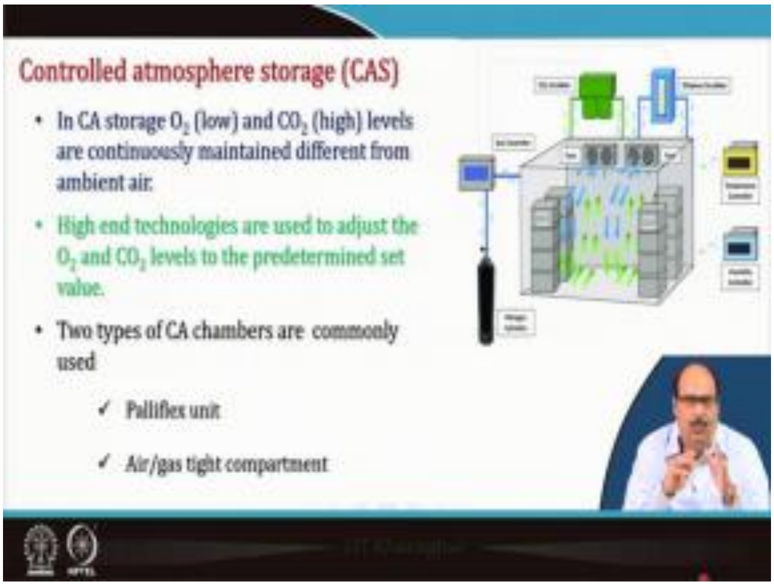
Post Harvest Operations and Processing of Fruits, Vegetables, Spices And Plantation Crop Products
Professor H.N Mishra
Agricultural and Food Engineering Department
Indian Institute of Technology, Kharagpur

Lecture 55
Controlled Atmosphere Storage

This lecture covers various concepts related to controlled atmosphere storage (CAS), design aspects of CA chamber, the gaseous composition in a controlled atmosphere, sensors used in CAS unit, and few case studies on CAS of fruits and vegetables.

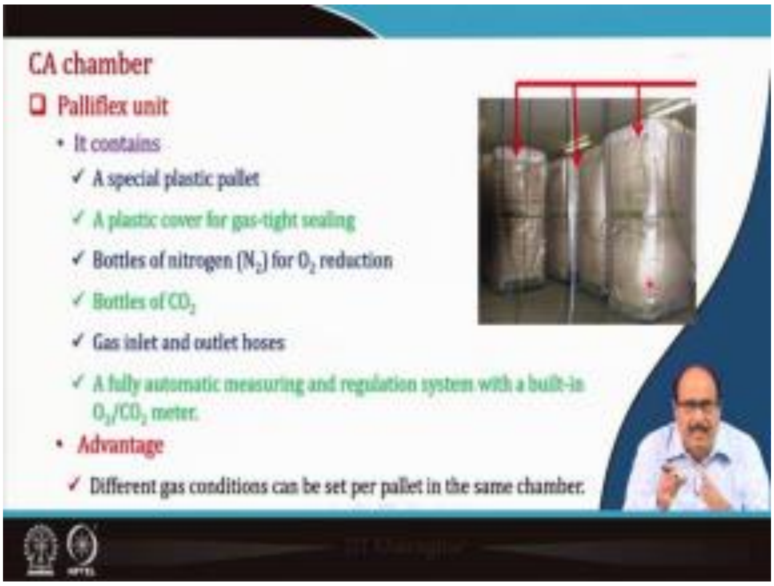


.



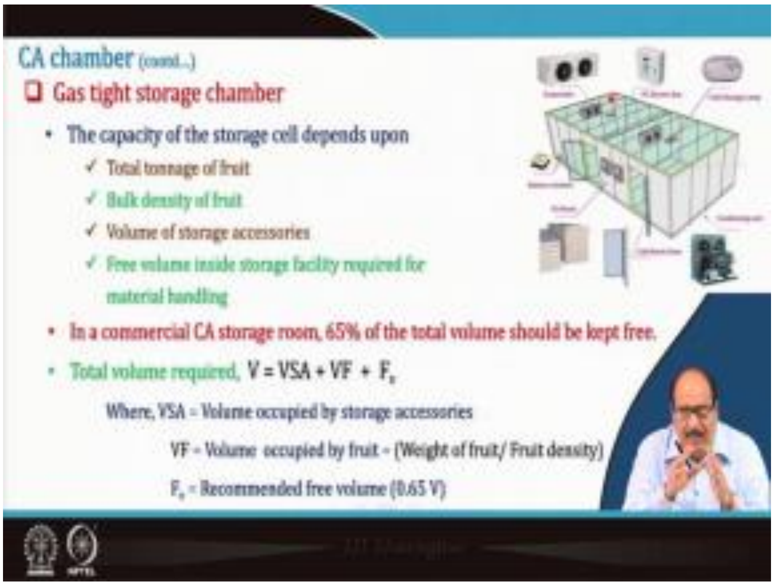
Controlled Atmosphere Storage (CAS)

In CA storage O2 (low) and CO2 (high) levels are continuously maintained different from ambient air. High end technologies are used to adjust the O2 and CO2 levels to the predetermined set value. Generally, O_2 level is brought down and CO_2 level is raised to regulate the respiration process of the commodity. There are two types of CA chambers, which are commonly used: 1) Palliflex unit and 2) Air or gas tight chambers.



Palliflex unit

It contains a special plastic pallet, a plastic cover for gas-tight sealing, bottles of nitrogen (N_2) for oxygen reduction, bottles of CO_2, gas inlet and outlet hoses and a fully automatic measuring and regulation system with a built in O_2/CO_2 meter. The major advantage of this unit is different gas conditions can be set per pellet in the same chamber.



Gas tight storage chamber

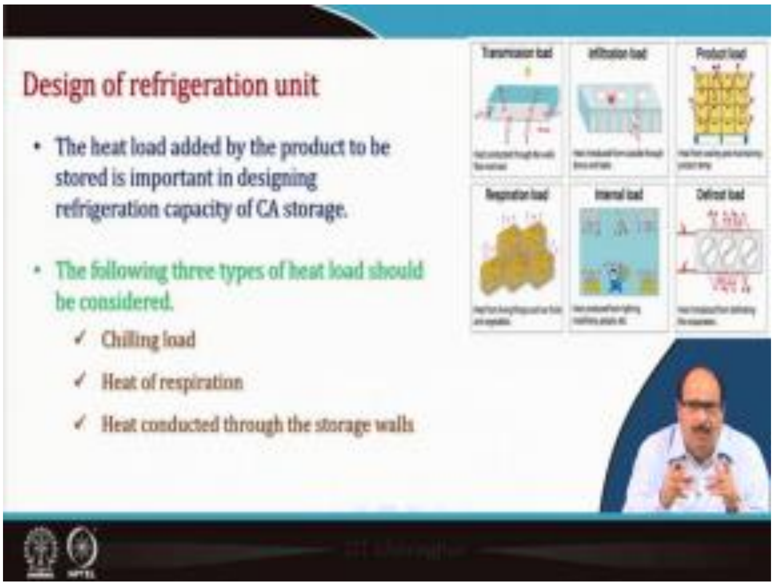
The capacity of the storage cell depends upon total tonnage of the fruit or vegetable stored inside the room, bulk density of the fruit or vegetable, volume of storage accessories, free volume inside storage facility required for material handling. In a commercial CA storage room, it is recommended that 65% of the total volume should be kept free for easy movement of gases and it facilitates in maintaining the proper gaseous composition.

Total volume required, $V = VSA + VF + F_v$

Where, VSA = Volume occupied by storage accessories

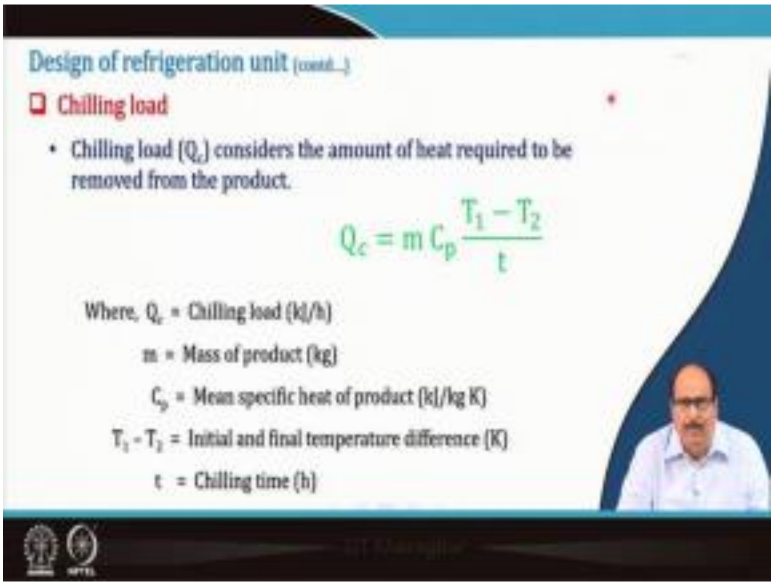
VF = Volume occupied by fruit = (Weight of fruit/ Fruit density)

F_v = Recommended free volume (0.65 V)



Design of a refrigeration unit

The heat load added by the product to be stored in the unit is important in designing the refrigeration capacity of CA storage unit. The following three types of heat load should be considered: 1) Chilling load, 2) Heat of respiration, and 3) Heat conducted through the storage walls.



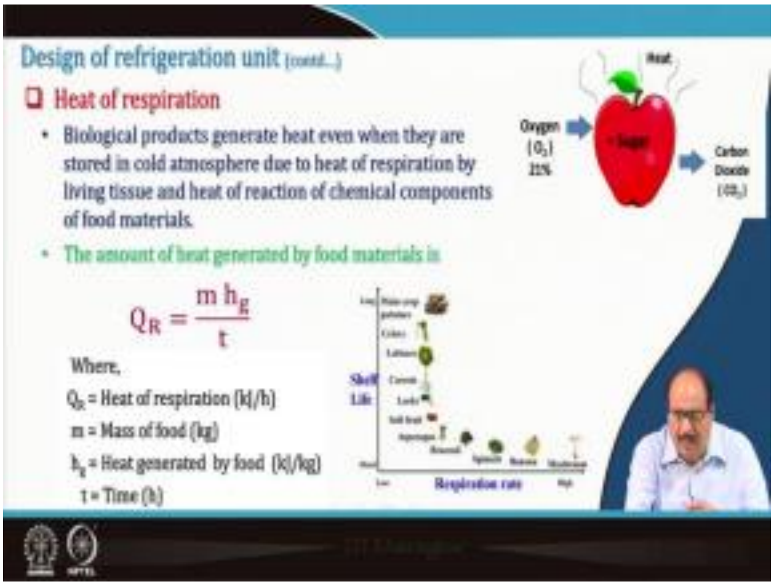
Chilling load

This chilling load Q_c considers the amount of heat required to be removed from the product.

$$Q_c = m\,C_p \frac{T_1 - T_2}{t}$$

Where,

Q_c = Chilling load (kJ/h)
m = Mass of product (kg)
C_p = Mean specific heat of product (kJ/kg K)
$T_1 - T_2$ = Initial and final temperature difference (K)
t = Chilling time (h)



Heat of respiration

Biological products generate heat even when they are stored in cold atmosphere due to heat of respiration by living tissue and heat of reaction of chemical components of food materials.
The amount of heat generated by food materials;

$$Q_R = \frac{m\,h_g}{t}$$

Where,

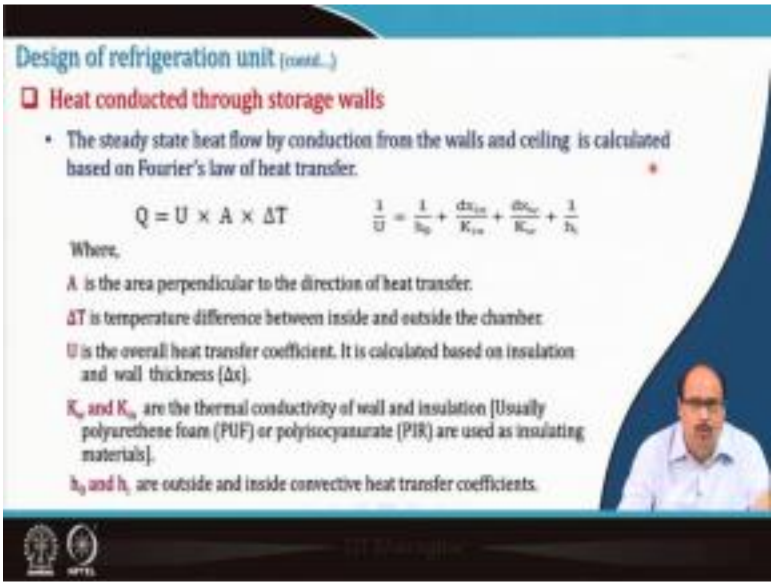
Q_R = Heat of respiration (kJ/h)
m = Mass of food (kg)
h_g = Heat generated by food (kJ/kg h)
t = Time (h)

Heat conducted through storage walls

The steady state heat flow by conduction from the walls and ceiling is calculated based on Fourier’s law of heat transfer.

$$Q = U \times A \times \Delta T$$

$$\frac{1}{U} = \frac{1}{h_0} + \frac{dx_{in}}{K_{in}} + \frac{dx_w}{K_w} + \frac{1}{h_i}$$



Where,

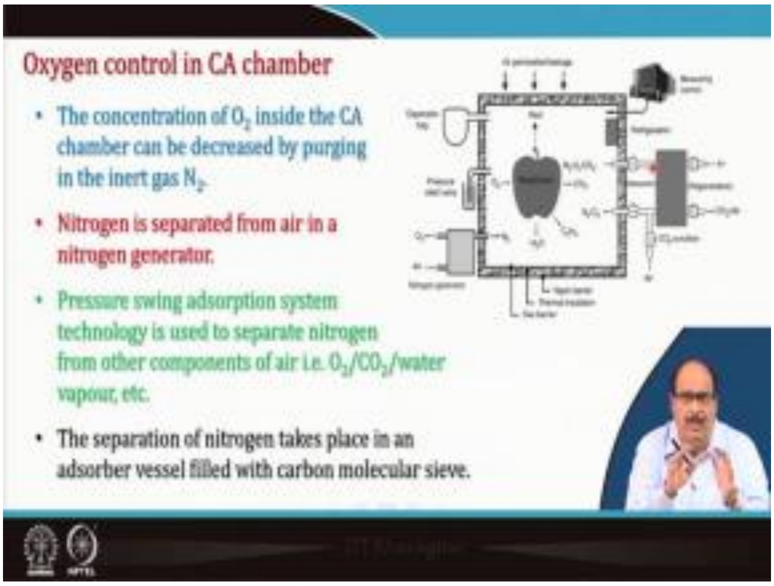
A is the area perpendicular to the direction of heat transfer.

ΔT is temperature difference between inside and outside the chamber.

U is the overall heat transfer coefficient. It is calculated based on insulation and wall thickness (Δx).

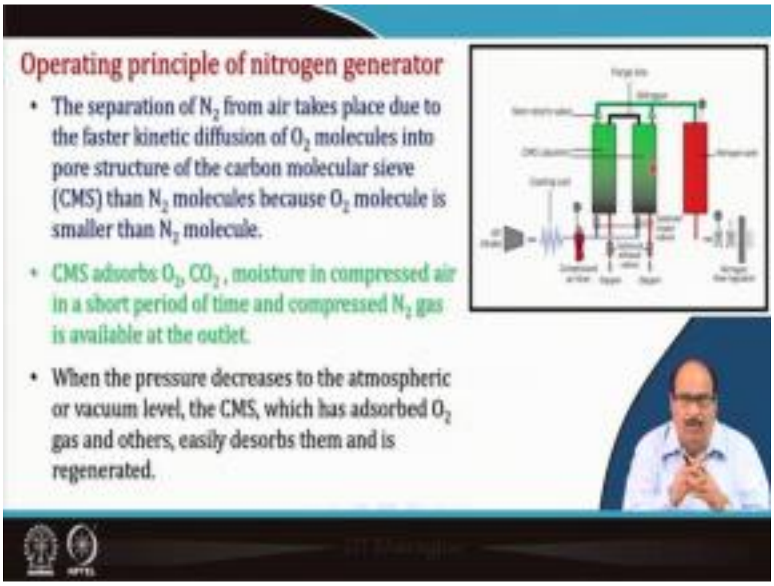
K_w and K_{in} are the thermal conductivity of wall and insulation [Usually polyurethene foam (PUF) or polyisocyanurate (PIR) are used as insulating materials].

h_0 and h_i are outside and inside convective heat transfer coefficients.



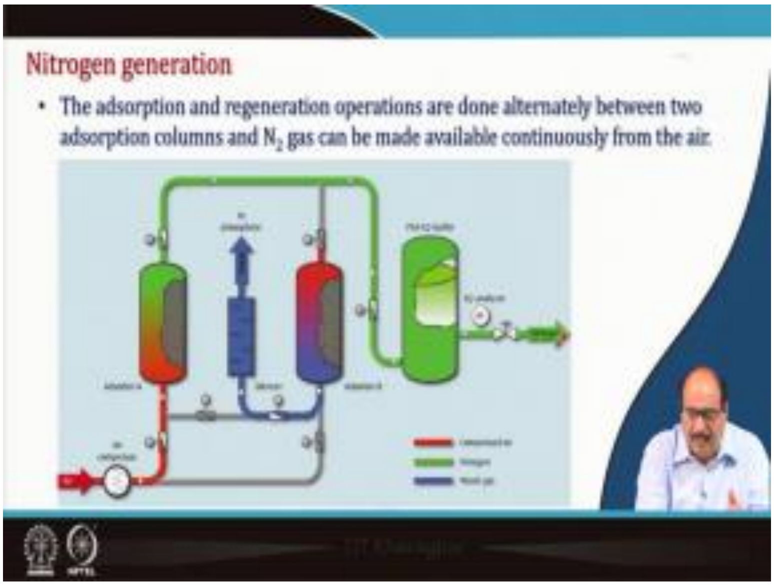
Oxygen control in CA chamber

The concentration of oxygen inside the CA chamber can be decreased by purging the inert gas nitrogen gas. Nitrogen is separated from air in a nitrogen generator. Pressure swing adsorption system technology is used to separate nitrogen from other components of air i.e. O2/CO2/water vapour, etc. The separation of nitrogen takes place in an adsorber vessel filled with carbon molecular sieve.



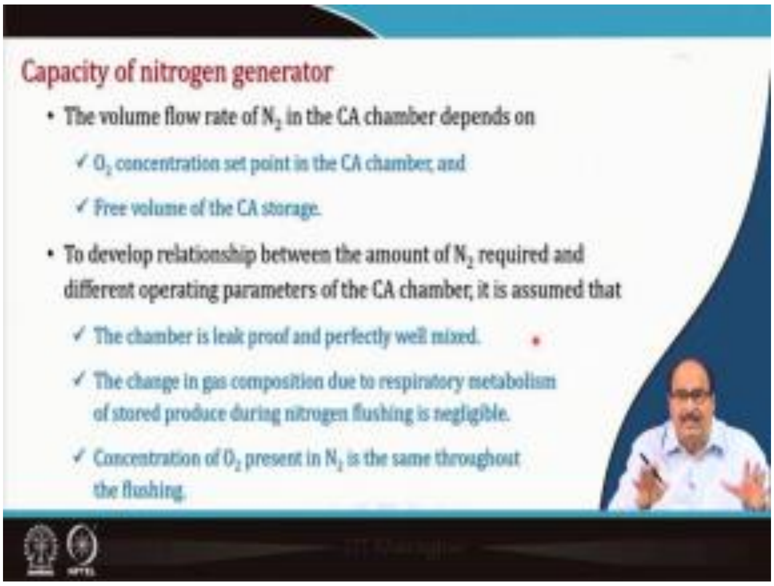
Operating principle of nitrogen generator

The separation of N_2 from air takes place due to the faster kinetic diffusion of O_2 molecules into pore structure of the carbon molecular sieve (CMS) than N_2 molecules because O_2 molecule is smaller than N_2 molecule. CMS adsorbs O_2, CO_2, moisture in compressed air in a short period of time and compressed N_2 gas is available at the outlet. When the pressure decreases to the atmospheric or vacuum level, the CMS, which has adsorbed O_2 gas and others, easily desorbs them and is regenerated.



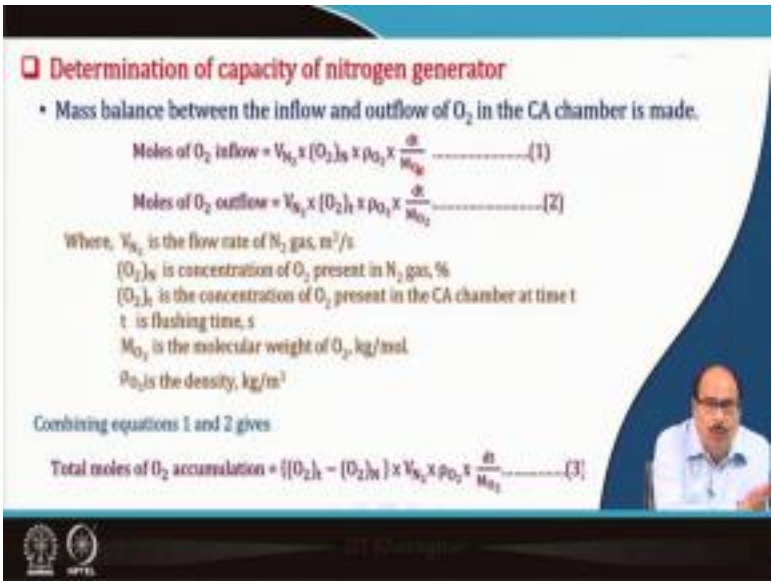
Nitrogen generation

The adsorption and regeneration operations are done alternatively between two adsorption columns and nitrogen gas can be made available continuously from the air. In the shown figure, red colour represents the compressed air passing through the Absorber A or Absorber B (when one works (i.e. absorption), the other absorber is in stand-by (i.e. desorption)). As the compressed air passes into absorber bed, it absorbs moisture, oxygen, and carbon dioxide. After operating pressure is reached, nitrogen flows from Absorber bed A into nitrogen product receiver before entering the product pipe. There is an oxygen analyser to ensure that oxygen is under limit. Simultaneously, absorber bed B is depressurized to atmospheric pressure.



Capacity of nitrogen generator

The volume flow rate of nitrogen in the CA chamber depends on mainly oxygen concentration set point in the CA chamber and free volume of the CA storage. To develop relationship between the amount of nitrogen required and different operating parameters of the CA chamber, it is assumed that the chamber is leak proof and perfectly well mixed. The change in gas composition due to respiratory metabolism of store produce during nitrogen flushing is negligible. And concentration of oxygen present in nitrogen is the same throughout the flushing.



Determination of capacity of nitrogen generator

Mass balance between the inflow of oxygen and outflow of oxygen in the CA chamber is done.

$$\text{Moles of } O_2 \text{ inflow} = V_{N_2} \text{ x } (O_2)_N \text{ x } \rho_{O_2} \text{ x } \frac{dt}{M_{O_2}} \text{ ....(1)}$$

$$\text{Moles of } O_2 \text{ outflow} = V_{N_2} \text{ x } (O_2)_t \text{ x } \rho_{O_2} \text{ x } \frac{dt}{M_{O_2}} \text{..........................(2)}$$

Where, V_{N_2} is the flow rate of N_2 gas, m^3/s

$(O_2)_N$ is concentration of O_2 present in N_2 gas, %

$(O_2)_t$ is the concentration of O_2 present in the CA chamber at time t

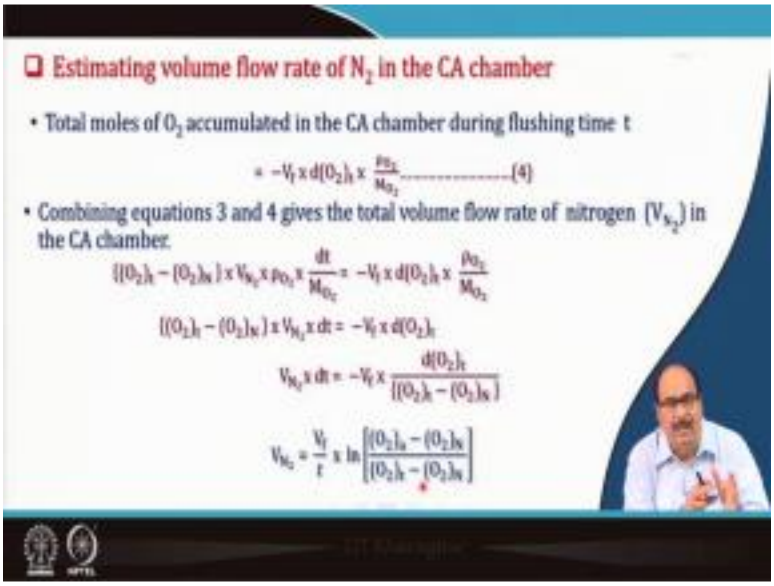
t is flushing time, s

M_{O_2} is the molecular weight of O_2, kg/mol.

ρ_{O_2} is the density, kg/m^3

Combining equations 1 and 2 gives

$$\text{Total moles of } O_2 \text{ accumulation} = \{(O_2)_t - (O_2)_N\} \text{ x } V_{N_2} \text{ x } \rho_{O_2} \text{ x } \frac{dt}{M_{O_2}} \text{...............(3)}$$



Estimate the volume flow rate of nitrogen in the CA chamber

Total moles of O_2 accumulated in the CA chamber during the flushing time, t=

$$= -V_f \text{ x } d(O_2)_t \text{ x } \frac{\rho_{O_2}}{M_{O_2}} \text{............................(4)}$$

Combining equations 3 and 4 gives the total volume flow rate of nitrogen (VN2) in the CA chamber.

$$\{(O_2)_t - (O_2)_N\} \text{ x } V_{N_2} \text{ x } \rho_{O_2} \text{ x } \frac{dt}{M_{O_2}} = -V_f \text{ x } d(O_2)_t \text{ x } \frac{\rho_{O_2}}{M_{O_2}}$$

$$\{(O_2)_t - (O_2)_N\} \text{ x } V_{N_2} \text{ x } dt = -V_f \text{ x } d(O_2)_t$$

$$V_{N_2} \text{ x } dt = -V_f \text{ x } \frac{d(O_2)_t}{\{(O_2)_t - (O_2)_N\}}$$

$$V_{N_2} = \frac{V_f}{t} \times \ln\left[\frac{(O_2)_a - (O_2)_N}{(O_2)_t - (O_2)_N}\right]$$

Humidity control

The moisture loss of store product inside the CA chamber reduces if the relative humidity levels are kept above 90 %. A humidification system maintains the relative humidity up to the desired level. The relative humidity in the storage facility can be controlled by the fine water spray or stream.

Determination of capacity of humidifier

Final humidity inside the CA chamber is determined based on the principle of mass and energy balance.

Let, the flow rate, humidity ratio and enthalpy of the

Initial air stream in the CA chamber be m_1, h_1, H_1

Saturated air stream from the humidifier be m_2, h_2, H_2

Finally, desired air stream in the CA chamber be m_3, h_3, H_3

The mass balance is done by balancing the air flow rate.

$$m_3 = m_1 + m_2 \qquad \ldots..(1)$$

Determination of capacity of humidifier

Final humidity ratio in the CA chamber is determined by humidity balance equation.

$$m_3 h_3 = m_1 h_1 + m_2 h_2 \qquad \ldots..(2)$$

Enthalpy of the air stream in the CA chamber, can be determined by the energy balance equation.

$$m_3 H_3 = m_1 H_1 + m_2 H_2 \qquad \ldots..(3)$$

By solving equations 1, 2 and 3 one can determine the mass flow rate of water jet in the CA chamber for the desired humidity control.

CO_2 control in CA facility

- Air contains 0.03 % CO2.
- Target value of CO2 set in CA chamber is usually greater than that present in air; it varies with product. For example, 5 % CO2 is required for CA storage of guava.

  Rate of CO_2 accumulation in the CA chamber due to product respiration:

  $$CO_{2\ accumulated}\ (cc/h) = (\text{Mass of stored product}) \times (\text{Rate of } CO_2 \text{ production per kg product})$$

  Rate of CO_2 flow in the CA chamber from cylinder:

$$CO_{2\ required}\ (cc/h) = \frac{\text{Target value of } CO_2 \text{ set, \%} - 0.03}{100} \times \text{Free volume inside CA chamber}$$

CO_2 control in CA facility

- If CO_2 required > CO_2 accumulated
  Then CO_2 gas is purged in the CA from CO_2 cylinders.
- If CO_2 accumulated > CO_2 required
  Then the CO_2 level inside the CA is maintained by using CO_2 scrubbers.
- Air from the storage area is removed by the CO2 scrubber, and the CO2 purified air is then fed back in.
- The CO_2 scrubber has a cycle of two activities
  Absorption - Removal of the CO_2 by using an active carbon filter.
  Regeneration - Cleaning of the active carbon filter.

Ethylene control

Ethylene gas may be added to the CA chamber to induce ripening.

$$C_2H_{4\ required}\ (cc/h) = \frac{\text{Amount of C2H4 tobe maintained in CA chamber \%}}{100} \text{ x Free volume inside CA chamber}$$

Ethylene decomposers remove it from cold stores based on catalytic combustion. The C_2H_4 decomposer uses O_2 to combust ethylene to form CO_2 and water. This enables C_2H_4 to be kept at the required (ppm or ppb) levels.

The capacity of the ethylene decomposer can be estimated based on the following equation:

$$F = \frac{R \text{ x } M}{C \text{ x } D}$$

Where, F = output of the compressor (m^3/h)

M = total tonnage of the fruit

R = ethylene production of fruit (μL kg^{-1} h^{-1})
C = required ethylene concentration (ppm*)
D = efficiency ratio (standard is 95%) (0.95)

Sensors used in CA chamber

Oxygen sensor

Zirconia sensors are used for measurement of oxygen. Zirconia ceramic cells only allow oxygen ions to pass through at high temperatures. With reference gas on one side and sample gas on the other, the oxygen ions move from the side with the highest concentration to that with the lowest concentration. The movement of ions generates an electromotive force (EMF) which can be measured to determine the oxygen content.

Carbon dioxide sensor

When a light source is exposed to a gas stream containing CO_2, energy from the infrared region of the spectrum is absorbed by the gas. The amount of light absorbed by the gas stream is directly proportional to the CO_2 content in the gas stream.

Ethylene sensors

Silicon carbide based gas sensor is normally used for ethylene detectors. There reducing box and it comes here there is a flow container air led and then it is connected with the ethylene monitory device. So, the sensors is calibrated it senses this and then display it in the monitor.

Factors affecting the quality of the store products:

- Species of crop
- Cultivars of crop
- Concentration of the gases in the store
- Crop temperature
- Degree of ripeness of the climacteric fruit
- State of maturity of the crop at harvest
- Growing conditions before harvest
- Presence of ethylene in the store

Advantages of a CA is storage

- A considerable decrease in respiration rate, with a reduction in climacteric maximum, accompanied by an expansion of both pre-climacteric and post-climacteric periods.
- A reduction in the effect of ethylene on metabolism due to the interaction of O_2 with ethylene, with a consequent delay of appearance of senescence symptoms.
- An extension in storage life.
- The preservation of an excellent firmness of flesh, due to effect of CO_2 concentration on the enzymes acting on cellular membranes.
- A high turgidity is achieved, such that fruits are more juicy and crisp.
- A smaller loss of acidity, sugars and vitamin C, so that the nutritional and sensory quality is higher.
- A limited degradation of chlorophyll, with a consequent higher stability of colour.
- Some physiological alterations, such as chill injuries, spot, decay, browning, water core and scald are prevented, or greatly limited.
- Moulds can be reduced, in particular under low O_2, high CO_2 atmospheres.

Threshold levels of oxygen or carbon dioxide required to cause injury to some fruit and vegetable.

For example, in apricot, CO_2 injury the level occurs when it is > 5 % followed by loss of flavour, flesh browning. Similarly, the oxygen injury level occurs when O_2 < 1%. In banana, injuries occur when CO_2 level < 7 % and O_2 level < than 1 %. Similarly, in cabbage, CO_2 injury level occurs at levels > 10 %, and O_2 injury level takes place with levels < 2 %. In mango, injuries occur at CO_2 level >10 % and O_2 level < 2 %. The levels of CO_2 and O_2 along with their related symptoms for different fruits and vegetables are described here in this table.

Pilot scale CMA storage facility designed, developed and fabricated in FCTL, IIT KGP is shown here.

The chamber has got four chambers, and each chamber has got the storage facility. Each chamber can store up to 250 kg of fruits and vegetables, so the overall storage capacity is 1000 kg. It has a unique feature of independently controlling each of the chamber. Each chamber can be individually opened/closed and it can be centrally monitored with central controlling system.

Individual chambers have PLC control as well as central PLC control. The temperature can be controlled from 0 to 50 ℃, O_2 from 0.1 to 25 %, CO_2 from 0.1 to 25 %, relative humidity (RH) from 10 to 95 % and ethylene from 1 to 1000 ppm. The condition can be maintained either to advance the ripening or to extend the shelf life.

In summary, CA technology has been undergoing continuous development and refinement during last few decades, leading to continuing construction of CA facilities worldwide. CA storage commonly uses low oxygen (O_2) levels and high carbon dioxide (CO_2) levels in the storage atmosphere combined with refrigeration. In CA storage, inside a food storage room is the gas composition that is continually monitored and adapted to maintain the optimum concentration within completely close tolerances. CA storage is the enclosure of food in a gas impermeable facility inside which the gaseous environment with respect to CO_2, O_2, N_2 (nitrogen gas), water vapor & other trace gases has been changed and is selectively controlled to increase shelf life.

These are the references for further study lecture. Thank you