Fundamentals of Food Process Engineering
Prof. Jayeeta Mitra
Department of Agricultural and Food Engineering
Indian Institute of Technology, Kharagpur

Lecture - 20
Evaporation and Concentration (Contd.)

Hello everyone, welcome to NPTEL online certification course on Fundamentals of Food Process Engineering. We will continue today with the topic evaporation and concentration. So, in the last class we have seen that how we can design the single effect evaporator and we can calculate the steam economy and heat transfer area or heat exchanger area.

Today we will continue with the design of multiple effect evaporator also, but before going into that we will just look into a few cases, where evaporator is used effectively. So, first is the biological material.

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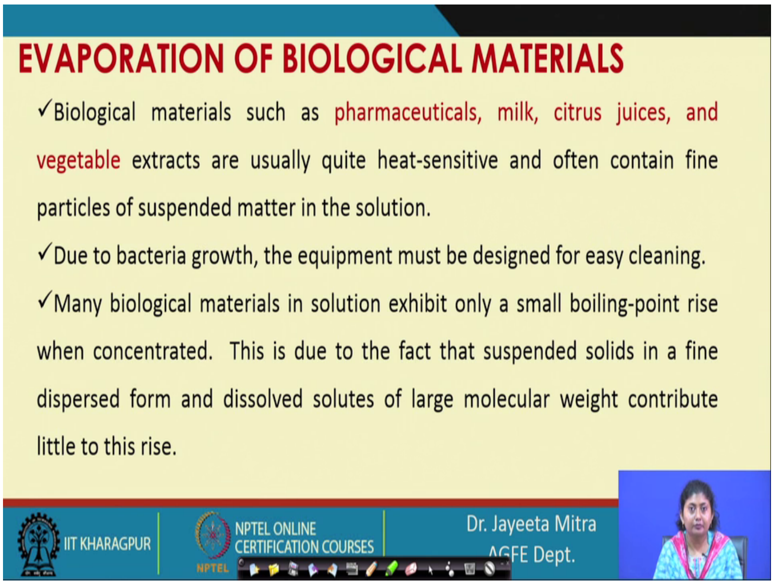

EVAPORATION OF BIOLOGICAL MATERIALS

✓Biological materials such as pharmaceuticals, milk, citrus juices, and vegetable extracts are usually quite heat-sensitive and often contain fine particles of suspended matter in the solution.

✓Due to bacteria growth, the equipment must be designed for easy cleaning.

✓Many biological materials in solution exhibit only a small boiling-point rise when concentrated. This is due to the fact that suspended solids in a fine dispersed form and dissolved solutes of large molecular weight contribute little to this rise.

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Which is you know very heat sensitive material and for them we use often evaporator to make them concentrated for example, milk, fruit juices, etcetera.

So, these materials they contain fine particles and suspended matter in the solution and what happen that during evaporation sometime those material can be deposited in the surface of the liquid side. And if they are not cleaned properly then maybe bacterial growth can generate and the contamination will be high so the equipment the evaporator should be designed in such a way proper cleaning can be done.

So, all this biological material that we are talking about, they exhibit a small boiling point rise when concentrated because they have the suspended solids in the finely dispersed form or have the large molecules that are you know dissolved, ok. So, they generally provide a very less rise in the boiling point because their nature is not like you know sodium hydroxide solution or NaCl solution like that.

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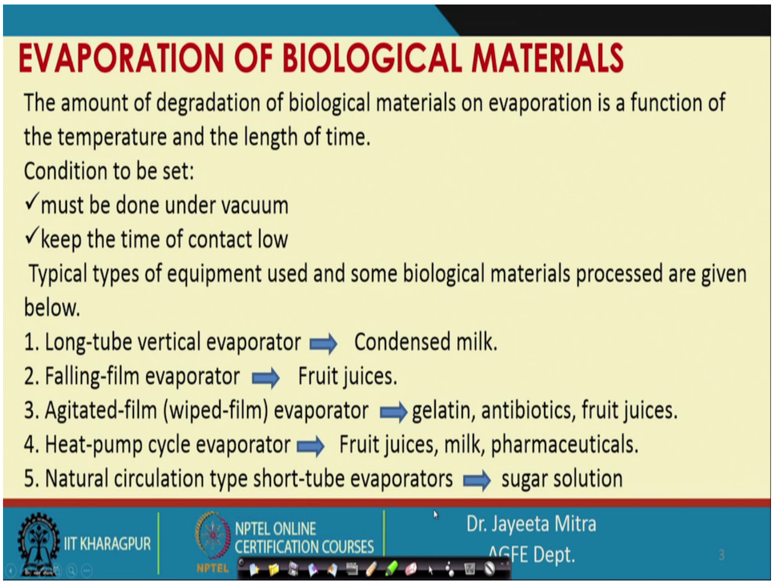

EVAPORATION OF BIOLOGICAL MATERIALS

The amount of degradation of biological materials on evaporation is a function of the temperature and the length of time.

Condition to be set:

✓must be done under vacuum

✓keep the time of contact low

Typical types of equipment used and some biological materials processed are given below.

1. Long-tube vertical evaporator ⇒ Condensed milk.
2. Falling-film evaporator ⇒ Fruit juices.
3. Agitated-film (wiped-film) evaporator ⇒ gelatin, antibiotics, fruit juices.
4. Heat-pump cycle evaporator ⇒ Fruit juices, milk, pharmaceuticals.
5. Natural circulation type short-tube evaporators ⇒ sugar solution

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So, the amount of degradation of biological material during evaporation that is basically a function of temperature and length of the time.

So, we have to design in such a way so that the heat sensitive material does not expose to the temperature for a longer time ok. So, we will design or we will take the heat transfer area a smaller one so, that way we can design them. And another thing we can do is to reduce the temperature we can operate the evaporator chamber under vacuum so that the boiling point will come down. So, another one case is we can operate under vacuum, another is we can keep the time of contact low. So, we can see few equipments that is used for a biological material, one is long tube vertical evaporator that is specifically used for the condensed milk, ok.

So, so, the reason is when we use this long tube vertical evaporators. So, as they become concentrated as they come down they will become concentrated. So, heat transfer will be difficult ok. So, and because there, because their high viscosity mobility is also a problem, that is why we use the long tube vertical evaporator for them.

Then there is falling film evaporator, these are mostly used for the fruit juices, agitated film evaporator those are used for antibiotics, fruit juices and gelatin also because all these cases we need a continuous agitation to increase the heat transfer because towards the end of evaporation as they become concentrated they may stick to the surface and reduce the heat transfer coefficient.

There is also heat pump cycle evaporator for fruit juice milk and pharmaceutical because these are very heat sensitive materials so they are, you know utilised by the heat pump cycle evaporator method. Natural circulation type short tube evaporator these are used for sugar solution.

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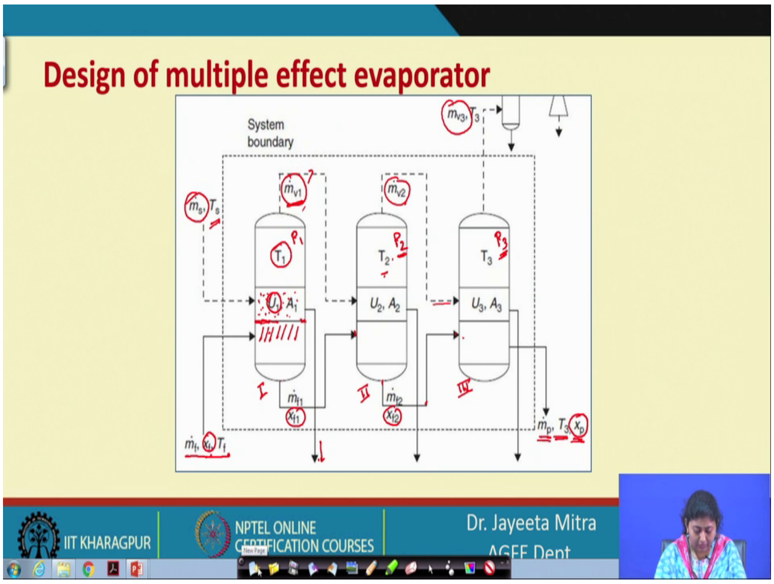

Design of multiple effect evaporator

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Now, we will discuss the design of multiple effect evaporator, let us first see the configuration of multiple effect evaporator. So, here we are considering three effect ok, triple effect evaporator and here this is forward feed evaporator, forward feed triple effect evaporator.

So, this is the first effect ok, this is the second one and this is the third effect. So, we can observe that first, in the first effect feed is entering the mass flow rate of the feed is m f dot, x f is the concentration of solid in the feed stream T f is the temperature of feed and that is entering in the first effect ok.

So, in the first effect temperature is T 1 this is the saturation vapor temperature or boiling temperature at the pressure, let us say if the pressure is P 1 in the first effect and here one side of the heat exchange surface this feed is there and the other side there is steam. So, this is the heat transfer area across which this heat transfer is taking place, where the overall heat transfer coefficient including the steam side and the material or the conductive material or the surface through which this you know heat transfer heat exchange is taking place.

So, the conductivity of that material and the convective heat transfer in the liquid side. So, together we have calculated this U 1 and m s dot is the mass flow rate of the steam that is entering at a temperature T s. Now, these steam is condensed here going out by this stream and whatever evaporation takes place in the first effect that is causing this vapour flow rate m v 1 dot from the first effect and that is coming out from the first effect entering into the second one.

Whereas, the concentrated feed or concentrated liquid that is coming out by the evaporation of feed that is going to enter to the next effect ok. So, what is happening in the next effect as we have discuss, that the pressure in the first effect is higher than that is in the second one and eventually the second one the pressure is higher than the third one ok.

So, to the high pressure side, from the high pressure to the low pressure we are sending the feed. So, no requirement of pump is there so feed is going from first to the second effect and again from the concentrated liquid which is coming from the second effect is going to enter into the third one. From the third we are finally, getting the product ok, which is very high in the concentration of the solid that is x p and coming out at a temperature T 3.

So, T 3 is the temperature that is with respect to the pressure P 3 in the chamber and again T 2 is the temperature which is prevailing in the second effect corresponding to the pressure P 2. M v 2 is the vapour that is generated in the second effect and that is utilised in the third effect for heat exchange with the input stream or input feed which is entering from the second effect to the third one, this vapour which is generated in the third effect finally, goes to the condenser ok.

So, this is the total system so eventually this x f which is the concentration of solid in the feed will be concentrated in the x f 1, further concentrated in x f 2 and we are getting product x x p that is highly concentrated. So, utilising the same steam m s dot we are now generating vapour m v 1, then m v 2 and m v 3 dot. So, m v 1 dot, m v 2 dot and m v 3 dot.

So, we can see that how we are increasing the steam economy as well and in more general cases we consider that this three effects are equal in size, that is the heat transfer area available are same. And that is in most of the cases a design criteria, for you know the iteration that we perform that when this area are almost close to each other or within a variation of 10 percent we shall stop further iteration ok.

So, that will be our final design of the multiple effect evaporator. Now, let us see how we can step by step perform the overall balance, solid balance, enthalpy balance and finally, design the system.

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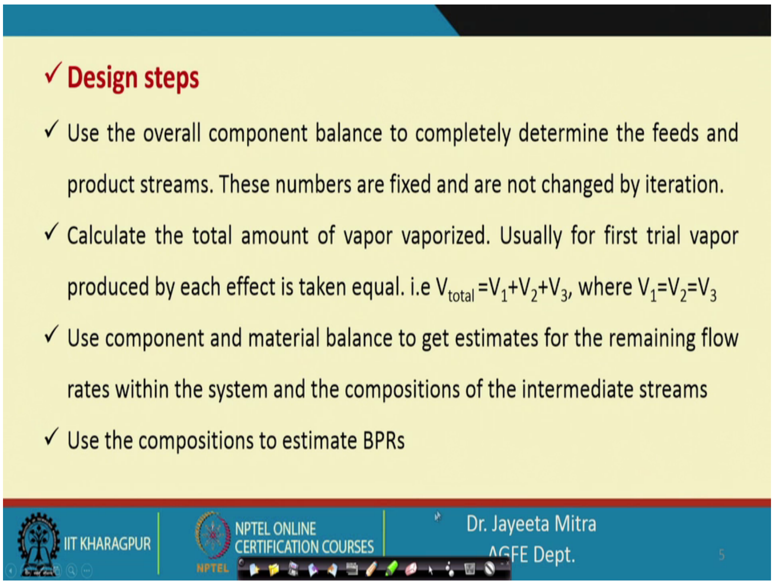

✓ **Design steps**

- ✓ Use the overall component balance to completely determine the feeds and product streams. These numbers are fixed and are not changed by iteration.
- ✓ Calculate the total amount of vapor vaporized. Usually for first trial vapor produced by each effect is taken equal. i.e $V_{total} = V_1+V_2+V_3$, where $V_1=V_2=V_3$
- ✓ Use component and material balance to get estimates for the remaining flow rates within the system and the compositions of the intermediate streams
- ✓ Use the compositions to estimate BPRs

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So, there are few design steps we will follow them one by one, first is use the overall component balance to completely determine the feeds and product streams, these numbers are fixed and are not changed by iteration. So; obviously, numbers will be fixed of the you know in feed and the product streams because you know the number of effect that you are going to design, if it is a three effect system. So, one feed stream is entering, one concentrate from the first, another from the second and lastly from the third.

So, three concentrated streams are coming out and similarly the vapour V 1, V 2 and V 3 ok. So, those are not going to change through the whole system, I mean their number does not change, but value may change as you perform iteration one after the other ok. So, calculate the total amount of vapor vaporized.

So, that is V total that is V 1 plus V 2 plus V 3, V 1 the vapor you are getting in the first effect, V 2 in the second effect and V 3 in the third effect and normally we consider that equal amount of vapor is generated that is V 1 equal to V 2 equal to V 3. Then use component and material balance to get estimates for the remaining flow rates within the system and the composition of the intermediate streams.

So, what we are doing in the third step that is component and material balance component and material balance to get estimate from the remaining flow rates within the system and the composition of the intermediate stream. That means, we need to know the fraction of the solid in the streams that is coming out and that can be done by the component balance and the overall material balance.

And once we get the concentration we know that concentration has a relation with boiling point rise ok, although the biological material we have seen that they does not provide very high boiling point rise. But to identify how much amount of elevation is there or to understand how a boiling point elevation effect the situation, effect the operation in a multiple effect evaporator we will solve. Now including boiling point rise; however, small the value maybe because that will help you in designing a system where actually there exist a, significant amount of boiling point elevation right.

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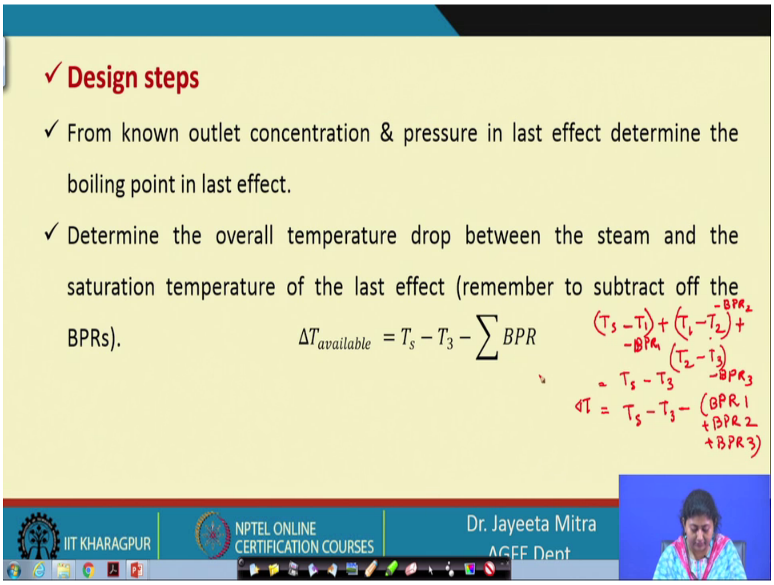

✓ Design steps

- ✓ From known outlet concentration & pressure in last effect determine the boiling point in last effect.
- ✓ Determine the overall temperature drop between the steam and the saturation temperature of the last effect (remember to subtract off the BPRs). $\Delta T_{available} = T_s - T_3 - \sum BPR$

$$\underset{-BPR_1}{(T_s - T_1)} + \overset{-BPR_2}{(T_1 - T_2)} + \underset{-BPR_3}{(T_2 - T_3)}$$

$$= T_s - T_3$$

$$\Delta T = T_s - T_3 - (BPR1 + BPR2 + BPR3)$$

So, so from the known outlet concentration and pressure in the last effect, determine the boiling point in the last effect then determine the overall temperature drop between the steam and the saturation temperature of the last effect ok. So, total delta T that we are getting in case of a triple effect evaporator that will be T s minus T 3 minus boiling point elevation.

So, if you want to understand that how this is generating. So, we know that T s is the steam that is entering in the first effect, temperature of the steam that is entering in the first effect. Now, the boiling point in the first effect corresponding to let us say pressure T p1 is T 1, so in the first effect we are getting this much delta T. Now, this T 1 the vapor is coming out at this T 1 temperature only and that is going to enter into the second effect as steam ok.

So, in the second effect we are getting T 1 minus T 2 where T 2 is the boiling point temperature corresponding to pressure p 2 in the second effect now this steam that is coming out at T 2 this vapor that is coming out will enter into the third effect ok. So, in the third effect we are finally getting, T 2 minus T 3 that is we are getting T s minus T 3 when there is no boiling point elevation. Now, if boiling point elevation happens or it occurs then in the first effect ok, in the first effect what will be the concentration because of that some boiling point elevation will be there, similarly; in the third effect as well and in the fourth effect as well ok.

So, when T 1 comes out it includes that boiling point elevation, but when it enters in the next effect ok. So, in the next effect the effect of that elevation is not there. So, that we cannot consider there, that that is why what we do? That the total difference will be total delta T that we can get when the boiling point rise exist will be T s minus T 3 minus delta or let us say.

Let us say I can write boiling point rise in 1 plus boiling point rise in 2 plus boiling point rise in 3 ok. So, this is, this is coming because when boiling point rise will exist here it will be T 1 that that is getting in the in the first effect that will include minus BPR 1. Here also we will get T 2 minus BPR 2 and the T 3 also we will getting minus BPR 3 right.

So, all together we can take as T s minus T 3 minus summation of all the boiling point rise that has occurred in the system in all the 3 effects right. So, this is how we can calculate the total delta T available.

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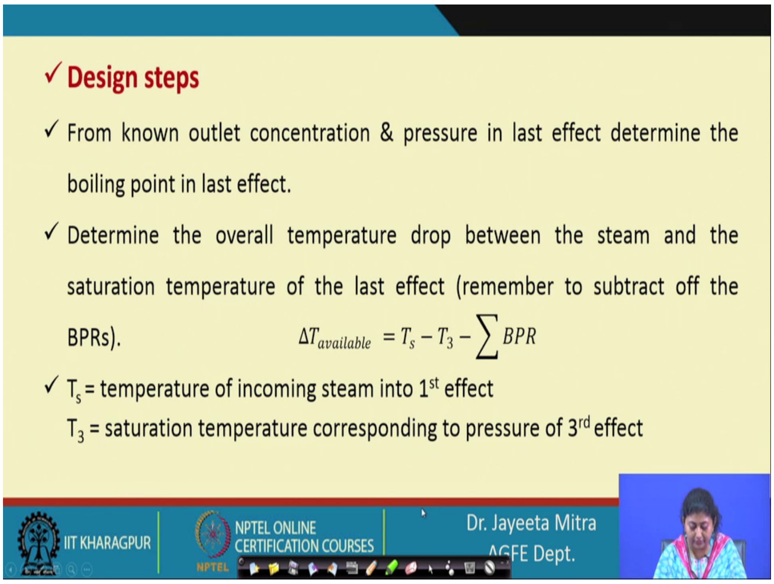

✓ **Design steps**

✓ From known outlet concentration & pressure in last effect determine the boiling point in last effect.

✓ Determine the overall temperature drop between the steam and the saturation temperature of the last effect (remember to subtract off the BPRs). $\Delta T_{available} = T_s - T_3 - \sum BPR$

✓ T_s = temperature of incoming steam into 1st effect

T_3 = saturation temperature corresponding to pressure of 3rd effect

So, T s and T 3 it is already defined.

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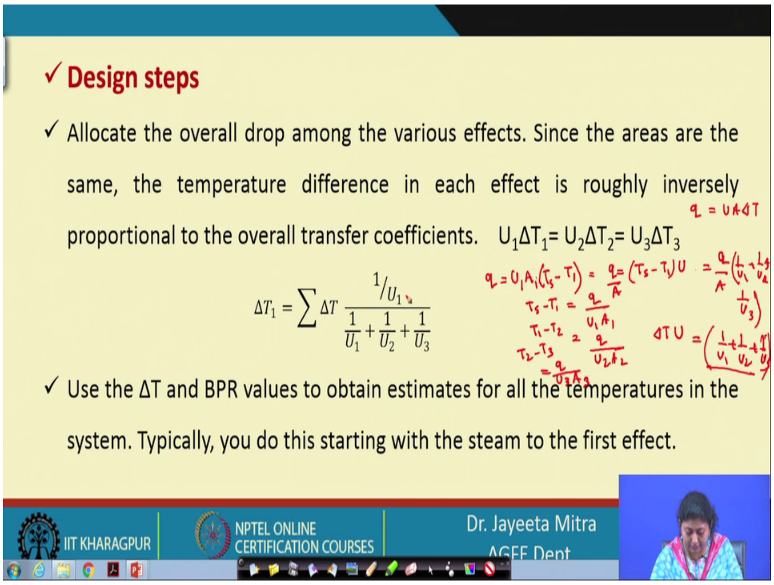

✓ **Design steps**

✓ Allocate the overall drop among the various effects. Since the areas are the same, the temperature difference in each effect is roughly inversely proportional to the overall transfer coefficients. $U_1\Delta T_1 = U_2\Delta T_2 = U_3\Delta T_3$

$$\Delta T_1 = \sum \Delta T \frac{1/U_1}{\frac{1}{U_1}+\frac{1}{U_2}+\frac{1}{U_3}}$$

$q = UA\Delta T$

$q = U_1A_1(T_s - T_1) = \frac{q}{A} = (T_s - T_1)U = \frac{q}{A}\left(\frac{1}{U_1}+\frac{1}{U_2}+\frac{1}{U_3}\right)$

$T_s - T_1 = \frac{q}{U_1A_1}$

$T_1 - T_2 = \frac{q}{U_2A_2}$

$T_2 - T_3 = \frac{q}{U_3A_3}$

$\Delta T U = \left(\frac{1}{U_1}+\frac{1}{U_2}+\frac{1}{U_3}\right)$

✓ Use the ΔT and BPR values to obtain estimates for all the temperatures in the system. Typically, you do this starting with the steam to the first effect.

Then allocate the overall drop among the various effects since the areas are the same. So, we will consider as I said that this will be a design consideration that all the areas of the three effect will be same. So, the temperature difference in each effect is roughly, inversely proportional to the overall transfer coefficients ok. So, U 1 delta T 1 equal to U 2 delta T 2 that is equal to U 3 delta T 3. So, U 1, U 2, U 3 are the overall heat transfer coefficient in the first second and third effect.

And delta T 1 delta, T 2 and delta T 3 are the temperature difference in all the three effect respectively ok. So, definitely since the temperature of steam that is being entered and the pressure that is inside the chamber all are different. So, U 1, U 2, U 3 will be different; however, the temperature difference in each effect is roughly inversely proportional to the overall transfer coefficient ok. So, that means, we can write here as delta T 1, if we want to calculate delta T 1 ok, so that will be equal to summation of delta T into 1 by U 1 divided by 1 by U 1 plus 1 by U 2 plus 1 by U 3.

So, use the delta T and boiling point rise values to obtain estimate of all the temperatures in the system and we can start with the steam entering in the first effect, right. So, if you think about that how we can derive this you can calculate like this that, if we identify the effect, if we identify the total effect that is actually you know because this is equal this is equal amount of heat transfer is taking place where in all the effect ok. So, what we can write is T s minus T 1 because q that is equal to UA delta T right. So, here we can write that q that is equal to U 1 that is in the first effect into A 1 into the temperature difference in the first effect T s 1.

T s 1 minus T 1 ok, so if I can write T s minus T 1 that is equal to q by U 1 A 1 ok. Similarly, T 1 minus T 2 that is equal to q by U 2, A 2 and T 2 minus T 3 that is equal to T 2 minus T 3 that is equal to q divided by U 3 by A 3 right. So, if we add now all these equation all the three equation. So, we are getting T s minus T 1 that is the overall heat transfer so, q will be equal to overall delta T into U into A ok.

So, that is equal to, since q by A is same we can write 1 by U 1 plus 1 by U 2 plus 1 by U 3 right so; that means, if q equal to this one T s minus T s minus T T s minus T 1 U A. So, this we have added at all them and then we are getting this so here we can take q A in this side because the area is same.

So, finally, we are getting finally, we are getting delta T into U that is equal to 1 by U 1 ok, 1 by U 1 plus 1 by U 2 plus 1 by U 3 right, so ok, what we have done is here we have added all these temperature to find the total area that is q equal to U A delta T.

So, total area U A delta T is coming equal to all this summation of all the overall heat transfer coefficient ok. Now, if we want to calculate this any you know any temperature drop so that will be summation of delta T into 1 by this, I mean any effect the divided by 1 by 1 plus 1 by U 2 plus 1 by U 3, into overall heat transfer coefficient of any effect that we are interested in ok.

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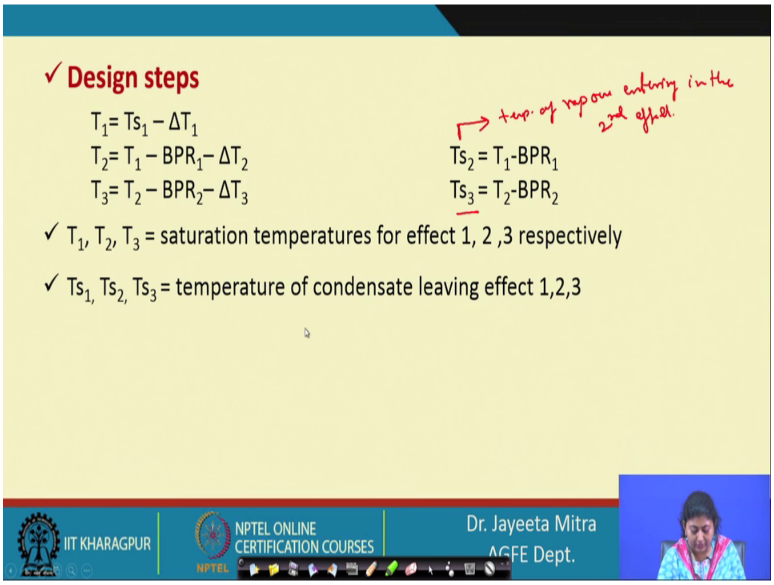

✓ **Design steps**

$T_1 = Ts_1 - \Delta T_1$

$T_2 = T_1 - BPR_1 - \Delta T_2$

$T_3 = T_2 - BPR_2 - \Delta T_3$

→ temp. of vapour entering in the 2nd effect.

$Ts_2 = T_1 - BPR_1$

$Ts_3 = T_2 - BPR_2$

✓ T_1, T_2, T_3 = saturation temperatures for effect 1, 2 ,3 respectively

✓ Ts_1, Ts_2, Ts_3 = temperature of condensate leaving effect 1,2,3

So, if there is boiling point elevation exist so we can calculate this T 1 equal to T s 1 minus delta T 1, similarly T 2 that is equal to T 1 minus boiling point elevation minus this.

Because T 1 there is a temperature at which this vapour came out ok, but that has included this boiling point rise in that first effect. So, we are taking that minus, then T s 2, T s 2 will be what? T 1 minus boiling point rise in the first effect. So, this is the steam actually that is entering in the, this is the temperature of the vapour entering in the second effect ok. Similarly, T s 3 which is entering in the third effect the temperature of the steam, which is entering in the third effect right.

And T 2 will be equal to T 1 minus boiling point rise minus delta T 2. So, this T 2 which is the temperature in the second effect T 3 which is the temperature in the third effect, and yes. So, T 1, T 2, T 3 these are the saturation temperature for the effect 1, 2, 3 and T s 1, T s 2, T s 3 these are the temperature of condensate leaving the effect, 1, 2 and 3. So, T s 1 this is the condensate that is leaving the first effect T s 2 which is leaving the second effect and T s three which is the condensate which is leaving the third effect.

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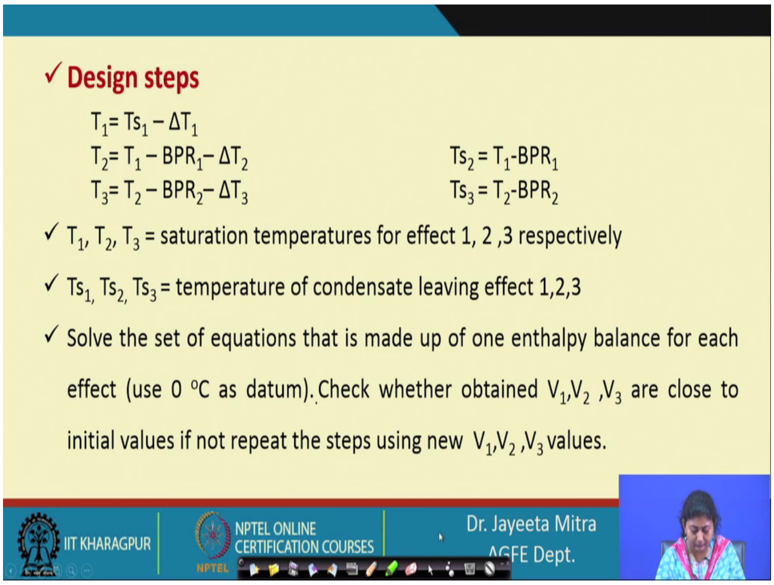

✓ **Design steps**

$T_1 = Ts_1 - \Delta T_1$

$T_2 = T_1 - BPR_1 - \Delta T_2$ $Ts_2 = T_1 - BPR_1$

$T_3 = T_2 - BPR_2 - \Delta T_3$ $Ts_3 = T_2 - BPR_2$

✓ T_1, T_2, T_3 = saturation temperatures for effect 1, 2 ,3 respectively

✓ Ts_1, Ts_2, Ts_3 = temperature of condensate leaving effect 1,2,3

✓ Solve the set of equations that is made up of one enthalpy balance for each effect (use 0 °C as datum). Check whether obtained V_1,V_2 ,V_3 are close to initial values if not repeat the steps using new V_1,V_2 ,V_3 values.

Now, solve the set of equation that is made up of one enthalpy balance for each effect ok, then check whether the V 1, V 2, V 3 are close to each other and then we can have the new values if they are not each other the iteration will goes on.

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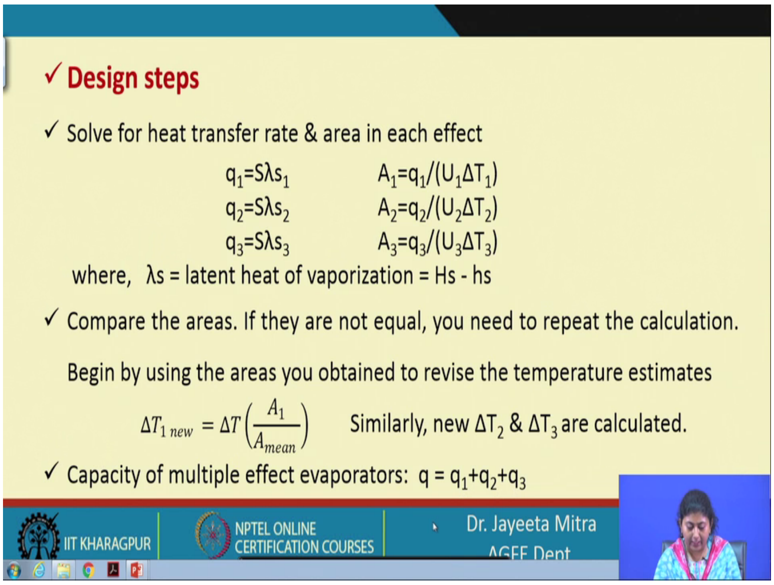

✓ **Design steps**

✓ Solve for heat transfer rate & area in each effect

$q_1 = S\lambda s_1$ $A_1 = q_1/(U_1 \Delta T_1)$

$q_2 = S\lambda s_2$ $A_2 = q_2/(U_2 \Delta T_2)$

$q_3 = S\lambda s_3$ $A_3 = q_3/(U_3 \Delta T_3)$

where, λs = latent heat of vaporization = Hs - hs

✓ Compare the areas. If they are not equal, you need to repeat the calculation. Begin by using the areas you obtained to revise the temperature estimates

$$\Delta T_{1\,new} = \Delta T\left(\frac{A_1}{A_{mean}}\right)$$

Similarly, new ΔT_2 & ΔT_3 are calculated.

✓ Capacity of multiple effect evaporators: $q = q_1 + q_2 + q_3$

Finally, will solve for heat transfer rate and area in each effect so, we will calculate that q 1 that is equal to S into lambda s 1 and A 1 that is equal to q 1 by U 1 by delta T 1. Similarly, A 2 and A 3, so lambda s is latent heat of vaporization, steam at that temperature where it is entering minus the liquid enthalpy at that temperature,

temperature again we will compare the area and find that they are close to each other or not.

So, then the new delta T that will take, so that will be delta T into A 1 by A mean and similarly we will calculate delta T 2 and delta T 3 because, see delta T 1 surface area will be proportional to heat transfer, I mean if the area is higher. So, higher number higher amount of heat transfer will be there and since we have we can calculate that the delta T 1 in that is the change of temperature in the first effect proportional to the area.

And finally, the capacity of the multiple effect evaporator will be q that is equal to q 1 plus q 2 plus q 3 because the total heat transfer we are getting in the system in the first second and third effect. So, that is why we will add them together.

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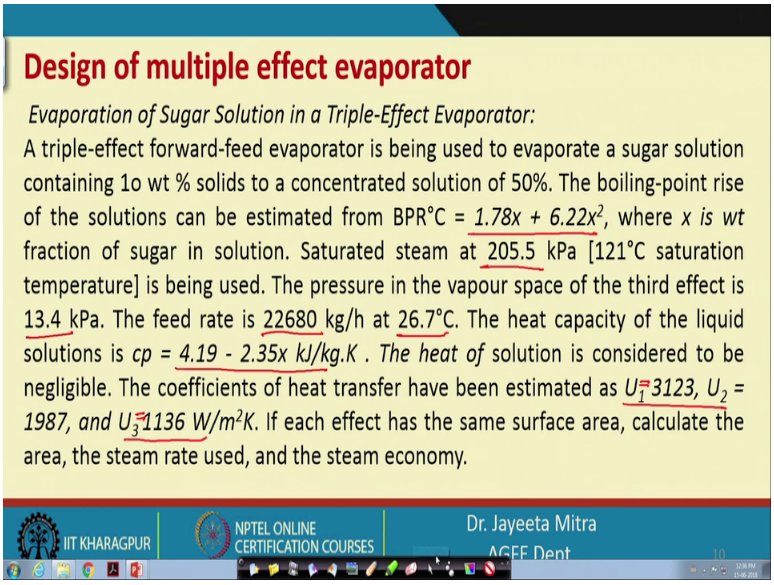

Design of multiple effect evaporator

Evaporation of Sugar Solution in a Triple-Effect Evaporator:

A triple-effect forward-feed evaporator is being used to evaporate a sugar solution containing 1o wt % solids to a concentrated solution of 50%. The boiling-point rise of the solutions can be estimated from BPR°C = $1.78x + 6.22x^2$, where *x is wt* fraction of sugar in solution. Saturated steam at 205.5 kPa [121°C saturation temperature] is being used. The pressure in the vapour space of the third effect is 13.4 kPa. The feed rate is 22680 kg/h at 26.7°C. The heat capacity of the liquid solutions is $cp = 4.19 - 2.35x$ *kJ/kg.K . The heat of* solution is considered to be negligible. The coefficients of heat transfer have been estimated as $U_1 = 3123$, $U_2 = 1987$, and $U_3 = 1136$ W/m^{2}K. If each effect has the same surface area, calculate the area, the steam rate used, and the steam economy.

So, just quickly I will discuss problem that is a triple effect forward feed evaporator is being used to evaporate sugar solution having 10 weight percent solids to a concentrated solid of 50 percent. Boiling point rise is governed by this equation, where x is the fraction weight fraction of the sugar in the solution. Saturated steam at 205.5 kilo pascal, this is been used that is entered in the first effect. Pressure in the vapour space of third effect is given that is 13.4 that means, corresponding to this we can calculate the temperature in the third effect. Feed rate is given, temperature is given cp is again by concentration equation is given and U 1, U 2 and U 3 this is given, U 1, U 2 and U 3 is given. So, if the each effect has the same surface area, calculate the area and the steam used, and the steam economy.

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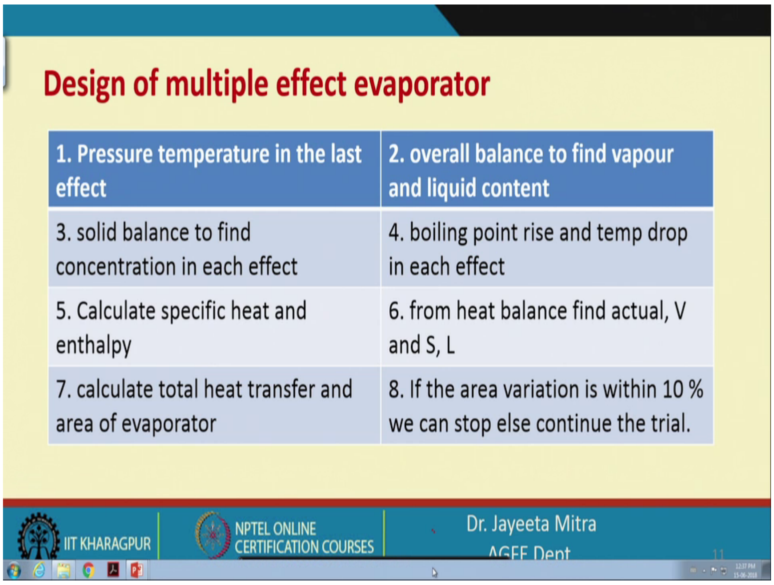

Design of multiple effect evaporator

1. Pressure temperature in the last effect	2. overall balance to find vapour and liquid content
3. solid balance to find concentration in each effect	4. boiling point rise and temp drop in each effect
5. Calculate specific heat and enthalpy	6. from heat balance find actual, V and S, L
7. calculate total heat transfer and area of evaporator	8. If the area variation is within 10 % we can stop else continue the trial.

So, steps will be this way, first is pressure temperature in the last effect because the pressure is given. So, the temperature correspondingly we can calculate, then is overall balance to find the vapour and the liquid content, overall balance to find the vapour and liquid content ok. So, then solid balance to find the concentration in each effect from the concentration we can calculate boiling point rise and temperature drop. Finally, calculate the specific heat and from that enthalpy, from the heat balance we can find out actual V, S and L and check with what we have assume. Then calculate the total heat transfer area of the evaporator and if you are getting within ten percent variation we will stop otherwise the iteration will continue, ok.

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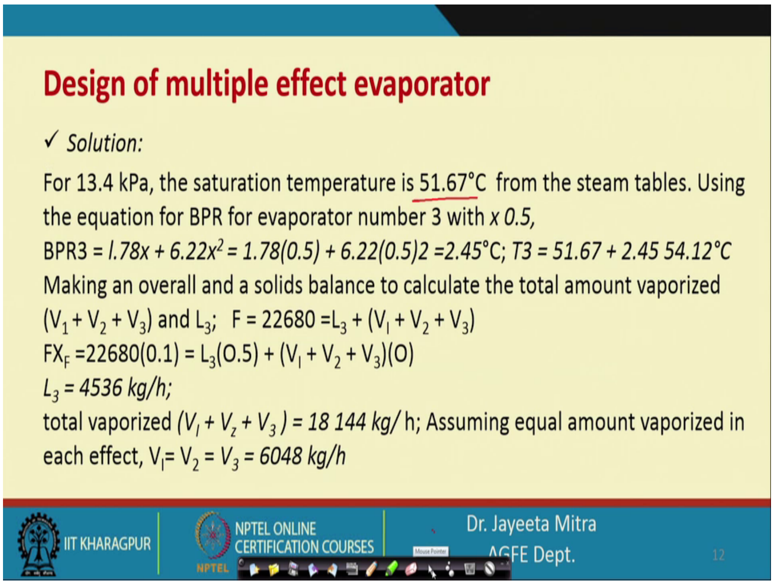

Design of multiple effect evaporator

✓ *Solution:*

For 13.4 kPa, the saturation temperature is 51.67°C from the steam tables. Using the equation for BPR for evaporator number 3 with *x 0.5,*

BPR3 = *l.78x + 6.22x*^{2} = *1.78(0.5) + 6.22(0.5)2* =*2.45*°C; *T3 = 51.67 + 2.45 54.12°C*

Making an overall and a solids balance to calculate the total amount vaporized $(V_1 + V_2 + V_3)$ and L_3; F = 22680 =$L_3 + (V_l + V_2 + V_3)$

FX_F =22680(0.1) = L_3(O.5) + $(V_l + V_2 + V_3)$(O)

$L_3 = 4536$ *kg/h;*

total vaporized $(V_l + V_z + V_3) = 18\ 144$ *kg/* h; Assuming equal amount vaporized in each effect, $V_l = V_2 = V_3 = 6048$ *kg/h*

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So, first, in 13.4 kilo pascal saturation temperature we have calculated. So, this saturation temperature from the steam table is coming 51.67 and the from the steam table we have calculated this. Now, equation for the boiling point rise in the effect 3 where the concentration of weight fraction given is 0.5. So, we will find the boiling point rise in the third effect right, using that concentration formula. So, we have added that T 3, we are getting now T 3 then we are making an overall balance of total feed will be you know divided into L 3 that is the product we are getting plus V 1, V 2, V 3 that is the evaporation occurred from the evaporator. So, by doing the balance of the solid concentration we are getting, what is the amount of L 3, right.

So, F into X F that is L 3 into 0.5 plus V 1 plus V 2 plus V 3 into 0. So, we are getting L 3, putting into L 3 we are calculating V and taking equal V in all the cases. So, we are getting 6048 kg per hour, this is the system.

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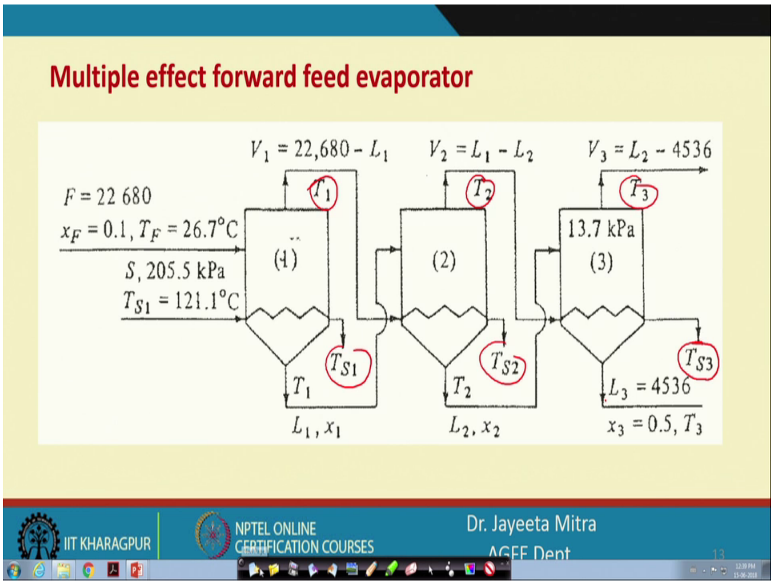

Multiple effect forward feed evaporator

So, third effect we have calculated this L 3 and this is a forward feed evaporator ok. So, we have calculated we need to calculate T S3, T S2 and T S1, we have calculated T 3, now we will calculate T 2 and T 1 how because we need to identify the boiling point elevation in all the effect.

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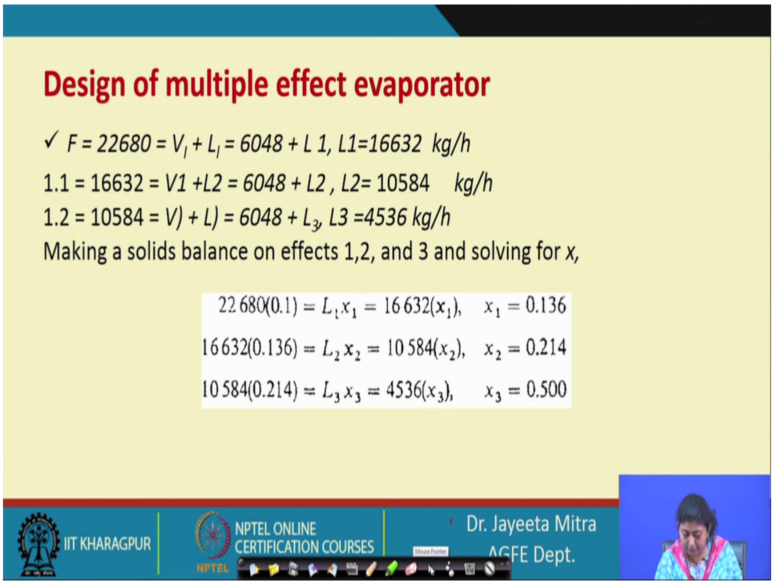

Design of multiple effect evaporator

✓ F = 22680 = $V_l + L_l$ = 6048 + L 1, L1=16632 kg/h

1.1 = 16632 = V1 +L2 = 6048 + L2 , L2= 10584 kg/h

1.2 = 10584 = V) + L) = 6048 + L_3, L3 =4536 kg/h

Making a solids balance on effects 1,2, and 3 and solving for x,

$$22\,680(0.1) = L_1 x_1 = 16\,632(x_1), \quad x_1 = 0.136$$
$$16632(0.136) = L_2 x_2 = 10\,584(x_2), \quad x_2 = 0.214$$
$$10\,584(0.214) = L_3 x_3 = 4536(x_3), \quad x_3 = 0.500$$

So, we will first calculate, what is L 1 and do the balance on L 1 ok.

So, L 1, V 1 plus L 1 equal to 6048 plus L 1, L 1 is this one, now again using that L 1 value L 1 is equal to V 1 plus L 2. So, we will calculate L 2 and then again using L 2 this will be L 1 and this will be L 2, so using that we can calculate. So, this is V 3 and L 3, we can calculate L 3, L 3 is equal to 4536 kg per hour.

Now, making a solid balance on the effect 1, 2 and 3 and solving for x ok, so x will calculate first ok. So, in the first effect 22680 into 0.1 this is the solid, that is L 1, X 1 that will be this L 1 that we are getting 16632 into X 1. So, X 1 is 0.136.

Similarly, X 2 is 0.214 and X 3 is 0.500.

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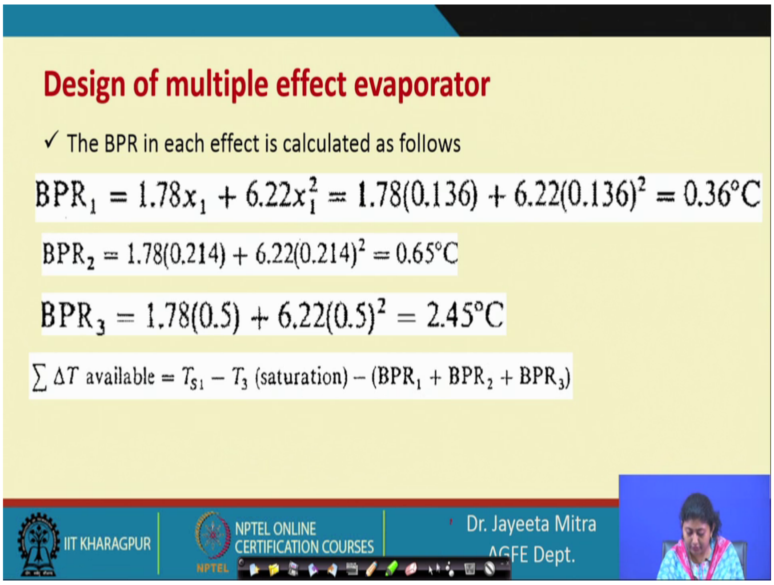

Design of multiple effect evaporator

- ✓ The BPR in each effect is calculated as follows

$$BPR_1 = 1.78x_1 + 6.22x_1^2 = 1.78(0.136) + 6.22(0.136)^2 = 0.36°C$$

$$BPR_2 = 1.78(0.214) + 6.22(0.214)^2 = 0.65°C$$

$$BPR_3 = 1.78(0.5) + 6.22(0.5)^2 = 2.45°C$$

$$\sum \Delta T \text{ available} = T_{S1} - T_3 \text{ (saturation)} - (BPR_1 + BPR_2 + BPR_3)$$

So, boiling point rise will use in this equation to find the boiling point rise in each effect 1, 2 and 3 and finally, delta T available that we are getting that will be T s1 saturation temperature of the steam entering in the first effect minus T 3 that is saturation temperature minus all 3 boiling point rise.

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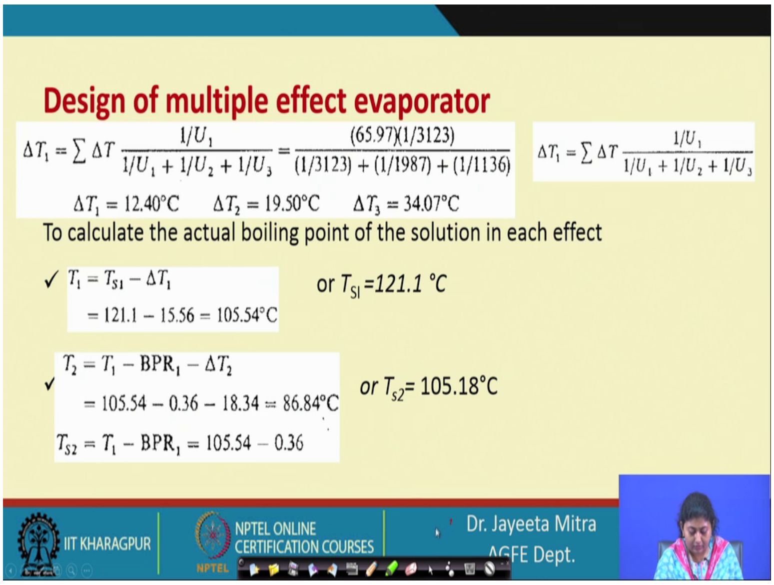

Design of multiple effect evaporator

$$\Delta T_1 = \sum \Delta T \frac{1/U_1}{1/U_1 + 1/U_2 + 1/U_3} = \frac{(65.97)(1/3123)}{(1/3123) + (1/1987) + (1/1136)}$$

$$\Delta T_1 = \sum \Delta T \frac{1/U_1}{1/U_1 + 1/U_2 + 1/U_3}$$

$\Delta T_1 = 12.40°\text{C}$ $\Delta T_2 = 19.50°\text{C}$ $\Delta T_3 = 34.07°\text{C}$

To calculate the actual boiling point of the solution in each effect

✓ $T_1 = T_{S1} - \Delta T_1$

$= 121.1 - 15.56 = 105.54°\text{C}$

or T_{SI} =*121.1 °C*

✓ $T_2 = T_1 - \text{BPR}_1 - \Delta T_2$

$= 105.54 - 0.36 - 18.34 = 86.84°\text{C}$

$T_{S2} = T_1 - \text{BPR}_1 = 105.54 - 0.36$

or T_{s2}= 105.18°C

So, then we know that delta T 1 that is temperature rise in, temperature difference in the first effect will be summation delta T 1 by U 1 by 1 by U 1 plus 1 by U 2 plus 1 by U 3 all these are given values. So, similarly delta T 1 delta T 2 and delta T 3 will calculate ok.

So, to calculate the boiling point of the solution in each effect so T 1 that will be equal to T s1 minus delta T 1 because T s1 at which the liquid has condensate because of the because of the boiling point elevation. So, T 1 will be T s1 minus delta T 1, so 121.1 minus 15.56 that is equal to 105.54.

Now, how we have calculated here 15.56 because here 12.4, 19.5 and delta T 3 is has come 34.07. However, we have considered this after first trial that the temperature higher amount of you know difference we are getting in the first effect. So, that is why we have increased this a bit proportionately and reduce the other temperature drop in the delta T 2 and delta T 3.

So, here T 1 is 105.54 ok, similarly T 2 we have calculated T 2 was T 1 minus boiling point rise minus delta T 2 and that we are getting 86.84. So, T 2 is 86.84 and T s2 will be that is the condensate from the second effect will be T 1. That means, what is entered minus BPR 1 boiling point rise. So, that we are getting 105.18.

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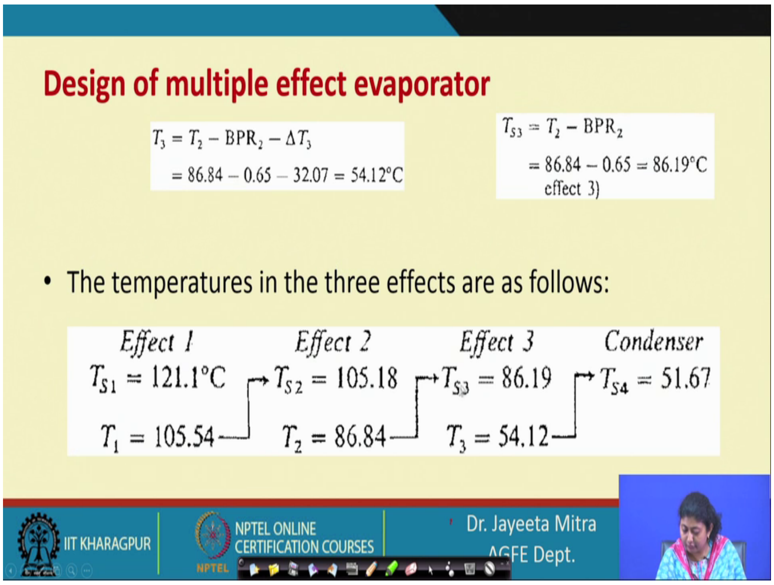

Design of multiple effect evaporator

$$T_3 = T_2 - \text{BPR}_2 - \Delta T_3$$
$$= 86.84 - 0.65 - 32.07 = 54.12^\circ\text{C}$$

$$T_{S3} = T_2 - \text{BPR}_2$$
$$= 86.84 - 0.65 = 86.19^\circ\text{C}$$
effect 3)

- The temperatures in the three effects are as follows:

$$\begin{tikzcd}
\textit{Effect 1} & \textit{Effect 2} & \textit{Effect 3} & \textit{Condenser} \\
T_{S1} = 121.1^\circ\text{C} & T_{S2} = 105.18 & T_{S3} = 86.19 & T_{S4} = 51.67 \\
T_1 = 105.54 \arrow[ur] & T_2 = 86.84 \arrow[ur] & T_3 = 54.12 \arrow[ur] &
\end{tikzcd}$$

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Similarly, for the third effect we have calculated that T 2 that is entered minus boiling point rise minus delta T 3 that is the difference in the third effect. So, T 3 we are getting 54.12 so T 3 that will be that 86.84 minus boiling point elevation 86.19.

The temperature in the three effect, now we have calculated. So, T s 1 that the steam has entered T 1 that vapour that has gone to the next effect as T s2. So, it has been reduced because the boiling point elevation has been deducted then T 2, the effect temperature in the in the second one that is going as T 3 , again boiling point rise has been removed from this value and similarly for the third one.

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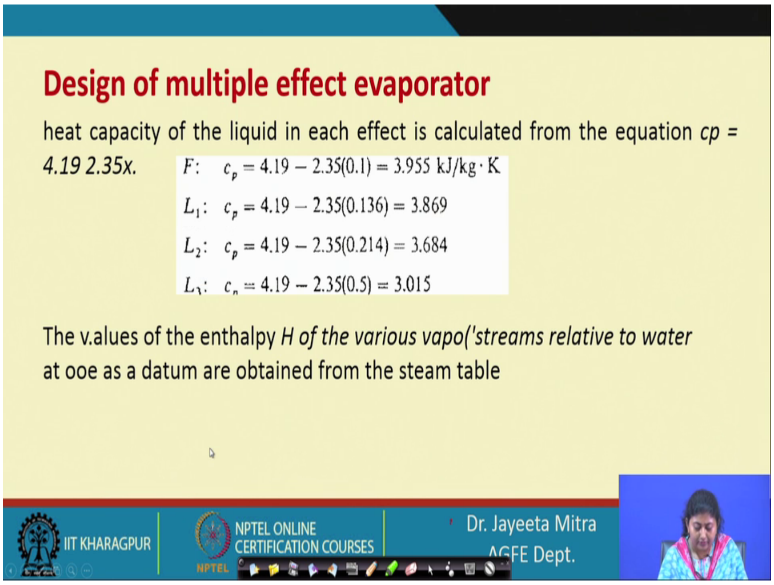

Design of multiple effect evaporator

heat capacity of the liquid in each effect is calculated from the equation *cp = 4.19 2.35x.*

$F: \quad c_p = 4.19 - 2.35(0.1) = 3.955 \text{ kJ/kg} \cdot \text{K}$

$L_1: \quad c_p = 4.19 - 2.35(0.136) = 3.869$

$L_2: \quad c_p = 4.19 - 2.35(0.214) = 3.684$

$L_3: \quad c_p = 4.19 - 2.35(0.5) = 3.015$

The v.alues of the enthalpy *H of the various vapo('streams relative to water* at ooe as a datum are obtained from the steam table

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So, heat capacity again formula is given. So, all the heat capacity we will calculate and will use that 0 datum temperature.

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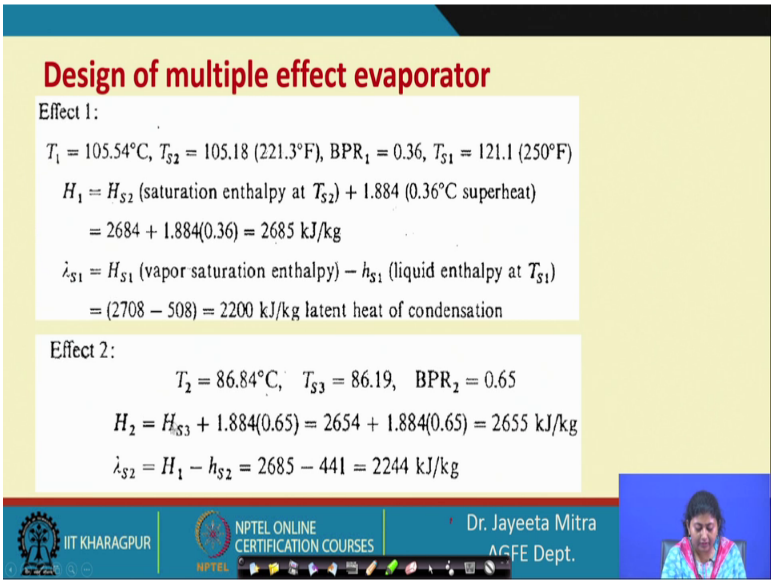

Design of multiple effect evaporator

Effect 1:

$T_1 = 105.54°\text{C}, \ T_{S2} = 105.18 \ (221.3°\text{F}), \ \text{BPR}_1 = 0.36, \ T_{S1} = 121.1 \ (250°\text{F})$

$H_1 = H_{S2}$ (saturation enthalpy at T_{S2}) $+ 1.884$ (0.36°C superheat)

$= 2684 + 1.884(0.36) = 2685$ kJ/kg

$\lambda_{S1} = H_{S1}$ (vapor saturation enthalpy) $- h_{S1}$ (liquid enthalpy at T_{S1})

$= (2708 - 508) = 2200$ kJ/kg latent heat of condensation

Effect 2:

$T_2 = 86.84°\text{C}, \quad T_{S3} = 86.19, \quad \text{BPR}_2 = 0.65$

$H_2 = H_{S3} + 1.884(0.65) = 2654 + 1.884(0.65) = 2655 \text{ kJ/kg}$

$\lambda_{S2} = H_1 - h_{S2} = 2685 - 441 = 2244 \text{ kJ/kg}$

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To make all the heat balance in the first effect, second effect and third effect. So, in the first effect H 1 that is the enthalpy that is equal to H s2 saturation enthalpy at T s2 plus 1.884 into the boiling point rise because, it has become superheated so that we will include.

So, H 1 we have calculated. So, lambda S1 will be H s1 that is the vapour saturation enthalpy minus H s1 that is the liquid enthalpy ok. Effect 2 we are getting 86.84 that is T 2, T s3 is 86.19, boiling point rise is 0.65. So, H 2 that is enthalpy will be the saturation enthalpy plus the because of the boiling point rise 1.884 into 0.65.

So, that is H 2 the steam that is entering again lambda s2 that we have calculated in the second effect. So, like this heat transfer in all such effects we have calculated.

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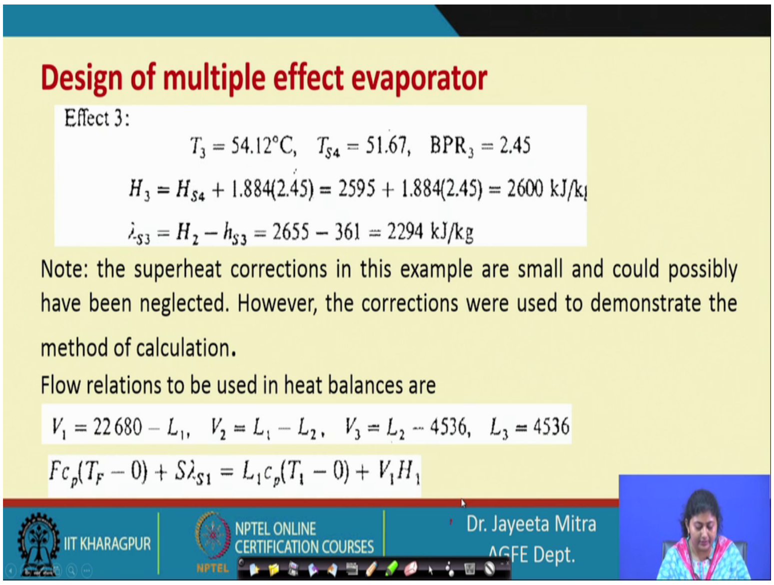

Design of multiple effect evaporator

Effect 3:

$$T_3 = 54.12°C, \quad T_{S4} = 51.67, \quad BPR_3 = 2.45$$

$$H_3 = H_{S4} + 1.884(2.45) = 2595 + 1.884(2.45) = 2600 \text{ kJ/k}$$

$$\lambda_{S3} = H_2 - h_{S3} = 2655 - 361 = 2294 \text{ kJ/kg}$$

Note: the superheat corrections in this example are small and could possibly have been neglected. However, the corrections were used to demonstrate the method of calculation.

Flow relations to be used in heat balances are

$$V_1 = 22\,680 - L_1, \quad V_2 = L_1 - L_2, \quad V_3 = L_2 - 4536, \quad L_3 = 4536$$

$$Fc_p(T_F - 0) + S\lambda_{S1} = L_1c_p(T_1 - 0) + V_1H_1$$

And using that enthalpy finally, we can calculate that V 1, V 2, V 3 that all the effect what we are getting right.

So, this way doing the overall balance, solid balance and enthalpy balance.

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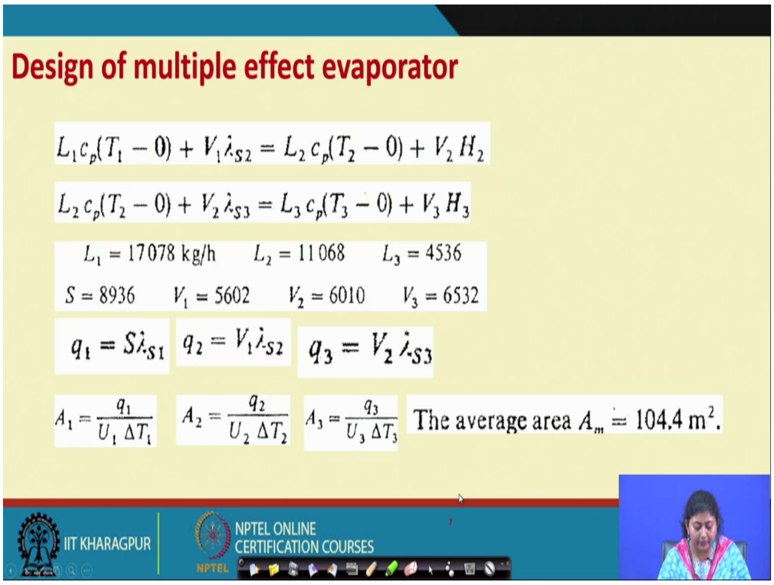

Design of multiple effect evaporator

$$L_1 c_p(T_1 - 0) + V_1 \lambda_{S2} = L_2 c_p(T_2 - 0) + V_2 H_2$$

$$L_2 c_p(T_2 - 0) + V_2 \lambda_{S3} = L_3 c_p(T_3 - 0) + V_3 H_3$$

$L_1 = 17078$ kg/h $\quad L_2 = 11068 \quad L_3 = 4536$

$S = 8936 \quad V_1 = 5602 \quad V_2 = 6010 \quad V_3 = 6532$

$q_1 = S\lambda_{S1} \quad q_2 = V_1\lambda_{S2} \quad q_3 = V_2\lambda_{S3}$

$A_1 = \frac{q_1}{U_1 \Delta T_1} \quad A_2 = \frac{q_2}{U_2 \Delta T_2} \quad A_3 = \frac{q_3}{U_3 \Delta T_3}$ The average area $A_m \doteq 104.4$ m^2.

We can calculate the total vapour that is generated and also calculate the total heat transfer area, ok. So, once we got all the values of steam we can calculate the q 1, q 2, q 3 that is the heat transfer and find out the area A 1, A 2, A 3 ok. So, if the area are almost equal within the 10 percent variation our iteration stops here, so.

Thank you. We will stop here.