Mass Transfer Operations 2

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Lecture 31

Concluding Remarks: Part 1

So welcome back to Mass Transfer Operations 2, were we have successfully completed the entire syllabus within the stipulated time period and I expect that you have learned a lot from this basic separation processes and technologies which are widely used in this chemical and allied industries namely humidification and say the dehumidification operation in terms of air conditioning, then various drying operations and liquid-liquid extractions followed by the solid liquid extraction that is leaching process then membrane based separation process and their applications and adsorption processes and desorption processes and ion exchange and lastly this crystallization processes.

Now I will be briefing the entire syllabus and will be trying to one clarify the some portions which I could not complete or touch during the this one of the different chapters and we will first start with humidification and air conditioning process like this is that was the first chapter

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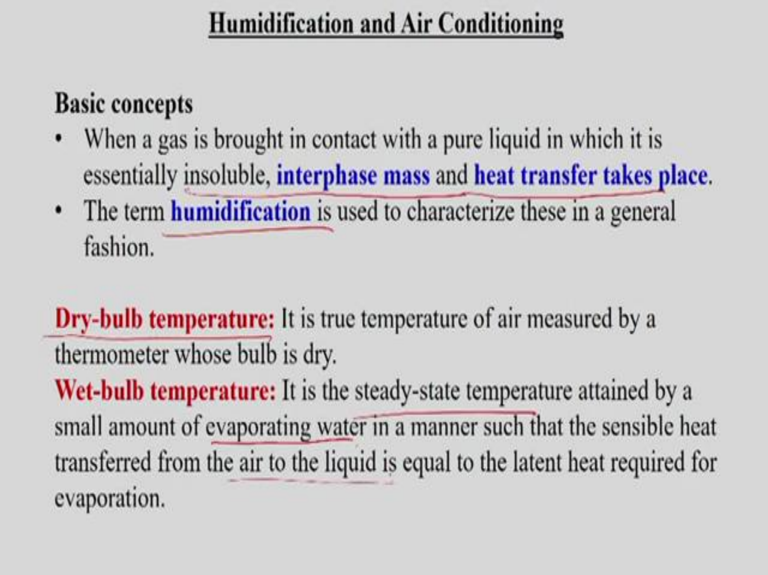

Humidification and Air Conditioning

Basic concepts

- When a gas is brought in contact with a pure liquid in which it is essentially insoluble, **interphase mass** and **heat transfer takes place**.
- The term **humidification** is used to characterize these in a general fashion.

Dry-bulb temperature: It is true temperature of air measured by a thermometer whose bulb is dry.

Wet-bulb temperature: It is the steady-state temperature attained by a small amount of evaporating water in a manner such that the sensible heat transferred from the air to the liquid is equal to the latent heat required for evaporation.

And from humidification and air conditioning we discussed in the beginning about the basic concepts like we can say when this gas is brought in contact with a pure liquid in which it is essentially insoluble, then interphase mass transfer as well as the heat transfer takes place. So we can say this humidification and dehumidification or air conditioning processes are simultaneous heat and mass transfer operations. The term humidification operation actually is used to characterize this processes in a generalized fashion and for that actually we have learned the definition of wet bulb temperature and dry bulb temperature that say whenever we will be talking about this dry bulb temperature that is we can say true temperature of the air measured by say a thermometer whose bulb is dry.

And for this wet bulb temperature say that we discussed that it is a steady state temperature attained by a small amount of evaporating water and in a manner such that the sensible heat transferred actually from this air to the liquid for the evaporation is equal to the latent heat required for this evaporation. So in case of this wet bulb temperature we have discussed that it is equivalent to this adiabatic saturation temperature for air water system but for other systems the adiabatic saturation temperature and wet bulb temperature may be varied or but in very narrow range.

But whenever we will be talking about any wet bulb temperature then a small portion of this liquid is in the evaporation mode and for that evaporation it will take some amount of say we can say heat from this we can say liquid fuel and during this evaporation and then that equilibrium temperature will be showing the wet bulb temperature, so it was dependent on the how much amount of that the some liquid this one we have liquid was there in the vapor form in the air, so if this we can say relative humidity in terms of we can say if this one if it is liquid is water then if the relative humidity is very high then we can say vapor temperature will be high also, because there the dropping will be very less because there the evaporation will be in a smaller quantity.

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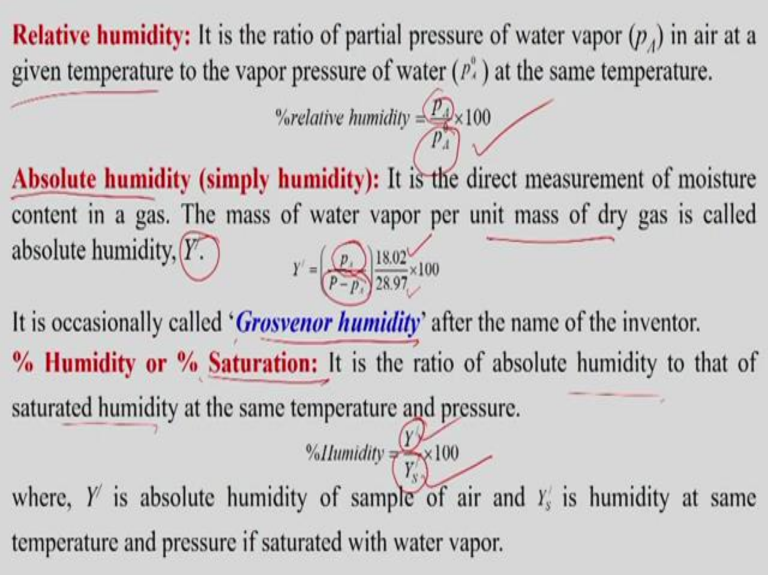

Relative humidity: It is the ratio of partial pressure of water vapor (p_A) in air at a given temperature to the vapor pressure of water (p_A^0) at the same temperature.

$$\%relative\ humidity = \frac{p_A}{p_A^0} \times 100$$

Absolute humidity (simply humidity): It is the direct measurement of moisture content in a gas. The mass of water vapor per unit mass of dry gas is called absolute humidity, Y'.

$$Y' = \left(\frac{p_A}{P - p_A}\right)\frac{18.02}{28.97} \times 100$$

It is occasionally called '*Grosvenor humidity*' after the name of the inventor.

% Humidity or % Saturation: It is the ratio of absolute humidity to that of saturated humidity at the same temperature and pressure.

$$\%Humidity = \frac{Y'}{Y_S'} \times 100$$

where, Y' is absolute humidity of sample of air and Y_s' is humidity at same temperature and pressure if saturated with water vapor.

And then we learned about this relative humidity that say it is the ratio of the partial pressure of this water vapor let us say in air actually even in a given temperature to the vapor pressure, so of this water at the same temperature and you can say this at the same temperature, so that is we can say relative humidity which the ratio between this we can say partial pressures and so it gives this how much humidity is there relative to the saturation humidity, so it is not the explicit value but whenever we will be taking about the this absolute humidity whatever we have discussed that the simply humidity that is the direct measurement of the we can say moisture content in a gas.

So the mass of the water vapor per unit mass of dry is actually is called the absolute humidity or Y prime. We is frequently used this Y prime for the calculation of the in the say we can say cooling tower or dehumidification chamber or we can say this air conditioning system. Like Y prime is this ratio between we can say this what partial pressure of a particular gas divided by this whatever the relative pressure is there means total P minus PA into this molecular weight of this water divided molecular weight of air into hundred means this in terms of hundred percent.

So here this in term of percentage, so it is always generally called also Grosvenor humidity also after the name of this inventor. Then we describe about the percentage saturation, so that was you can say how much saturated is a particular we can this air.

So it is the ratio of this absolute humidity to that of the saturated humidity like say Y prime by YS prime means how much amount of we can say water vapor is required to saturate in that particular temperature, So that is we can say from there we can say how much percentage saturation or percentage humidity is there, so this Y prime by YS prime into hundred that is in terms of percentage.

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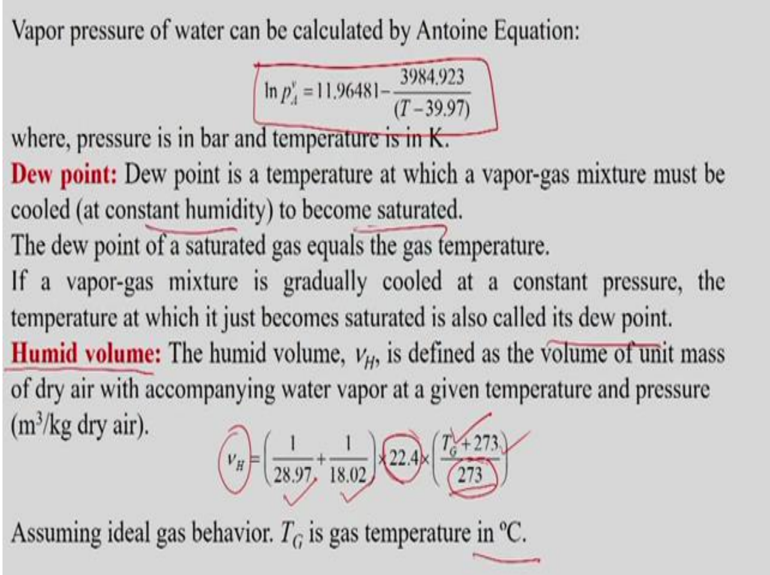

Vapor pressure of water can be calculated by Antoine Equation:

$$\boxed{\ln p_A^v = 11.96481 - \frac{3984.923}{(T-39.97)}}$$

where, pressure is in bar and temperature is in K.

Dew point: Dew point is a temperature at which a vapor-gas mixture must be cooled (at constant humidity) to become saturated.

The dew point of a saturated gas equals the gas temperature.

If a vapor-gas mixture is gradually cooled at a constant pressure, the temperature at which it just becomes saturated is also called its dew point.

Humid volume: The humid volume, v_H, is defined as the volume of unit mass of dry air with accompanying water vapor at a given temperature and pressure (m^3/kg dry air).

$$\boxed{v_H} = \left(\frac{1}{28.97} + \frac{1}{18.02}\right) \times \boxed{22.4} \times \left(\frac{T_G + 273}{\boxed{273}}\right)$$

Assuming ideal gas behavior. T_G is gas temperature in °C.

Then this one we were able to calculate the vapor pressure of say suppose water, so in air water system using this Antoine equation, so in any of this temperature what will be this we can vapor pressure, so that we calculated using this equation:

$$\ln p_A^v = 11.96481 - \frac{3984.923}{(T-39.97)}$$ where, pressure is in bar and temperature is in K.

From there for any we can say temperature range we are able to calculate what is the, this one vapor pressure. From there actually we are able to calculate this what was the say we can say relative or percentage humidity or we can say percentage saturation also we are able to measure this one using the Antoine equation or whenever we have learned this psychrometric chart also from there also we are able to calculate what is the hundred percent saturation line with respect to we can say temperature.

And we learned also this dew point that is we can say one particular temperature, so it a temperature at which vapor gas mixture must be cooled or we can say at this constant humidity to become the saturated. So the dew point of saturated gas equals the gas temperature then if a vapor gas mixture is gradually cooled at constant pressure the temperature at which it just we can say become saturated is called its dew point.

So at dew point the first dew drop actually will be generated and then we have learned about the this humid volume that is also one important parameter for the in terms of we can say humidity or in the psychrometric properties the humid volume or VH actually was this defined as the volume of unit mass of dry air with accompanying water vapor at a given temperature.

$$v_H = \left(\frac{1}{28.97} + \frac{1}{18.02}\right) \times 22.4 \times \left(\frac{T_G + 273}{273}\right) \text{ m}^3\text{/kg dry air}$$

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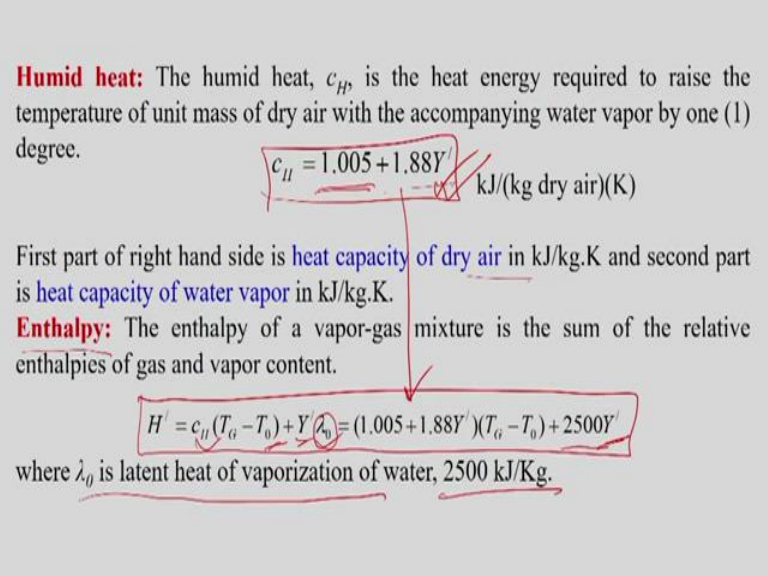

Humid heat: The humid heat, c_H, is the heat energy required to raise the temperature of unit mass of dry air with the accompanying water vapor by one (1) degree.

$$\boxed{c_H = 1.005 + 1.88Y'} \text{ kJ/(kg dry air)(K)}$$

First part of right hand side is heat capacity of dry air in kJ/kg.K and second part is heat capacity of water vapor in kJ/kg.K.

Enthalpy: The enthalpy of a vapor-gas mixture is the sum of the relative enthalpies of gas and vapor content.

$$\boxed{H' = c_H(T_G - T_0) + Y'\lambda_0 = (1.005 + 1.88Y')(T_G - T_0) + 2500Y'}$$

where λ_0 is latent heat of vaporization of water, 2500 kJ/Kg.

Then we have learned also the humid heat that humid heat or we say this CH that is we can say we expressed in using one equation like:

$$c_H = 1.005 + 1.88Y' \text{ kJ/(kg dry air)(K)}$$

And so that we can see the first part of this right hand side 1.005 that is the heat capacity of the dry air and the second part is the heat capacity of the water vapor because this the humidity and this into 1.88 and the enthalpy

$$H' = c_H(T_G - T_0) + Y'\lambda_0 = (1.005 + 1.88Y')(T_G - T_0) + 2500Y' \text{ kJ/kg}$$

where λ_0 is latent heat of vaporization of water, 2500 kJ/Kg.

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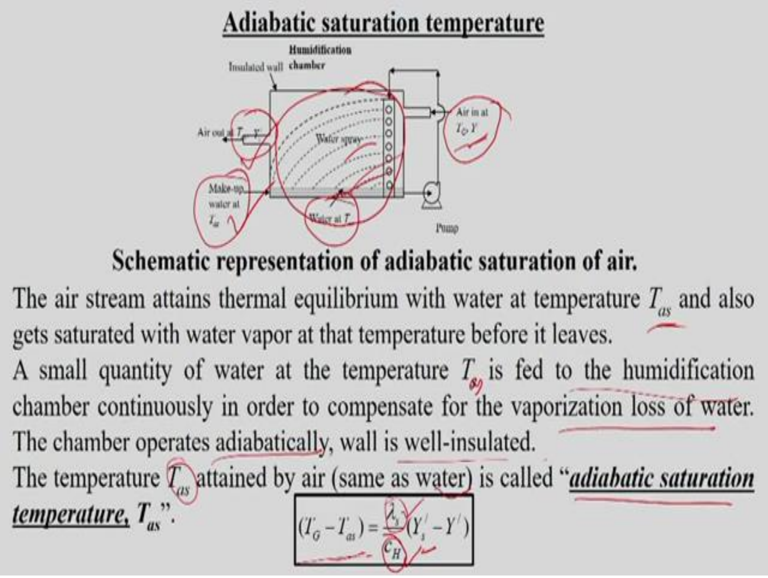

Adiabatic saturation temperature

Schematic representation of adiabatic saturation of air.

The air stream attains thermal equilibrium with water at temperature T_{as} and also gets saturated with water vapor at that temperature before it leaves.

A small quantity of water at the temperature T_{as} is fed to the humidification chamber continuously in order to compensate for the vaporization loss of water.

The chamber operates adiabatically, wall is well-insulated.

The temperature T_{as} attained by air (same as water) is called "***adiabatic saturation temperature,*** T_{as}".

$$\boxed{(T_G - T_{as}) = \frac{\lambda_s}{c_H}(Y'_s - Y')}$$

Then we have learned in detail about the adiabatic saturation temperature that suppose one the system is there suppose this is one particular say reserve what type thing and water is say distributed here through the sprayer like this.

And suppose air this dry air with this Y prime is entering with temperature TG or gas temperature and then this air whatever is entering inside this chamber that is we can say well insulated chamber, so that is now saturated with water vapor and this water is at TAS particular temperature the adiabatic saturation temperature and this air is now saturated is water vapor and that is why this we allowed this dry air to enter with un saturation.

Wherever it is unsaturated then it is coming out as this TAS with YS prime, so that YS prime actually is nothing but the saturation humidity of air at that condition, at that condition means at that particular pressure and then make up water some amount of we already discussed that whenever we talked this wet bulb temperature or adiabatic saturation temperature the system is maintained adiabatically and since small amount of water actually is evaporated to we can say this one to decrease the temperature from this TG or gas temperature to this we can say adiabatically saturated one.

And at that condition some amount of water is lost during this evaporation, so for that surround a makeup water actually is added and that is also added at that particular temperature to not to disturb the temperature of whatever gas that is saturated and is exiting the we can say this chamber adiabatic chamber or we can say that is you can say humidification chamber where humidifying the gas and then whenever the humidification operation is complete then we can say it is saturated one.

So that is why air stream attends the thermal equilibrium with water at temperature TAS and also get saturated with water vapor at the temperature before it leaves the, so we can say the humidification chamber, so a small quantity of water at the temperature TS actually is TAS is fed to the humidification chamber continuously in order to compensate for the vaporization loss of water.

So the chamber operate adiabatically and wall is well insulated that so you can say adiabatically saturation means the air is saturated with water vapor and the temperature TAS that is we can say temperature of the gas means air leaving this chamber as well as the temperature of this water entering as the makeup water, so attend by this air the same as like water is called this adiabatic saturation temperature.

So this TG minus TA is what about the dropping the temperature is nothing but this lamda S that is we can say this how much amount of latent heat is supplied by this how much amount of this one heat capacity is there into YS prime minus Y prime.

From there we can get this, what will be the adiabatic saturation temperature of this we can say air water resistance we will be able to calculate every easily and we already mentioned that this adiabatic saturation temperature for air water resistance system is same as this we can say wet bulb temperature that it may not be true for other systems.

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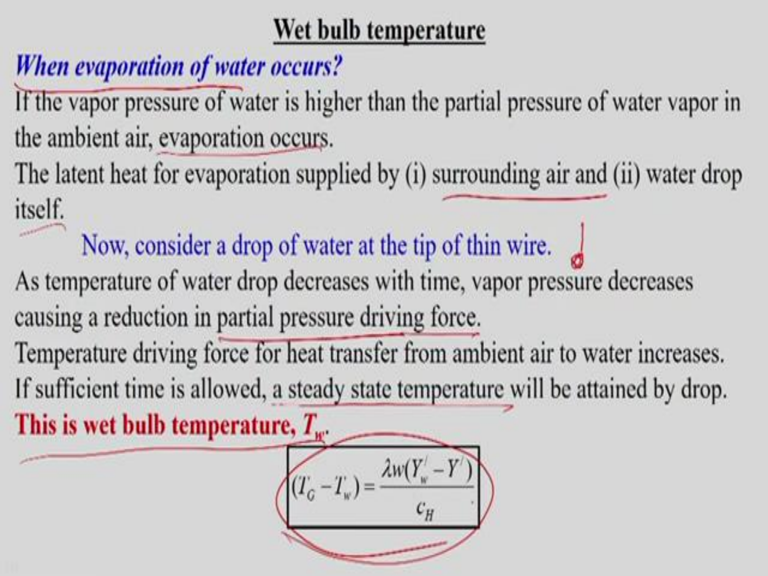

Wet bulb temperature

When evaporation of water occurs?

If the vapor pressure of water is higher than the partial pressure of water vapor in the ambient air, evaporation occurs.

The latent heat for evaporation supplied by (i) surrounding air and (ii) water drop itself.

Now, consider a drop of water at the tip of thin wire.

As temperature of water drop decreases with time, vapor pressure decreases causing a reduction in partial pressure driving force.

Temperature driving force for heat transfer from ambient air to water increases.

If sufficient time is allowed, a steady state temperature will be attained by drop.

This is wet bulb temperature, T_w.

$$\boxed{(T_G - T_w) = \frac{\lambda w(Y_w^{/} - Y^{/})}{c_H}}$$

Now this one when this evaporation in terms of wet bulb temperature when we can say evaporation of water occurs, so this we can say if the water pressure the vapor pressure of water is higher than the partial pressure of water vapor in the ambient air means were it is evaporating the evaporation will occur like that also we say vapor pressure of the water is higher than only the evaporation will occur. The latent heat for evaporation supplied by we say the surrounding air and this water drop itself were we can say the small portion actually of the latent heat during this evaporation is employed to evaporate the we can say small portion of water.

Now we can consider drop of water at the tip of thin wire like this say in a thin wire say one drop of water is hanging and as temperature of water drop decreases with time then vapor pressure decreases causing the reduction in the partial pressure or we can say in the form of this driving force and temperature driving force of the heat transfer from ambient air to water also increases.

$$(T_G - T_w) = \frac{\lambda w(Y_w^{/} - Y^{/})}{c_H}$$

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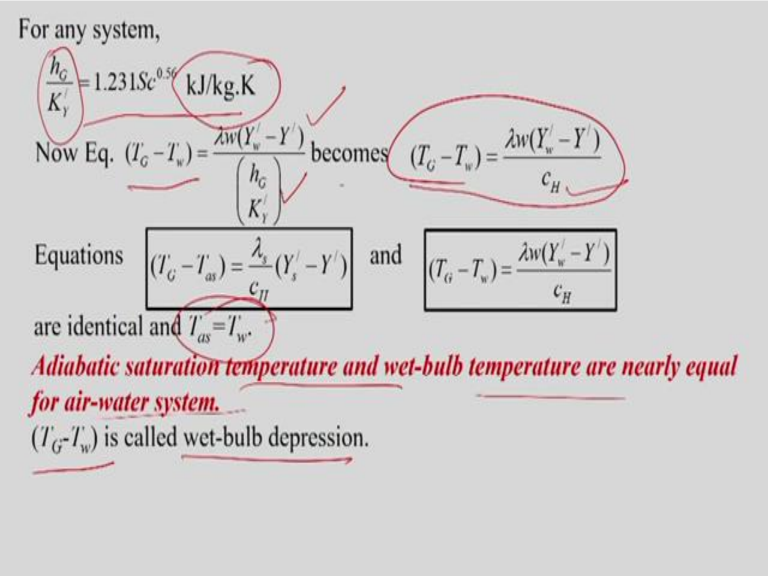

For any system,

$$\frac{h_G}{K_Y^{/}} = 1.231 Sc^{0.56} \text{ kJ/kg.K}$$

Now Eq. $(T_G - T_w) = \frac{\lambda w (Y_w^{/} - Y^{/})}{\left(\frac{h_G}{K_Y^{/}}\right)}$ becomes $(T_G - T_w) = \frac{\lambda w (Y_w^{/} - Y^{/})}{c_H}$

Equations $\boxed{(T_G - T_{as}) = \frac{\lambda_s}{c_H}(Y_s^{/} - Y^{/})}$ and $\boxed{(T_G - T_w) = \frac{\lambda w (Y_w^{/} - Y^{/})}{c_H}}$

are identical and $T_{as} = T_w$.

Adiabatic saturation temperature and wet-bulb temperature are nearly equal for air-water system.

$(T_G - T_w)$ is called wet-bulb depression.

$$\frac{h_G}{K_Y^{/}} = 1.231 Sc^{0.56} \text{ kJ/kg.K}$$

$$(T_G - T_w) = \frac{\lambda w (Y_w^{/} - Y^{/})}{c_H}$$

$T_{as} = T_w$.

So the adiabatic saturation temperature and wet bulb temperature are nearly equal for air water system and this TG minus TW or TG minus TAS this is called as wet bulb depression. So how much this depression will be there for one particular air water system in the humidification tower or we can say in the cooling tower that will control the efficiency of the cooling tower.

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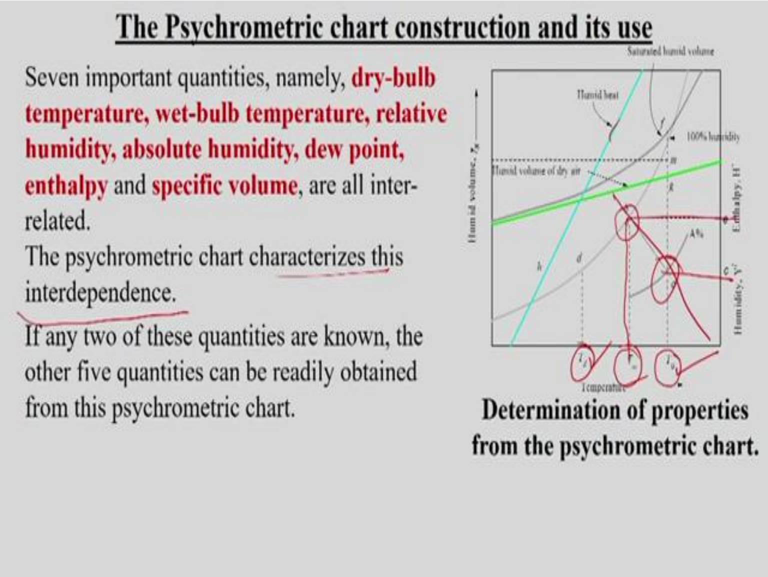

The Psychrometric chart construction and its use

Seven important quantities, namely, **dry-bulb temperature, wet-bulb temperature, relative humidity, absolute humidity, dew point, enthalpy** and **specific volume**, are all inter-related.

The psychrometric chart characterizes this interdependence.

If any two of these quantities are known, the other five quantities can be readily obtained from this psychrometric chart.

Determination of properties from the psychrometric chart.

And then we have learned the detail about the psychrometric chart construction and its use I think we have learned this one very clearly still we are now recapucalating this that seven important quantities like we can say dry bulb temperature then wet bulb temperature and then relative humidity, absolute humidity, dew point, enthalpy and specific volume this are all interrelated if we note two or three then other four or we can say four or five units will be able to measure or calculate from this psychrometric chart.

So there psychrometric chart actually characterizes this interdependency and if we know like this suppose if we know this dry bulb temperature and then we can say if we know this dry bulb temperature and this we can say wet bulb temperature or adiabatic saturation temperature from there we will be able to get what is the humidity or what is the dew point temperature everything we will be getting.

And what is the how much amount of humid volume will be there how much humid heat will be there and we can what is the absolute humidity or how value enthalpy values are there everything we will be able to get this one, so like this we can say any of this property can be obtained from this psychrometric chart but remember that it is a specific for a specific system like this for air water system this is a psychrometric chart for say air methanol system it will be different or for air ethanol system this pschrometric chart will be different and there characteristics will also entirely different.

But the trends are same if we know any of this if we know that what are this say adiabatic saturation line from there suppose we will be able to get suppose using this one were the hundred percent saturation is there from there we can get what is the adiabatic saturation temperature and how this one humidity is there, so in the beginning and if it is saturated adiabatically then what will be that particular humidity at that temperature like this.

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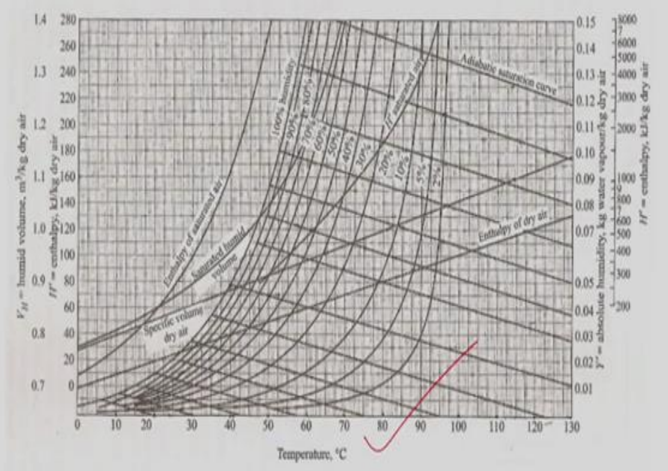

Figure : Psychrometric chart for air-water system at 1 atm total pressure.

So this is the we can say for air water system this is the psychrometric chart I think we have used several times for solving so many problems in both the humidification and drying also. Because the same psychrometric chart is used for the any of the drying of the wet solutes as well as this humidification operation as well as this air conditioning system because there water is evaporated in air, so that is why we able to use the psychrometric chart.

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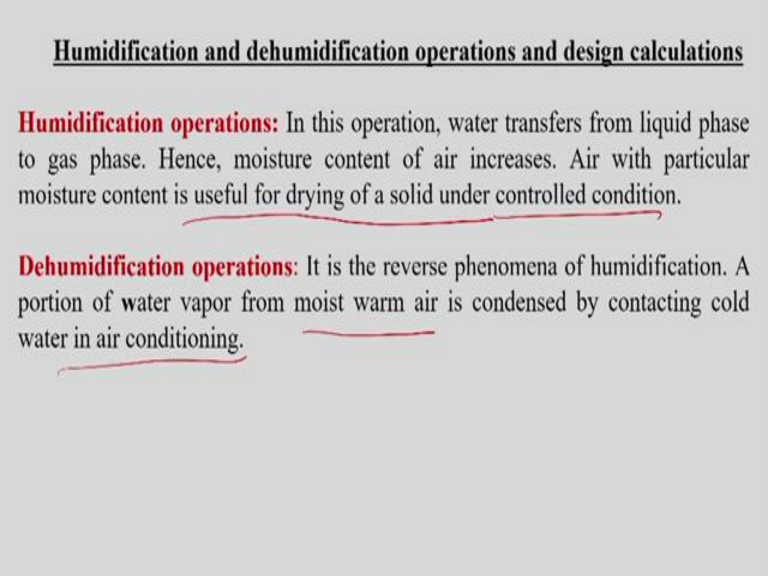

Humidification and dehumidification operations and design calculations

Humidification operations: In this operation, water transfers from liquid phase to gas phase. Hence, moisture content of air increases. Air with particular moisture content is useful for drying of a solid under controlled condition.

Dehumidification operations: It is the reverse phenomena of humidification. A portion of water vapor from moist warm air is condensed by contacting cold water in air conditioning.

Now this we can say for design calculation for humidification and dehumidification, so for humidification operation so in this operation we can say water transfers from liquid phase to the gas phase like this, small amount of water actually is evaporated during this evaporative cooling hence, the moisture content of air increases, so that is why suppose the saturated air enters from the bottom of this cooling tower and leaves the top of the cooling tower with more humidity.

So air with this particular moisture is useful for drying of the solid under the controlled condition, so that is one point. During this drying process also we have followed the same concept for dehumidification operation or this is the reverse of this humidification operation it is the reverse phenomena of humidification.

A portion of water vapor actually from moist air water in warm air is condensed by this contacting cold water in air conditioning system, so that is we can say reverse of the humidification operation, so this in air conditioning system, so we can say this one moist air is dehumidified and then temperature drops down inside this room.

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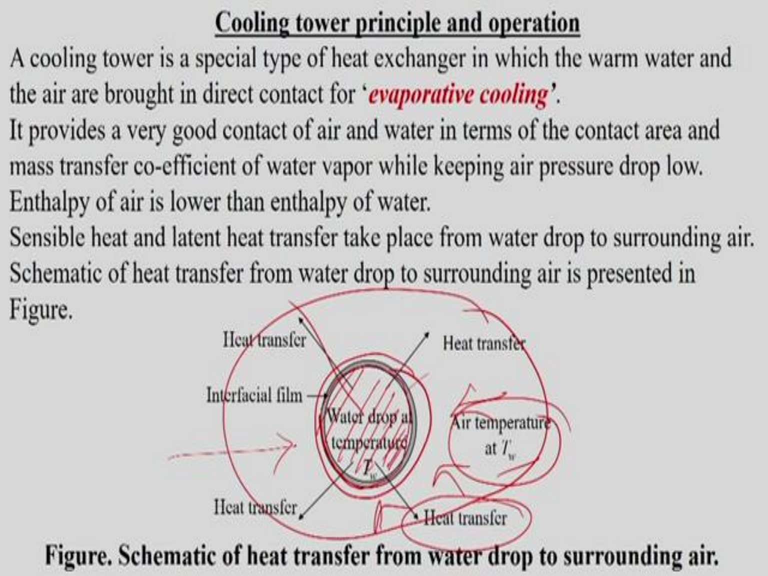

Cooling tower principle and operation

A cooling tower is a special type of heat exchanger in which the warm water and the air are brought in direct contact for '***evaporative cooling***'.

It provides a very good contact of air and water in terms of the contact area and mass transfer co-efficient of water vapor while keeping air pressure drop low.

Enthalpy of air is lower than enthalpy of water.

Sensible heat and latent heat transfer take place from water drop to surrounding air.

Schematic of heat transfer from water drop to surrounding air is presented in Figure.

Figure. Schematic of heat transfer from water drop to surrounding air.

So for this cooling tower principal and operation we learned that say cooling tower is special type of this heat exchanger in which this warm water and the air are brought in direct contact for evaporative cooling. So we have described this evaporative cooling in such a way that this it provides a very good contact of air and water in terms of the contact area like this suppose this is the water drop and this is the air, suppose this air is here and at temperature is TW and suppose one interfacial film is actually formed suppose this grey line and suppose this heat all over will be transferred from during this evaporative cooling like this.

So heat transfer will take place from this water drop to this air, so we can say sensible heat and latent heat are transferred take place from this water drop to the surrounding air like this were this is evaporating means whatever we are saying that if small portion of this enter liquid fuel is evaporating and for that how amount of sensible and heat and latent heat required to evaporate that is sufficient to drop the air temperature from TW to TAS or simply we can say T wet bulb, so that is why we can say this heat is transferred from water droplet to the surrounding air.

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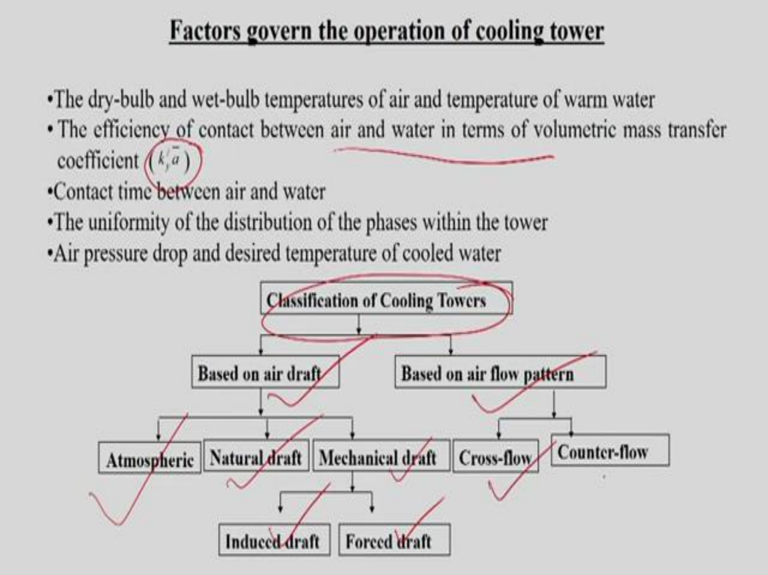

Factors govern the operation of cooling tower

- The dry-bulb and wet-bulb temperatures of air and temperature of warm water
- The efficiency of contact between air and water in terms of volumetric mass transfer coefficient $(k_y\bar{a})$
- Contact time between air and water
- The uniformity of the distribution of the phases within the tower
- Air pressure drop and desired temperature of cooled water

And the factors that govern the operation of the cooling tower that is mostly we can say dry bulb and wet bulb temperature of air and the temperature of the warm water and we also described in detail about that the functioning of air conditioning or cooling water is entirely dependent on the climate as well as this location. So were this we can say relative humidity is very high then we can say the efficiency of the cooling tower as well as the efficiency of dehumidification system or air conditioning system will be very less were the relative humidity of this ambient air is very less then efficiency will be very high.

So we can say in monsoon season the efficiency of the cooling tower drops down also the high humidity the efficiency of the air conditioning system drops down. Whereas the efficiency of both cooling tower and air the conditioning system is very high during this winter season because that time the dry bulb as well as the wet bulb temperature of the ambient air is very low at the same time this in during this in winter season the relative humidity of the air remains minimum, so many factors are there but this mostly this dry bulb temperature and wet bulb temperature this are the most important factors because this control the relative humidity.

The coefficient of contact between we can say air and water in terms of volumetric mass transfer coefficient k y a bar that is also important because we need this high value for high we can say efficiency. Then contact time between this air and water that we need to allow this air water to be in contact with this evaporating water or the flowing water, so we need to provide this more this one contact time. For that we can say in most of the cooling tower so many we can say wooden slots are applied or is kept to increase this contact between this air and water.

And the uniformity of the distribution of the phases within the tower, so that is also very important factor that if there are channeling then that will be very much detrimental for this we can say efficiency of the cooling tower, so channeling must not be there and that is the distribution should be uniform and for good cooling towers the distribution of water is done from the top using the sprayers and in air pressure drop and this desired temperature of the cooled water, so that is the this are also we can say factors that govern the operation of the cooling tower.

And we have also classified that cooling tower like this based on this air drop and based on the air flow pattern, so based on this air drop actually we had this atmospheric and natural draft, the mechanical draft and from mechanical draft we have this induced draft as well as this force draft. In based on this air flow pattern we have this cross flow and this counter flow this are the we can say basic classification of the cooling towers.

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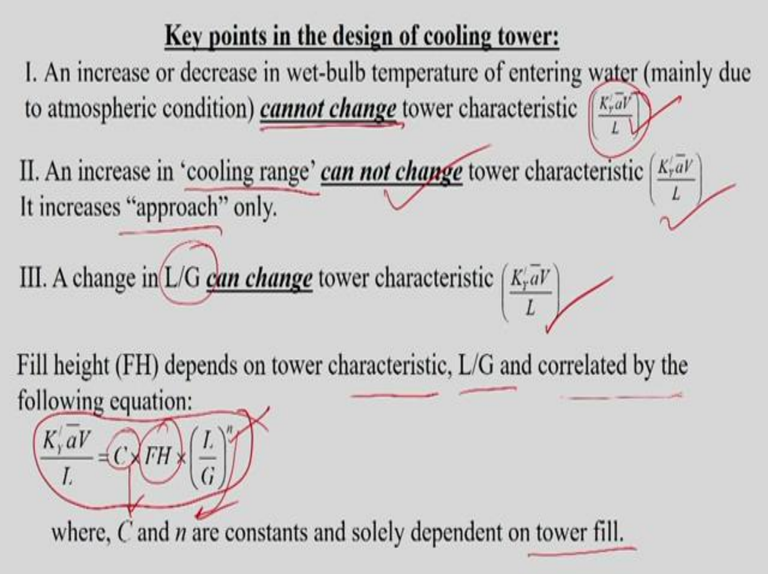

Key points in the design of cooling tower:

I. An increase or decrease in wet-bulb temperature of entering water (mainly due to atmospheric condition) ***cannot change*** tower characteristic $\left(\frac{K'_Y \bar{a} V}{L}\right)$

II. An increase in 'cooling range' ***can not change*** tower characteristic $\left(\frac{K'_Y \bar{a} V}{L}\right)$
It increases "approach" only.

III. A change in L/G ***can change*** tower characteristic $\left(\frac{K'_Y \bar{a} V}{L}\right)$

Fill height (FH) depends on tower characteristic, L/G and correlated by the following equation:

$$\frac{K'_Y \bar{a} V}{L} = C \times FH \times \left(\frac{L}{G}\right)^n$$

where, C and n are constants and solely dependent on tower fill.

And the key points in the design of the cooling towers are like this an increase or decrease in the wet bulb temperature of the entering water that is mainly due to the atmospheric condition like this I told that say in the winter or in the monsoon period or in maybe in summer, so we can say that will decrease and that cannot change this but this increase or decrease in this temperature actually cannot change the tower characteristics or we can say KyaV by L that cannot change actually that is we can say cannot change.

$$\frac{K_Y^{\prime}\bar{a}V}{L} = C \times FH \times \left(\frac{L}{G}\right)^n$$

where, *C* and *n* are constants and solely dependent on tower fill

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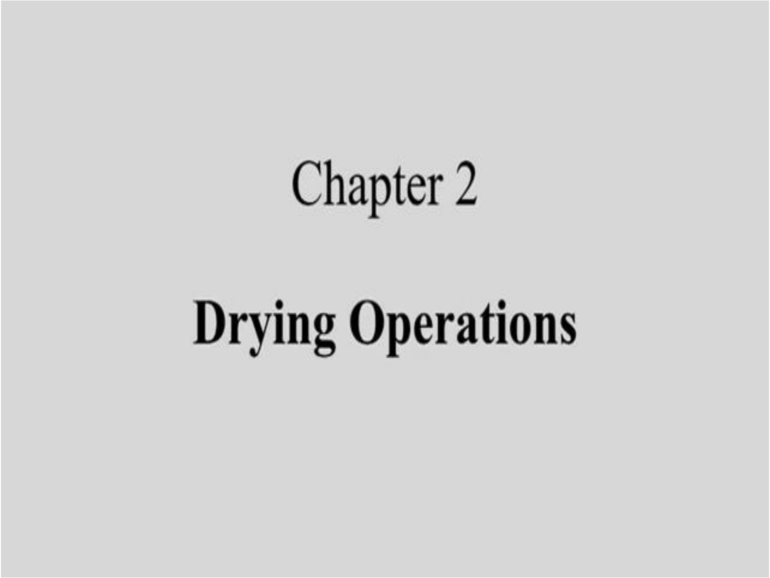

Chapter 2

Drying Operations

So we will be now discussing on the second chapter that is the drying operation again the drying operation also is simultaneous heat and mass transfer that we discussed in this humidification and dehumidification operation that the value of this wet bulb temperature and dry bulb temperature is this are controlling the we can say drying efficiency or in other terms we can say the wet bulb temperature and dry bulb temperature control the relative humidity. Here also drying operation means we will be discussing about the drying out weight solids that wet solids this wet is done on the solid with the help of this water, so water will be evaporating the concept is same like humidification operation.

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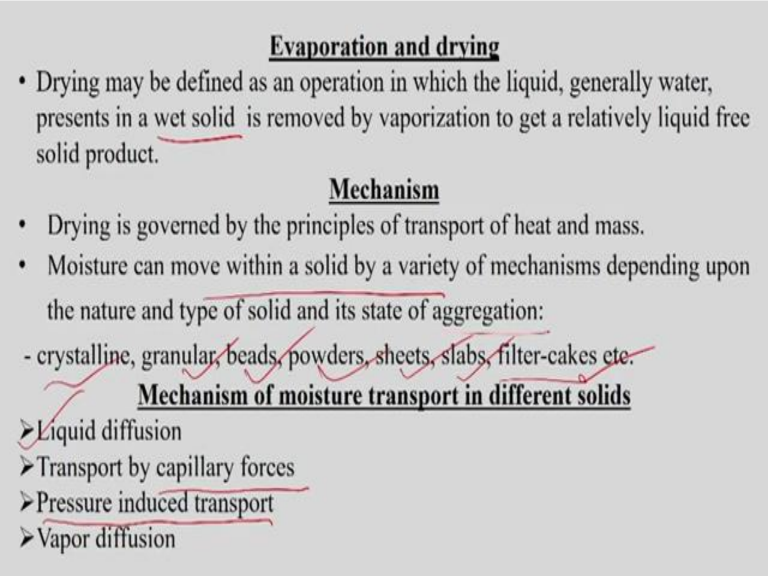

Evaporation and drying

- Drying may be defined as an operation in which the liquid, generally water, presents in a wet solid is removed by vaporization to get a relatively liquid free solid product.

Mechanism

- Drying is governed by the principles of transport of heat and mass.
- Moisture can move within a solid by a variety of mechanisms depending upon the nature and type of solid and its state of aggregation:

\- crystalline, granular, beads, powders, sheets, slabs, filter-cakes etc.

Mechanism of moisture transport in different solids

- ➢Liquid diffusion
- ➢Transport by capillary forces
- ➢Pressure induced transport
- ➢Vapor diffusion

Like there actually say evaporation and drying this two terms we need to understand we discussed also this one, the drying maybe be defined as an operation in which this liquid, generally water actually present in wet solid is removed by vaporization to get a relatively liquid free solid product but if you see this drying does not tell expresses it is that it will be like boom drying means the not a single drop of water vapor will be there inside this wet solid but a relatively less amount of the water will be there inside the so that is why it is called say this vaporization or evaporation.

So and the mechanism of the drying process is that, that is governed by the principle of transport of both heat and mass just like humidification or dehumidification in other words we can say the drying operation is nothing but this dehumidification of we can say wet solid like this in air conditioning that dehumidification of air was there air in drying operation dehumidification of wet solid but the concept is same.

So moisture can move actually within the solid by a variety of mechanism depending upon the nature and type of the solid and its state of this aggregation. So this like crystalline or granular or we can say beads or powders or we can say in terms of this different sheets or we can say this slabs like filter cake etc.

So the basic mechanism of this drying is like this liquid diffusion, liquid will be diffusing on the inner core of this solid like this one that will be diffused. Then transport by capillary force like this say if assume that in a wet solid this entire solid material has so many pores and this water is there if the inner core of the solid and it is coming out as the we can say due to this capillary force that is coming out at the top of this we can say wet solid and from there the evaporation is taking place.

Then pressure induced transport also is there means this one during this evaporation process some amount of pressure gradient takes place and then evaporation takes and another one is this vapor diffusion from the wet solid.

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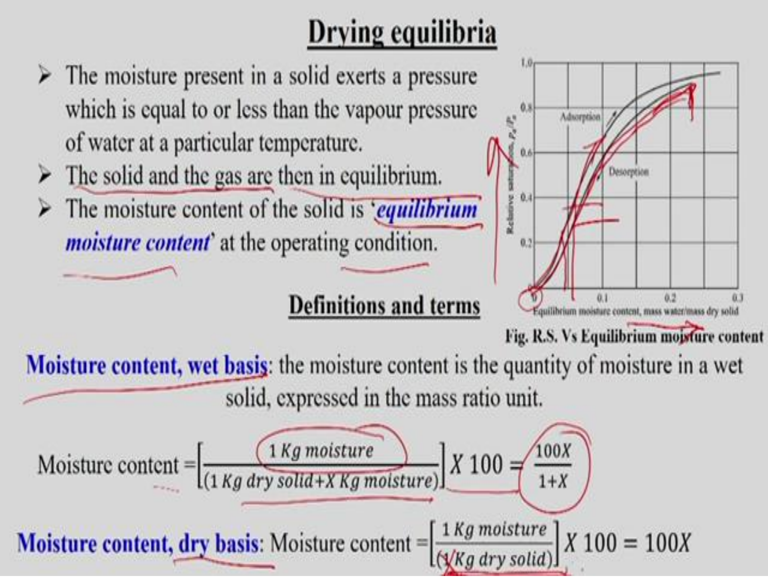

Drying equilibria

- The moisture present in a solid exerts a pressure which is equal to or less than the vapour pressure of water at a particular temperature.
- The solid and the gas are then in equilibrium.
- The moisture content of the solid is '***equilibrium moisture content***' at the operating condition.

Fig. R.S. Vs Equilibrium moisture content

Definitions and terms

Moisture content, wet basis: the moisture content is the quantity of moisture in a wet solid, expressed in the mass ratio unit.

$$\text{Moisture content} = \left[\frac{1\,Kg\ moisture}{(1\,Kg\ dry\ solid + X\,Kg\ moisture)}\right] X\ 100 = \frac{100X}{1+X}$$

Moisture content, dry basis: $\text{Moisture content} = \left[\frac{1\,Kg\ moisture}{(1\,Kg\ dry\ solid)}\right] X\ 100 = 100X$

And then we have discussed one important terminology that is we can say drying equilibria like this moisture present in solid exerts a pressure which is equal to or less than the vapor pressure of the water at a particular temperature. Say during desorption process if we start from here actually from the right hand side say suppose from this we can see equilibrium moisture content with this relative saturation say during this desorption or we can say this if this drying process the relative saturation decreases gradually and then we got one relative saturation of zero value.

So what was happening during this desorption process this water was separated slowly and slowly say the form of this water vapor and then what happen this some amount of the surface squeezing to place and then we can say surface drying was done some hot spots also appeared with discussed a lot on that, so that is why we say desorption process followed this line.

But wherever we will talking about this adsorption or we can say humidification it is entirely different story like this dry solid is there whenever we will be putting water on that, so this we can say it will try to swell up and then the surface area will be increasing gradually that is why you see this during this adsorption process thus relative saturation is higher than the we can say during this drying process.

Means whenever the we can say humidifying dry solid is taking place then we can say whenever this water will be added there then this we can say this the surface area will go on increasing and increasing, so we can say relative saturation also will be going on increasing for a particular we can for moisture content because the surface area will be increasing gradually. And that is why the solid and the gases are then in equilibrium.

The moisture content of the solid

Moisture content $=\left[\frac{Kg\ moisture}{(1\ Kg\ dry\ solid)}\right] X\ 100 = 100X$

And we learned that in dry basis that is we can say this 1 Kg moisture per we can say this one we can say per Kg dry solid then it is we can say like this sorry this X Kg moisture per 1 Kg dry solid that is why it is hundred X, so whenever we have this dry basis that was only we can say this solid free basis that was.

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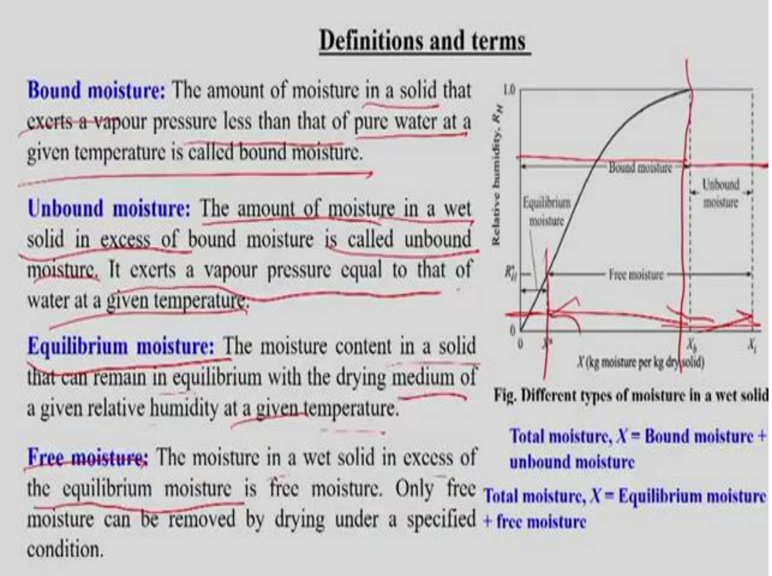

Definitions and terms

Bound moisture: The amount of moisture in a solid that exerts a vapour pressure less than that of pure water at a given temperature is called bound moisture.

Unbound moisture: The amount of moisture in a wet solid in excess of bound moisture is called unbound moisture. It exerts a vapour pressure equal to that of water at a given temperature.

Equilibrium moisture: The moisture content in a solid that can remain in equilibrium with the drying medium of a given relative humidity at a given temperature.

Free moisture: The moisture in a wet solid in excess of the equilibrium moisture is free moisture. Only free moisture can be removed by drying under a specified condition.

Fig. Different types of moisture in a wet solid

Total moisture, X = Bound moisture + unbound moisture

Total moisture, X = Equilibrium moisture + free moisture

Now we discussed about this bound moisture content that was we can say this amount of moisture, this one in a solid that exerts vapor pressure less than that of the pure water at a given temperature that we discussed about that this bound moisture, if I say this is the bound moisture.

So then we can say this remaining amount of this one that is we can say this out of this total moisture that is unbound moisture, so this unbound moisture we can say this one the amount of moisture in a wet solid actually in excess of the bound moisture so is called this unbound moisture means that is not actually bound with this solid.

That is excess amount any way it may be separated very easily, so it exerts a vapor pressure that is equal to that of that given this one water at the given temperature. So it is not bound with this wet solid another important terminology that we have learned that is equilibrium moisture content there equilibrium content in a solid that can remain in equilibrium with a drying medium of a given relative humidity, so at the we can say given temperature.

Like we can say this one suppose if we say this is the equilibrium moisture content then free moisture content was termed as the moisture in wet solid in excess of this equilibrium moisture like this one, so that is we can say this one free moisture. So this entire thing is here free moisture means which is not in equilibrium that only that free moisture is removed during this drying operation but equilibrium moisture content cannot be decreased during this drying operation, so that is important information that during this drying process we are able to separate only equilibrium moisture content.

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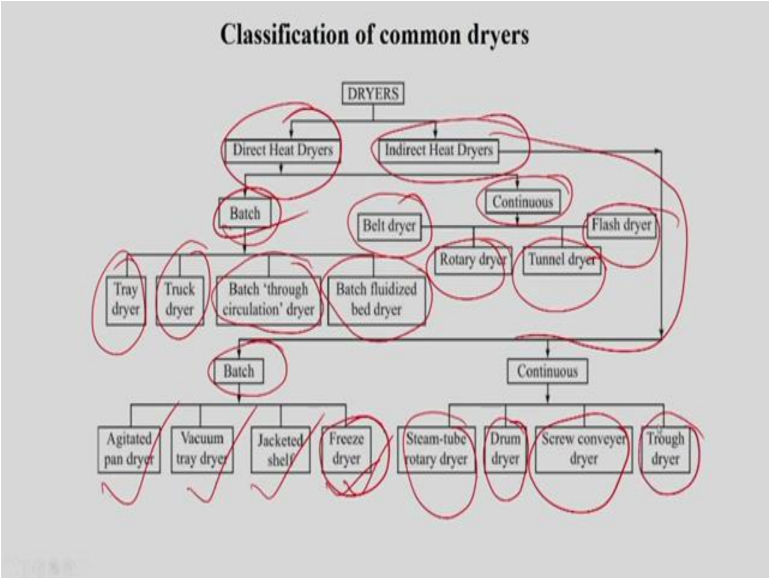

Classification of common dryers

DRYERS

Direct Heat Dryers

Indirect Heat Dryers

Batch

Continuous

Belt dryer

Flash dryer

Rotary dryer

Tunnel dryer

Tray dryer

Truck dryer

Batch 'through circulation' dryer

Batch fluidized bed dryer

Batch

Continuous

Agitated pan dryer

Vacuum tray dryer

Jacketed shelf

Freeze dryer

Steam-tube rotary dryer

Drum dryer

Screw conveyer dryer

Trough dryer

Then the classification of the common dryer actually we discussed in terms of direct heat drying and in terms of indirect heat drying like this in terms of direct heat drying that was one was batch and one was continuous, in batch that was tray dryer then truck dryer and we have this batch through circulation dryer then batch fluidized bed dryer.

In case of this we can say continuous dryer, we discussed about belt dryer then rotary dryer then tunnel dryer then flash dryer and in terms of we can say indirect heat dryer so we had this like batch also agitated pan dryer, vacuum tray dryer then jacketed shelf dryer then freeze dryer that is important thing, in case of this freeze dryer this one wet solid is dried at around minus fifty degree celsius due to the sublimation of say ice at this we can say vacuum condition.

We can say this is the (())(39:52) and in case of this continuous dryer that we can say using steam tube, we can say using drum dryer, we can say using this screw conveyer dryer or sometimes we can say this trough dryer.

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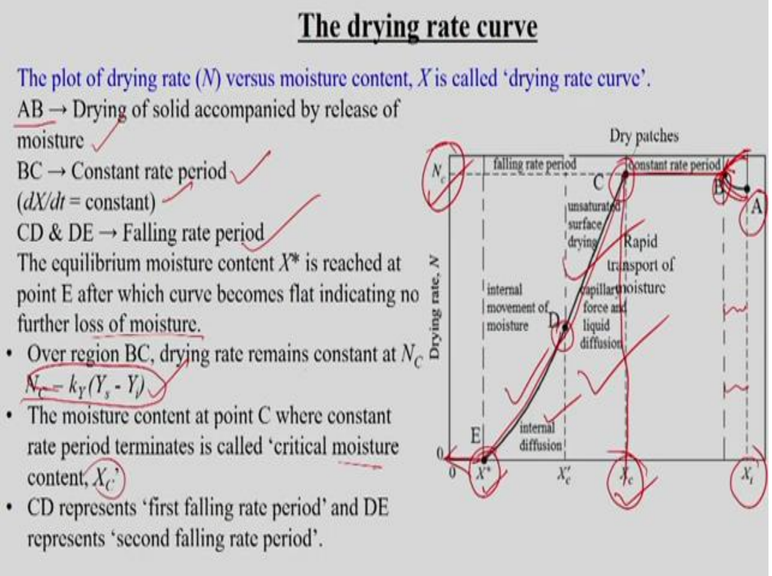

The drying rate curve

The plot of drying rate (N) versus moisture content, X is called 'drying rate curve'.

AB → Drying of solid accompanied by release of moisture

BC → Constant rate period

(dX/dt = constant)

CD & DE → Falling rate period

The equilibrium moisture content X^* is reached at point E after which curve becomes flat indicating no further loss of moisture.

- Over region BC, drying rate remains constant at N_C
  $N_C = k_Y(Y_s - Y_i)$
- The moisture content at point C where constant rate period terminates is called 'critical moisture content, X_C'
- CD represents 'first falling rate period' and DE represents 'second falling rate period'.

And we have also learned the details about the drying rate curve, so we started from this suppose this point A and then it move to point B by we can say this initial adjustment during this drying process that A be here also like this sometimes this drying rate may increase, sometimes this drying rate may decrease also during this initial adjustment.

Then we have one constant drying rate period, so we can say upto this point C the drying rate means was a constant means how much amount of water vapor came from the interior of the wet solid to the exterior that was evaporated in a constant rate, so that was NC and then this we can say whenever it reaches this XC means the moisture content of this we can say out of this constant rate period, out of that we can say some unsaturated surface drying took place then capillary force was there then we can say this moisture content was also less then we can say first falling rate started there from C to D and from D to E that we can say second falling rate due to we can say internal movement of the moisture and internal diffusion.

So that is we can say second falling then it reached the equilibrium moisture content, so like this we can say AB actually we can say from A to B that is drying of the solid accompanied by release of the moisture that is due this internal adjustment then B to C constant drying rate period that DX DT will be is equal constant.

And DNC DT was zero and CD and DE that is we can say first falling rate period and then second falling rate period. The equilibrium moisture content X star is reached at point E were we can say this one equilibrium moister content after which this curve becomes flat indicating that no drying, so no further loss of the moisture. So over a region of B and C we can say the drying rate remain constant that is we can say NC is equal to KY into YS minus YI that is initial moisture content. The moisture content at point C where the constant rate period terminates is called this critical moisture, so that is XC.

So here actually this we can say this XC is there. So CD represents the first falling rate period and DE represents the second falling rate period. In most of the cases first falling rate period actually is linearly decreasing for second rate sometimes this second falling rate period is the we can say decreasing with the square of the moisture content. But in many cases the decrease first falling and second falling rate are almost linear with the moisture content.

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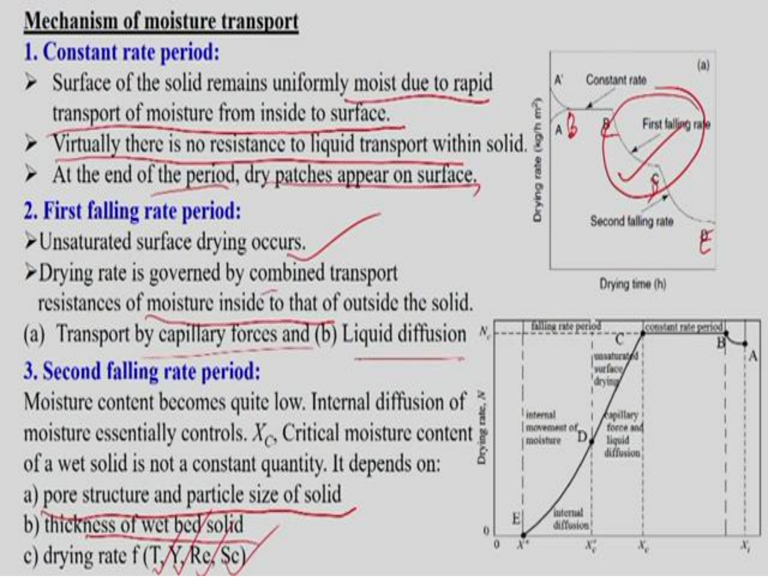

Mechanism of moisture transport

1. Constant rate period:

- Surface of the solid remains uniformly moist due to rapid transport of moisture from inside to surface.
- Virtually there is no resistance to liquid transport within solid.
- At the end of the period, dry patches appear on surface.

2. First falling rate period:

- Unsaturated surface drying occurs.
- Drying rate is governed by combined transport resistances of moisture inside to that of outside the solid.

(a) Transport by capillary forces and (b) Liquid diffusion

3. Second falling rate period:

Moisture content becomes quite low. Internal diffusion of moisture essentially controls. X_C, Critical moisture content of a wet solid is not a constant quantity. It depends on:

a) pore structure and particle size of solid

b) thickness of wet bed solid

c) drying rate f (T, Y, Re, Sc)

So the mechanism of the moisture transport also from this A point to B to C to D to E like here you can say this A to B, B to this is like this is C, C to D, D to E I can say, A to B here like this constant rate period that we can say surface of the solid remains uniformly moist to the rapid transport of the moisture from the inside to the surface.

Then virtually there is no resistance to liquid transport within the solid. At the end of the period dry patches actually appear on the surface. Then for first falling rate period like this, this C to D actually we can say unsaturated surface trying took place and then drying rate was governed by the combined transport resistance of the moisture inside to that of the outside solid like this and the transport by the capillary force and this liquid diffusion that for this you can say first falling rate.

From D to E like in second falling rate period we can say moisture content becomes quite low because that time this moisture content has decreased during this initial adjustment then constant drying rate period in first falling rate period, so internal diffusion of the moisture content essentially controls the drying second drying rate then XC that critical moisture content of water solid this wet solid actually is not constant quantity.

So it depends on we can say this pore structure and the particle size of the solid then thickness of the wet bed and we can say like temperature, humidity, renold's number, smith number all this actually controls the drying rate in the second falling rate and the second falling rate values are quite low and when it reaches this equilibrium moisture content at X star out of that the drying rate becomes zero like this one, drying rate out of this one become zero.

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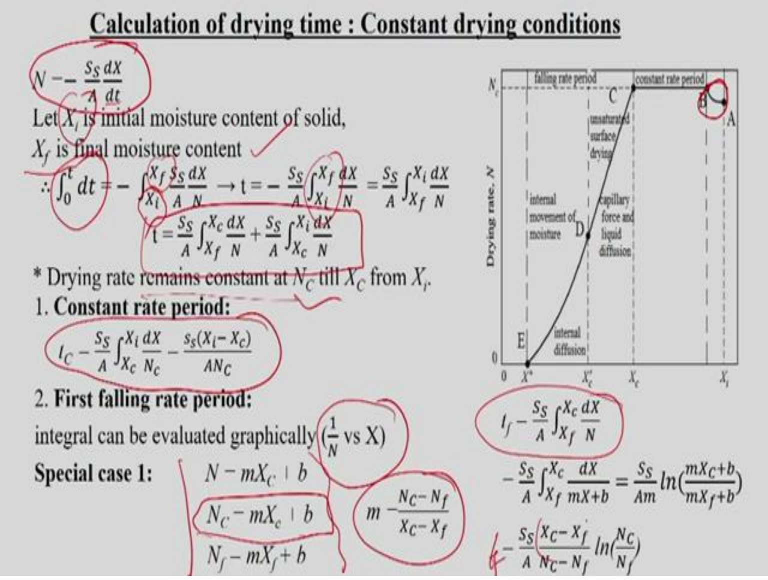

Calculation of drying time : Constant drying conditions

$N = -\frac{S_S}{A}\frac{dX}{dt}$

Let X_i is initial moisture content of solid,

X_f is final moisture content

$\therefore \int_0^t dt = -\int_{X_i}^{X_f}\frac{S_S}{A}\frac{dX}{N} \rightarrow t = -\frac{S_S}{A}\int_{X_i}^{X_f}\frac{dX}{N} = \frac{S_S}{A}\int_{X_f}^{X_i}\frac{dX}{N}$

$t = \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{N} + \frac{S_S}{A}\int_{X_c}^{X_i}\frac{dX}{N}$

* Drying rate remains constant at N_C till X_C from X_i.

1. **Constant rate period:**

$t_C = \frac{S_S}{A}\int_{X_c}^{X_i}\frac{dX}{N_c} = \frac{S_S(X_i - X_c)}{AN_C}$

2. **First falling rate period:**

integral can be evaluated graphically ($\frac{1}{N}$ vs X)

$t_f = \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{N}$

Special case 1:

$N = mX_C + b$

$N_C = mX_c + b$

$N_f = mX_f + b$

$m = \frac{N_C - N_f}{X_C - X_f}$

$= \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{mX+b} = \frac{S_S}{Am}ln(\frac{mX_C+b}{mX_f+b})$

$t_f = \frac{S_S}{A}\frac{X_C - X_f}{N_C - N_f}ln(\frac{N_C}{N_f})$

N =− $\frac{S_S}{A}\frac{dx}{dt}$

Let X_i is initial moisture content of solid,

X_f is final moisture content

∴ $\int_0^t dt = -\int_{X_i}^{X_f} \frac{S_S}{A}\frac{dX}{N} \rightarrow t = -\frac{S_S}{A}\int_{X_i}^{X_f}\frac{dX}{N} = \frac{S_S}{A}\int_{X_f}^{X_i}\frac{dX}{N}$

$t = \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{N} + \frac{S_S}{A}\int_{X_c}^{X_i}\frac{dX}{N}$

* Drying rate remains constant at N_C till X_C from X_i.

1. constant rate period:

$$t_C = \frac{S_S}{A}\int_{X_c}^{X_i}\frac{dX}{N_c} = \frac{s_S(X_i - X_c)}{AN_C}$$

2. First falling rate period: integral can be evaluated graphically ($\frac{1}{N}$ vs X)

Special case 1: $t_f = \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{\mathrm{N}}$

$N = mX_C + b$ $= \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{\mathrm{mX+b}} = \frac{S_S}{Am}\ln(\frac{mX_C+b}{mX_f+b})$

$N_C = mX_c + b$ $= \frac{S_S}{A}\frac{X_C - X_f}{N_C - N_f}\ln(\frac{N_C}{N_f})$

$N_f = mX_f + b$

$m = \frac{N_C - N_f}{X_C - X_f}$

special case 2: $N = BX^2$

$$N_c = B\,X^2_C$$

$$B = \frac{N_C}{X_c^2}$$

$$t_f = \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{\mathrm{B}X_C{}^2}$$

$$= \frac{S_S}{A}\int_{X_f}^{X_C} X^{-2}\, dX = \frac{S_S X_C^2}{AN_C}\left[\frac{1}{X_f} - \frac{1}{X_C}\right]$$

Drying rate at N = 0 at equilibrium moisture, X = X^*

$$\therefore 0 = m X^* + b \rightarrow b = - m X^*$$

$$\therefore \frac{N_C}{N_f} = \frac{mX_C - mX^*}{mX_f - mX^*} = \frac{X_C - X^*}{X_f - X^*}$$

$$t_f = \frac{S_S}{A}\frac{X_C - X_f}{N_C - N_f} \ln\left(\frac{X_C - X^*}{X_f - X^*}\right)$$

$$t_f = \frac{S_S}{A}\frac{X_C - X^*}{N_C} \ln\left(\frac{X_C - X^*}{X_f - X^*}\right)$$

$$t = t_C + t_f = \frac{s_s(X_i - X_c)}{AN_C} + \frac{S_S}{A}\frac{X_C - X^*}{N_C} \ln\left(\frac{X_C - X^*}{X_f - X^*}\right)$$

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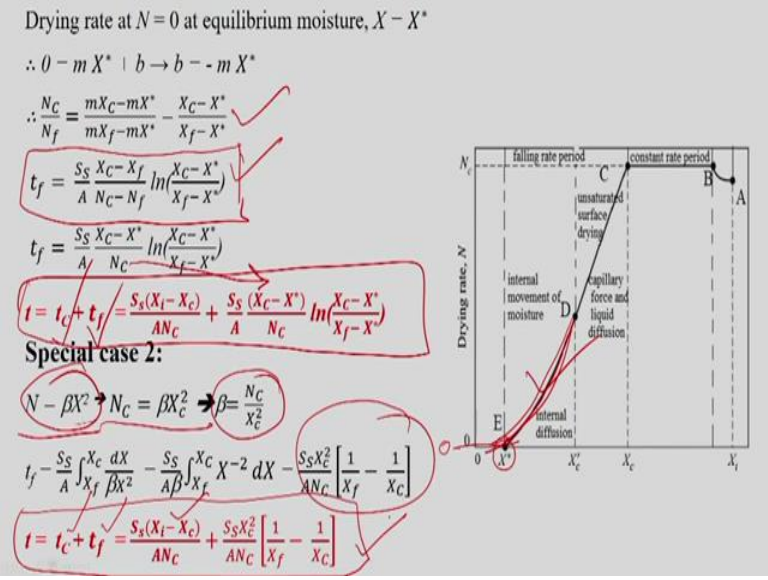

Drying rate at $N = 0$ at equilibrium moisture, $X - X^*$

$\therefore 0 - m X^* \mid b \rightarrow b - - m X^*$

$\therefore \frac{N_C}{N_f} = \frac{mX_C - mX^*}{mX_f - mX^*} - \frac{X_C - X^*}{X_f - X^*}$ ✓

$\boxed{t_f = \frac{S_S}{A}\frac{X_C - X_f}{N_C - N_f} ln\left(\frac{X_C - X^*}{X_f - X^*}\right)}$ ✓

$t_f = \frac{S_S}{A}\frac{X_C - X^*}{N_C} ln\left(\frac{X_C - X^*}{X_f - X^*}\right)$

$\boxed{t = t_c + t_f = \frac{S_s(X_i - X_c)}{AN_C} + \frac{S_S}{A}\frac{(X_C - X^*)}{N_C} ln\left(\frac{X_C - X^*}{X_f - X^*}\right)}$

Special case 2:

$N - \beta X^2 \rightarrow N_C = \beta X_c^2 \rightarrow \beta = \frac{N_C}{X_c^2}$

$t_f - \frac{S_S}{A}\int_{X_f}^{X_c}\frac{dX}{\beta X^2} - \frac{S_S}{A\beta}\int_{X_f}^{X_C} X^{-2}\, dX - \frac{S_S X_c^2}{AN_C}\left[\frac{1}{X_f} - \frac{1}{X_C}\right]$

$\boxed{t = t_c + t_f = \frac{S_s(X_i - X_c)}{AN_C} + \frac{S_S X_c^2}{AN_C}\left[\frac{1}{X_f} - \frac{1}{X_C}\right]}$ ✓

And drying rate N is equal to zero at equilibrium moisture content that we know this one that N is equal to zero here actually and in that case we can say 0 is equal to MX star plus b were b is equal to minus MX star will be and in that equation previous NC by Nf we will be getting as XC minus X star by Xf minus X star.

So total we can say falling rate time will be like this SS by A into XC minus Xf by NC minus Nf into LN that what is NC by is equal to XC minus X star by Xf minus X star, so this the final formula for total drying time will be like this, so that is constant time plus falling rate time so that will be SS by A into NC into Xi minus XC plus this term like this for falling rate SS by A into NC into XC minus X star into LN XC minus X star by Xf minus X star.

And the special case we can say whenever we talk about that if the falling rate is not linear like this it is we can say this curvy nature, so for getting the accurate we can say drying rate or we say drying time ultimately will be calculating the this one dryer design we will doing that dryer design that time we can say that N will be like this linearly we can say this one proportional to the square of the moisture content, so like this N is equal to beta into X square so like this part were this then NC will be like this beta into XC square, so from there actually we will be getting beta is equal to NC by XC square.

Now say we will be getting this total drying time considering that this we can say proportional to square of the moisture content that is the drying rate in the falling rate period then total drying time will be this constant drying time plus falling drying time that is equal to SS by A into NC into Xi minus XC plus this integration gives like this SS by ANC into XC square into one by Xf minus one by XC, so that we can say this one we can use this one if we know that the drying rate is proportional to the square of the moisture content then will be using this one if we know that drying rate is linearly decreasing with the moisture content then this will be the formula .

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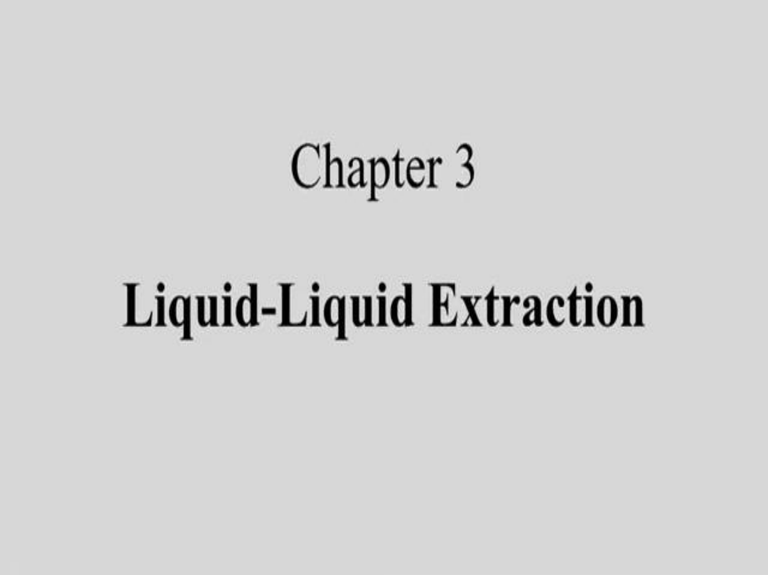
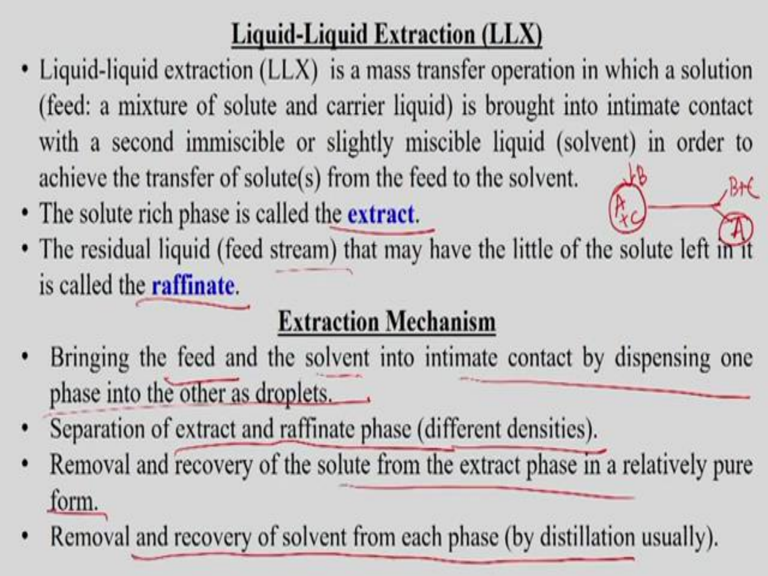


Chapter 3

Liquid-Liquid Extraction



Liquid-Liquid Extraction (LLX)

- Liquid-liquid extraction (LLX) is a mass transfer operation in which a solution (feed: a mixture of solute and carrier liquid) is brought into intimate contact with a second immiscible or slightly miscible liquid (solvent) in order to achieve the transfer of solute(s) from the feed to the solvent.
- The solute rich phase is called the **extract**.
- The residual liquid (feed stream) that may have the little of the solute left in it is called the **raffinate**.

Extraction Mechanism

- Bringing the feed and the solvent into intimate contact by dispensing one phase into the other as droplets.
- Separation of extract and raffinate phase (different densities).
- Removal and recovery of the solute from the extract phase in a relatively pure form.
- Removal and recovery of solvent from each phase (by distillation usually).

Now we will be discussing the third chapter that is we can say liquid-liquid extraction or simply extraction process. There actually we have described that say liquid-liquid extraction process is a mass transfer operation in which solution like feed that is a mixture of solute and the carrier liquid is brought into intimate contact with second immiscible or slightly miscible liquid means with that carrier solvent in order to achieve the transfer of the solute from the feed solvent to the extracting solvent, so we have like this suppose this is the carrier say we can say A is the carrier solvent plus C the target component.

Now we are adding here this B we can say this one we are adding this extracting solvent then it will be separated into two phases like B plus C then A will be separated. Like A is the we can say carrier solvent and C is the target component, so what we are doing in the liquid-liquid extraction process we are adding one second solvent that has the more miscibility with this target component then which is there in the carrier solvent A. The solute rich phase is called this extract and the residual liquid we can say this exhaust liquid are give feed stream that may have the little of the solute left in the this one we can say in a system is called the raffinate.

So raffinate is the exhaust feed carrier solvent actually is there and extracting solvent with the target component means this C. The extraction mechanism is like that bringing the feed means that carrier solvent and the solute and the solvent extracting solvent actually into intimate contact by dispensing one phase into the other phase as the droplets like this.

One mixture is there A and C will be there and the B will be flashed inside this one in terms of this droplets then it will be dispersed very easily, so that this B means this extracting solvent will be in intimate contact with C very easily, so that the C will be moving from A to B.

Then separation of extract and the raffinate phases like this must be the density difference will be there otherwise it will be though the B can attract C but after that how this B will separated from A, so that is why we need some different densities and then removal and recovery of the solute from the extract phase in a relatively pure form.

Then removal and recovery of the solvent from the each phase like means from the extract phase and the raffinate phase our interest will be in the extract phase because in the extract phase we have this extracting solvent and the target component whenever we will be separating this target component from the extract phase then we will be using this extracting solvent for the next batch of extraction process. But the exhaust solvent or we can say whatever the carrier solvent is there A that sometimes may not be used for the any other processes so we can throw that also depending on the situation.

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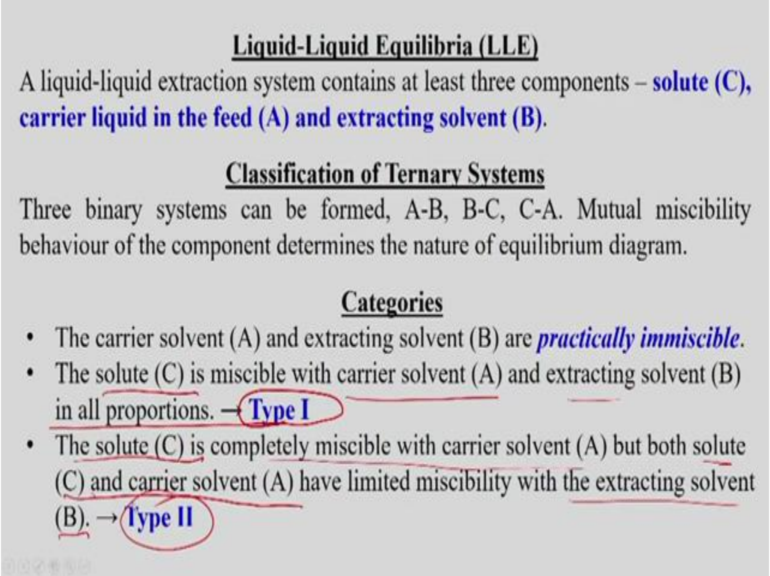

Liquid-Liquid Equilibria (LLE)

A liquid-liquid extraction system contains at least three components – **solute (C), carrier liquid in the feed (A) and extracting solvent (B).**

Classification of Ternary Systems

Three binary systems can be formed, A-B, B-C, C-A. Mutual miscibility behaviour of the component determines the nature of equilibrium diagram.

Categories

- The carrier solvent (A) and extracting solvent (B) are ***practically immiscible***.
- The solute (C) is miscible with carrier solvent (A) and extracting solvent (B) in all proportions. → **Type I**
- The solute (C) is completely miscible with carrier solvent (A) but both solute (C) and carrier solvent (A) have limited miscibility with the extracting solvent (B). → **Type II**

And we discussed a detail about this liquid-liquid equilibrium say liquid-liquid equilibrium means liquid-liquid extraction system contain at least three components like this target component solute C then carrier liquid A and extracting solvent B. So there actually we can say this one there must be relative miscibility of A, B and C and the important parameter is that say relative solubility of C in B must be greater than relative solubility in A.

So this three binary system are formed like this A-B, B-C, C-A then mutual miscibility behavior of the component determines the nature of the equilibrium diagram, so we can say that is the ternary diagram and then categories are like this carrier solvent and extracting solvent are practically miscible then that will be one system then we say this solute target component C is miscible with carrier solvent A and extracting solvent B in all proportions there we can say this is a type A or type one and the solute C is completely miscible with carrier solvent but both solute and this one both solute C and carrier solvent have limited miscibility with the extracting solvent B then we can say this is the type two. So but say both the type one and type two are available in the we can say this one any chemical allied industries.

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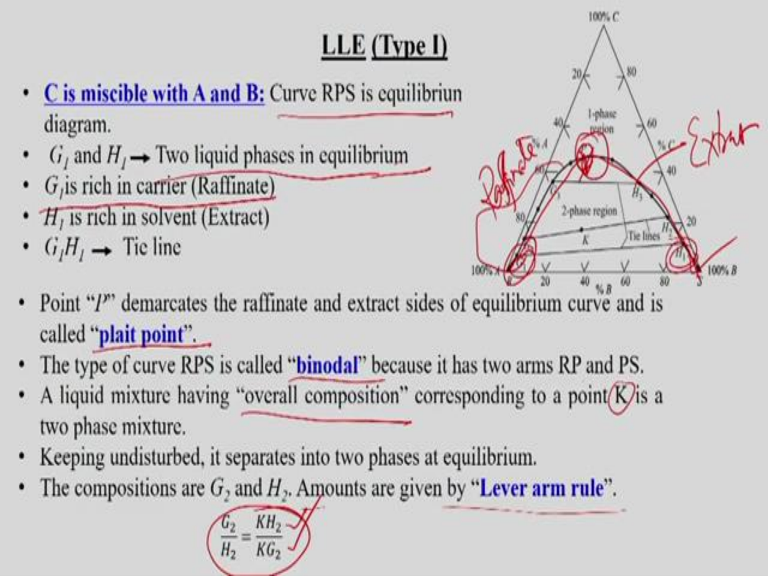

LLE (Type I)

- **C is miscible with A and B:** Curve RPS is equilibriun diagram.
- G_1 and H_1 → Two liquid phases in equilibrium
- G_1 is rich in carrier (Raffinate)
- H_1 is rich in solvent (Extract)
- G_1H_1 → Tie line
- Point “P” demarcates the raffinate and extract sides of equilibrium curve and is called “**plait point**”.
- The type of curve RPS is called “**binodal**” because it has two arms RP and PS.
- A liquid mixture having “overall composition” corresponding to a point K is a two phase mixture.
- Keeping undisturbed, it separates into two phases at equilibrium.
- The compositions are G_2 and H_2. Amounts are given by “**Lever arm rule**”.

$$\frac{G_2}{H_2} = \frac{KH_2}{KG_2}$$

And the like said type one like C is miscible with A and B, like in the beginning C was there in A and B is added from the outsides now C will be transferring from A to B, so like this curve RP and S actually we can say this one is the equilibrium curve, so we can say here G1 and H1 like this say G1 and H1 actually we can say this two liquid phases in the equilibrium and G1 you can say the rich in carrier we can say that you cannot see this part will be like raffinate and rafinnate and this part will be your extract.

And H1 that is rich in solvent that is extract, so G1H1 that is you can this is a tie line, so point P actually we can say this is demarcates the raffinate and extract sides of the equilibrium curve and is termed as this plait point. At plait point we can say this one here the we say this solute concentration in both the phases are same we can whenever the on system liquid-liquid extraction system reaches the plait point then separation stops, so the type of this curve RPS is called the bimodal because it has two different height because it has two arms like RP and PS.

A liquid mixture having this overall composition corresponding to point K is a two phase mixture, so keeping this undisturbed it separates into two phases like this one and this one two phases at equilibrium, so the composition are G2 and H2, so this amount are given by lever arm rule like this G2 by H2 is equal to the opposite lines means we can say this KH2 by KG2.The opposite of this arm.

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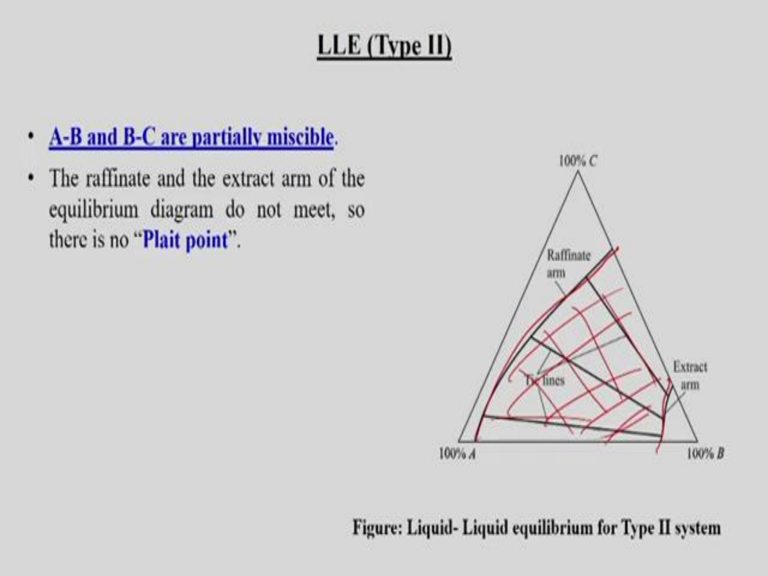

LLE (Type II)

- A-B and B-C are partially miscible.
- The raffinate and the extract arm of the equilibrium diagram do not meet, so there is no "**Plait point**".

Figure: Liquid- Liquid equilibrium for Type II system

And the type two like this we can say this AB and BC are partially miscible, so the raffinate and the extract arm of the equilibrium diagram do not meet actually you can say this raffinate arm and this extract arm, but if we can say this one can alter the say this one two phase region like this in V2 in this one if we can say contract at this part then this type two will be converted into type one that also we can say so there is no plait point here.

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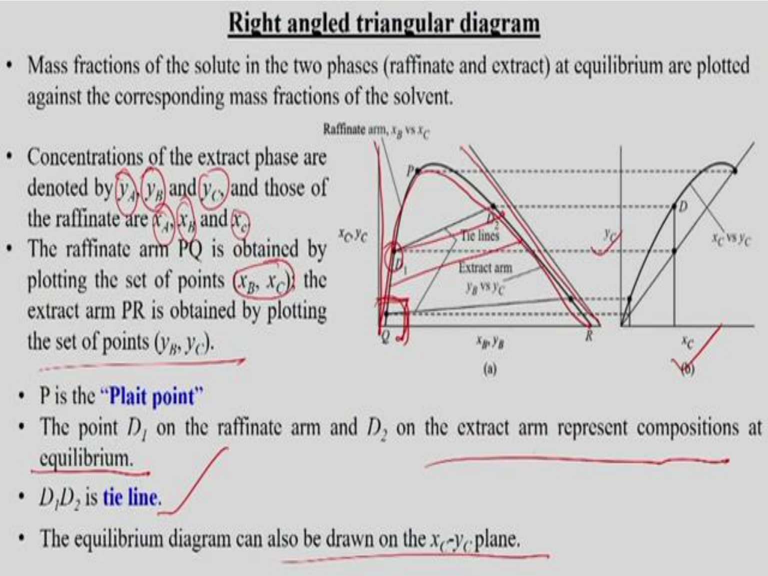

Right angled triangular diagram

- Mass fractions of the solute in the two phases (raffinate and extract) at equilibrium are plotted against the corresponding mass fractions of the solvent.
- Concentrations of the extract phase are denoted by y_A, y_B and y_C, and those of the raffinate are x_A, x_B and x_C.
- The raffinate arm PQ is obtained by plotting the set of points (x_B, x_C); the extract arm PR is obtained by plotting the set of points (y_B, y_C).
- P is the "**Plait point**"
- The point D_1 on the raffinate arm and D_2 on the extract arm represent compositions at equilibrium.
- D_1D_2 is **tie line.**
- The equilibrium diagram can also be drawn on the x_C-y_C plane.

But we can do this one if increase the temperature, so like this that will be discussing just later on and right angle triangle diagram we have this one suppose this if we say whatever the ternary diagram we have this one we can write we can draw this right angle triangle diagram.

So mass fraction of the solute in the two phases just like raffinate and extract at equilibrium are plotted against the corresponding mass fractions of the solvent. The concentration of the extract phase are denoted by YA, YB and YC and we can say concentration of the we say this one solute actually in we can say in the raffinate phase is like this XA, XB and XC.

So this are like this and the raffinate arm that PQ that is the raffinate arm and this extract arm is PR obtained by plotting the set of this point XB and XC that we have already solved so many problems the extract arm RP is obtained by plotting the set of points YB and YC and that P point is the plait point, the point D1 we can say this one D1 actually on the raffinate arm and D2 on the extract arm represent the compositions of the equilibrium.

And this D1 D2 that is we can say this in tie line, so all this are tie line whatever the we can say any tie line that is added in between this extract and raffinate arm will give the composition in the equilibrium condition.

The equilibria diagram can also be drawn using on the xC plane also like this xC and yC plane like this plane also we can draw this one, if we have this all xA, xB, xC and yA, yB and yC from there if you take this xC and yC it will be able to get the equilibrium diagram from there also we will be able to get the number of we can say theoretical stages etc also will be able to calculate from the equilibrium plot also that is also right angular but in terms of xC and yC.

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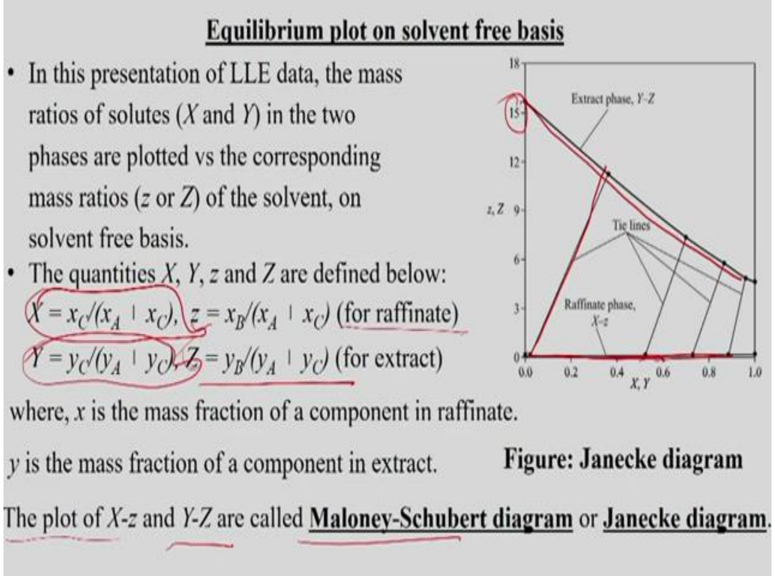

Equilibrium plot on solvent free basis

- In this presentation of LLE data, the mass ratios of solutes (*X* and *Y*) in the two phases are plotted vs the corresponding mass ratios (*z* or *Z*) of the solvent, on solvent free basis.
- The quantities *X*, *Y*, *z* and *Z* are defined below:

$X = x_C/(x_A + x_C)$, $z = x_B/(x_A + x_C)$ (for raffinate)

$Y = y_C/(y_A + y_C)$, $Z = y_B/(y_A + y_C)$ (for extract)

where, *x* is the mass fraction of a component in raffinate.

y is the mass fraction of a component in extract.

Figure: Janecke diagram

The plot of *X-z* and *Y-Z* are called **Maloney-Schubert diagram** or **Janecke diagram**.

And sometimes this solvent free basis also say have this one draw the equilibrium diagram in this presentation of this liquid-liquid data, the mass ratios of the solutes like X and Y in the two phases are plotted versus the corresponding mass ratios of small z and capital Z and there we can say this one capital X is actually plotted is calculated as xC by small xA plus small xC, where small z that is we can say small xB by xA plus xC that is in the raffinate part like this one in raffinate part it appears that it is matching with this xY xC's but that is not the case the values are very small that is why it is going with the XY plane like this.

And like this capital Y will be like this small yC divided by yA plus yC or capital Z will be like this yB by yA plus yC that is in the extract arm. You see the extract arm also the values are very high this Z values are sometimes 10, 12, 15 like this that values are actually we obtain. So that in extract arm we have always the high values and the tie lines also here like this are drawn in between this extract arm and raffinate arm. The plot of X - z and Y -Z are called this **Maloney-Schubert diagram** or simply **Janecke diagram** after the name of the scientist Janecke.

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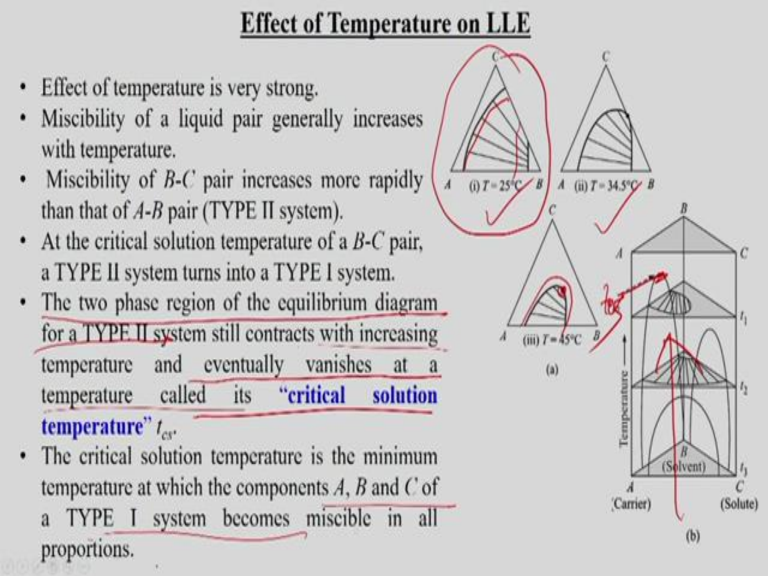

Effect of Temperature on LLE

- Effect of temperature is very strong.
- Miscibility of a liquid pair generally increases with temperature.
- Miscibility of *B*-*C* pair increases more rapidly than that of *A*-*B* pair (TYPE II system).
- At the critical solution temperature of a *B*-*C* pair, a TYPE II system turns into a TYPE I system.
- The two phase region of the equilibrium diagram for a TYPE II system still contracts with increasing temperature and eventually vanishes at a temperature called its **"critical solution temperature"** t_{cs}.
- The critical solution temperature is the minimum temperature at which the components *A*, *B* and *C* of a TYPE I system becomes miscible in all proportions.

Now you see this one in type two whatever we have learned that say there is no plait point then extract and raffinate not coinciding or we can they are not meeting each other, so like low temperature if we increase the temperature then we can say binary phase actually contracts like this way and if we further increase the temperature.

So it will give like say it will be getting one plot work plait point, so it is shown in this we can say three diagram that if we increase the temperature then we can say both the extract arm and raffinate arms will contract or in other words we can say solubility will go on increasing and then we will be getting one plait point.

And if we move further also means say if we increase the temperature further then one point will be there will be entirely all A, B, C will be miscible then we will not be able to separate and when this we can say type two will be converting into we can say two phase region of the equilibrium diagram for a type two system still contract with increasing the temperature and eventually vanishes at a temperature called this critical solution temperature or TCS like this is actually you can say this TCS this is actually critical solution temperature.

The critical solution temperature is the minimum temperature at which components A, B and C of type one actually system becomes miscible in all proportions or we can say this type two is converting into type one.

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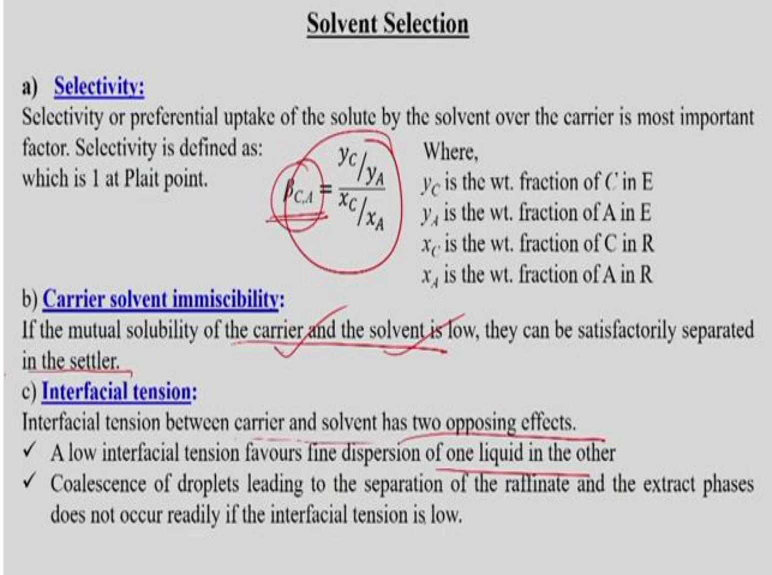

Solvent Selection

a) **Selectivity:**

Selectivity or preferential uptake of the solute by the solvent over the carrier is most important factor. Selectivity is defined as:

which is 1 at Plait point.

$$\beta_{C,A} = \frac{y_C/y_A}{x_C/x_A}$$

Where,

y_C is the wt. fraction of C in E

y_A is the wt. fraction of A in E

x_C is the wt. fraction of C in R

x_A is the wt. fraction of A in R

b) **Carrier solvent immiscibility:**

If the mutual solubility of the carrier and the solvent is low, they can be satisfactorily separated in the settler.

c) **Interfacial tension:**

Interfacial tension between carrier and solvent has two opposing effects.

- ✓ A low interfacial tension favours fine dispersion of one liquid in the other
- ✓ Coalescence of droplets leading to the separation of the raffinate and the extract phases does not occur readily if the interfacial tension is low.

And then one important parameter we discussed this one that solvent selection for this liquid-liquid extraction is very important or crucial criteria, so for that we discussed that the selectivity like selectivity of the preferential uptake of the solute by the solvent over the carrier is most important factor. Then selectivity is defined as:

$$\beta_{C,A} = (y_C / y_A) / (x_C / x_A) = y_E^{*}/x_R$$

So there will be no separation but for better this one separability we need beta greater than one. Then carrier solvent immiscibility that must be there otherwise if this mutual solubility of the carrier and the carrier solvent and the extracting solvent is very low then the can be satisfactorily separated this one what we called in the settler.

Then interfacial tension, so it has two different types of say effects. Interfacial tension between carrier and the solvent has two opposite effects like say a low interfacial tension that actually favors this fine dispersion of the one liquid in the other, but at the same time coalescence of the droplets leading to the separation of the raffinate and the extract phase actually does not occur readily if the interfacial tension is low.

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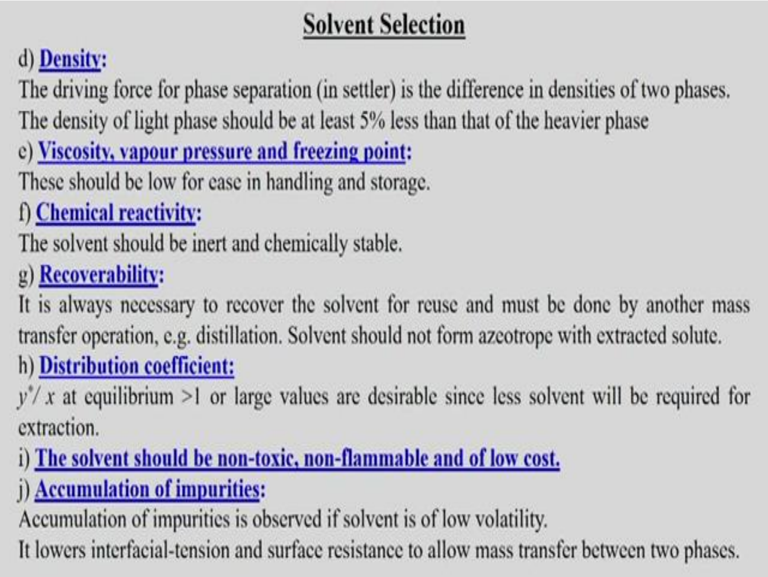

Solvent Selection

d) **Density:**

The driving force for phase separation (in settler) is the difference in densities of two phases. The density of light phase should be at least 5% less than that of the heavier phase

e) **Viscosity, vapour pressure and freezing point:**

These should be low for ease in handling and storage.

f) **Chemical reactivity:**

The solvent should be inert and chemically stable.

g) **Recoverability:**

It is always necessary to recover the solvent for reuse and must be done by another mass transfer operation, e.g. distillation. Solvent should not form azeotrope with extracted solute.

h) **Distribution coefficient:**

y^*/x at equilibrium >1 or large values are desirable since less solvent will be required for extraction.

i) **The solvent should be non-toxic, non-flammable and of low cost.**

j) **Accumulation of impurities:**

Accumulation of impurities is observed if solvent is of low volatility.

It lowers interfacial-tension and surface resistance to allow mass transfer between two phases.

And then density the driving force for the phase separation in the settler after the extraction is the difference in the densities of the two phases. The density of the we can say lighter phase actually should be at least five percent lesser than that of the heavier phases otherwise this will not be separated using this mixture settler, then viscosity, vapor pressure and freezing point and we can say this would be low in handling and storage actually.

Then chemical reactivity must not be there and the solvent should be inert and chemically stable and for require recoverability, so it is always necessary to recover the solvent for reuse and must be done by another mass transfer operation that is by distillation or like this then solvent not form this azeotrope with this extracted solute and the other point is this distribution coefficient, so we can say Y star by X at the equilibrium must be greater than one or large value that is we can say for the we can say this one for that less amount of the solvent will be required to extract the desire amount of the we can say target component.

Then the solvent should be non- toxic then non-flammable and low cost and then accumulation of impurities that should not be there, the accumulation of impurities is observed if solvent is of low volatility, so it lowers the interfacial tension and surface resistance and to allow mass transfer between two phases.

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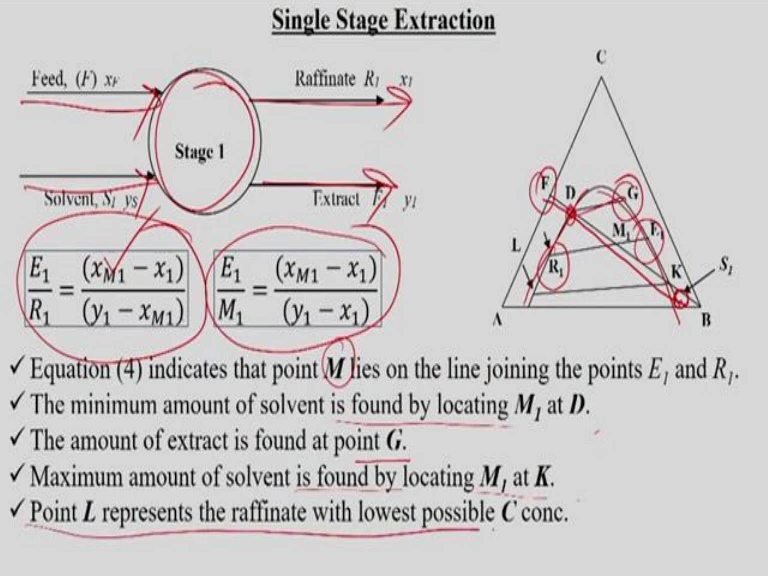

Single Stage Extraction

$$\frac{E_1}{R_1} = \frac{(x_{M1} - x_1)}{(y_1 - x_{M1})} \qquad \frac{E_1}{M_1} = \frac{(x_{M1} - x_1)}{(y_1 - x_1)}$$

- ✓ Equation (4) indicates that point ***M*** lies on the line joining the points E_1 and R_1.
- ✓ The minimum amount of solvent is found by locating $\boldsymbol{M_1}$ at ***D***.
- ✓ The amount of extract is found at point ***G***.
- ✓ Maximum amount of solvent is found by locating $\boldsymbol{M_1}$ at ***K***.
- ✓ Point ***L*** represents the raffinate with lowest possible ***C*** conc.

Now we have discussed about the single stage extraction process like this suppose this is the single stage and then feed is entering from here and solvent is added and then raffinate and the extract phases are separated:

$E_1/R_1 = (x_{M1} – x_1)/(y_1 – x_{M1})$

And then suppose this is the raffinate arm this is the extract arm and say this we can say this somewhere the solvent point is here nearby and then we have this feed line, so feed and soluble line is added will be explaining this one after this and then we can say this two equation actually indicate that M actually lies on the line joining this point we can say this one this E1 and we can say this one say R1.

And the minimum amount of the solvent is found by locating M1 at D actually we can say this one this is minimum amount of the solvent required to separate or to extract this one the amount of is found as point G and say this one good amount of we can say this extract just by getting the tie line value. The maximum amount of solvent is found by locating M1 at K and this point L represent the raffinate with the lowest possible solute concentration C.

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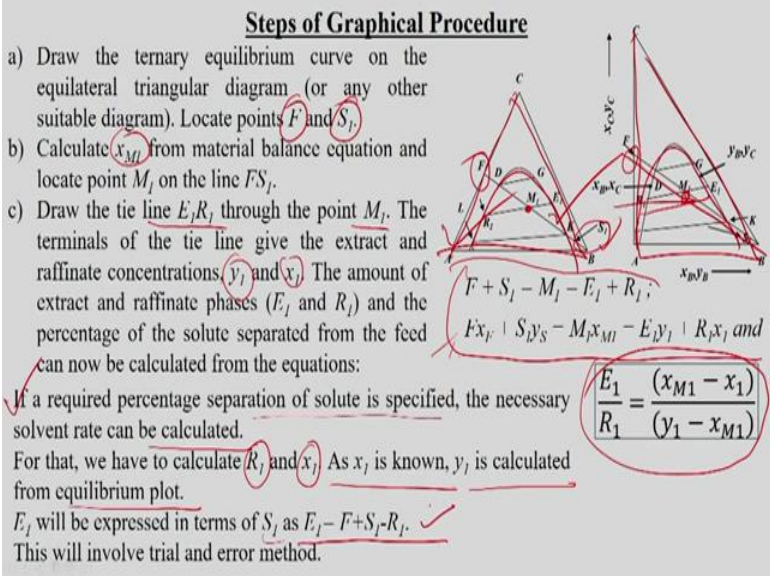

Steps of Graphical Procedure

a) Draw the ternary equilibrium curve on the equilateral triangular diagram (or any other suitable diagram). Locate points F and S_1.

b) Calculate x_{M1} from material balance equation and locate point M_1 on the line FS_1.

c) Draw the tie line E_1R_1 through the point M_1. The terminals of the tie line give the extract and raffinate concentrations y_1 and x_1. The amount of extract and raffinate phases (E_1 and R_1) and the percentage of the solute separated from the feed can now be calculated from the equations:

$$F + S_1 - M_1 - E_1 + R_1;$$

$$Fx_F + S_1y_S - M_1x_{M1} - E_1y_1 + R_1x_1 \text{ and}$$

$$\frac{E_1}{R_1} = \frac{(x_{M1} - x_1)}{(y_1 - x_{M1})}$$

If a required percentage separation of solute is specified, the necessary solvent rate can be calculated.

For that, we have to calculate R_1 and x_1. As x_1 is known, y_1 is calculated from equilibrium plot.

E_1 will be expressed in terms of S_1 as $E_1 - F + S_1 - R_1$.

This will involve trial and error method.

And the steps of the graphical procedure we have already derived described this one like say we need to locate this S1 we need to locate the F like draw the ternary diagram first we have to draw the this ternary diagram like this one or we have to draw this one and then we can say this one on the equilateral triangular diagram or any other diagram like this right angle diagram whatever maybe then we need to locate this point feed point and the solvent one.

Then we need to calculate the xM1 from the material balance equation and this we have to locate this point M actually M1 suppose this M1 we will be getting from here and then as we have the suppose this feed point and S1 and we know this M1 were it will be through this we need to draw this equilibrium tie line. Draw that then we need to draw tie line E1R1 through this point M1. The terminals of the tie line give the this extract and the raffinate, so extract will be this one and raffinate will be the in the left hand arm.

And from there we will be getting this Y1 and this X1. The amount of the extract and raffinate phases E1 and R1 this one and the percentage of the solute separated from the feed can now be calculated from the equation, like this two equation like this F plus S1 is equal to M1 that is equal to E1 plus R1 and from the component friends like F into xF plus S1 into yS that is all in terms of the solute concentration that is M1 into xM1 is equal to E1 into y1 plus R1 into x1 and from there actually we got this E1 by R1 is equal to xM1 minus x1 by Y1 minus xM1.

Or if required percentage separation of the solute specified the necessary solvent rate can be also calculated and for that we have to calculate this R1 and x1, as x1 is know then R1 is calculated from the equilibrium plot. And E1 will expressed in terms of S1 as E1 is equal to we can say this F plus S1 minus R1. This will involve trail and error method that we already solved these problems.

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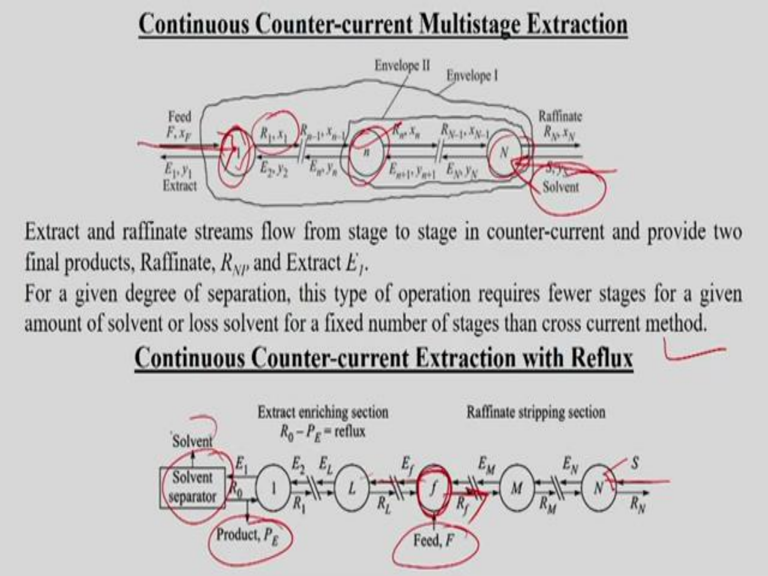

Continuous Counter-current Multistage Extraction

Extract and raffinate streams flow from stage to stage in counter-current and provide two final products, Raffinate, R_{NP} and Extract E_1.

For a given degree of separation, this type of operation requires fewer stages for a given amount of solvent or loss solvent for a fixed number of stages than cross current method.

Continuous Counter-current Extraction with Reflux

Now we have discussed about the continuous counter current multistage extraction process also there so many stages are there or but if you see this you know counter current mode, so suppose feed is entering from the stage one whereas the solvent is entering from the last stage and then we say raffinate of the stage one is the feed for the stage two and the extract of this stage two will feed to the stage one like that way. So the extract and raffinate streams flow from stage to stage in counter current and these provide two final products like raffinate RNP and extract E1.

For a given degree of separation this type of operation requires fewer stages for a amount of the solvent or less solvent for a fixed number of stages than cross flow we can say this one method. And we have also discussed about the continuous current extraction with reflux also there somewhere you can say this one we have used some reflux like say we have taken out sometimes the product, we have used this feed somewhere in the feed there also the calculation is same like this suppose feed is entering in the F number of we can stages then it is separated into EF like this and RF and you see the solvent actually is added from this N we can say this stage and the solvent separated from the first stage is taken from here.

So that type of system is there, so there are different configurations and the basic concepts are same like this we need to do the mass balance and component balance and then from the ternary diagram we will be able to get that where the feed point location is there, where the we can say this solvent point location is there and from there how this different stages are there and from there say E1 R1, E2 R2, E3 R3 will be calculating and there actually will be say we assume that the all this stages are in equilibrium with each other that is why E1 R1 the two stages are joint with this tie line.

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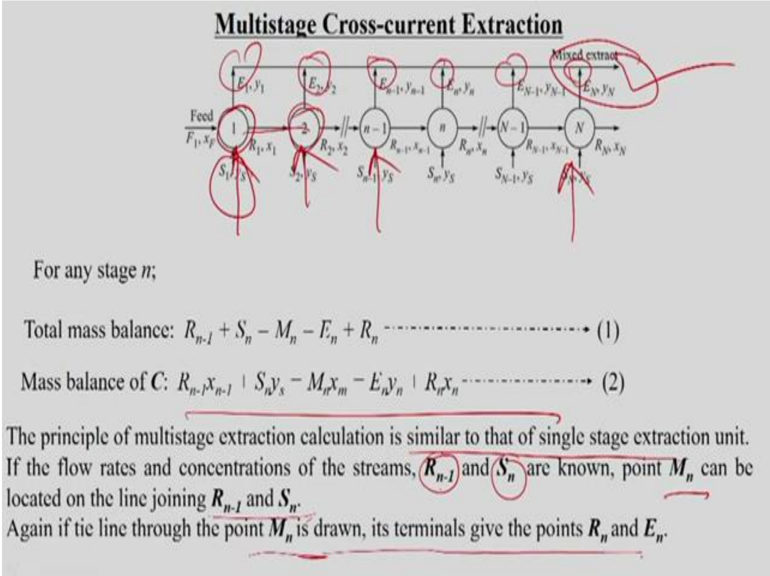

Multistage Cross-current Extraction

For any stage n;

Total mass balance: $R_{n-1} + S_n = M_n = E_n + R_n$ ------→ (1)

Mass balance of C: $R_{n-1}x_{n-1} + S_n y_s = M_n x_m = E_n y_n + R_n x_n$ ------→ (2)

The principle of multistage extraction calculation is similar to that of single stage extraction unit. If the flow rates and concentrations of the streams, $\boldsymbol{R_{n-1}}$ and $\boldsymbol{S_n}$ are known, point $\boldsymbol{M_n}$ can be located on the line joining $\boldsymbol{R_{n-1}}$ and $\boldsymbol{S_n}$.

Again if tie line through the point $\boldsymbol{M_n}$ is drawn, its terminals give the points $\boldsymbol{R_n}$ and $\boldsymbol{E_n}$.

Now this multi stage cross current extraction process like this feed has entered from the stage one and the solvent is given in this stage one and the stage two, stage three like that in all the stages actually separated solvents are there and from the all the stages whatever the extracts are obtained this are all added in a common header and then mixed extract is obtained but the like this any other this extraction process whatever the multi stage processes whatever raffinate is obtained from stage one is given like the feed to the stage two and the calculations are like same.

The principal of multistage extraction calculation is similar to that of single stage extraction like this. If the flow rates and concentration of the stream RN1 and minus 1 and SN are known point MN can be located on the this one line joining RN1 minus one and SN. Like that whatever we have drawn in this single stage extraction process, again if the tie line through this one point MN is drawn, its terminals give RN and EN, so every time actually we got the similar type of we can say trends means say whenever the extracts and raffinate are in equilibrium then added with the tie line and from there we got the equilibrium composition, so thank you very much for your kind patience.