Fundamentals of Food Process Engineering

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Lecture – 19
Evaporation and Concentration (Contd.)

Hello everyone, welcome to the NPTEL online certification course on Fundamentals of Food Process Engineering. We will continue today with the topic of Evaporation and Concentration. In the previous classes of this particular chapter we have discussed that what are the different types of evaporators?

And what kind of evaporators is typically used for what kind of application; we have discussed a bit of that. And also we have discuss the boiling point elevation in the last class and single effect evaporator, multiple effect evaporator. And basically what are the different way by which we can increase the effectiveness in the evaporator ok.

So, today we will actually solve few numericals, we will see how we can we can determine we can calculate the heat and mass balance in evaporator and find out steam economy or effectiveness etcetera ok. So, let us starts with those topics.

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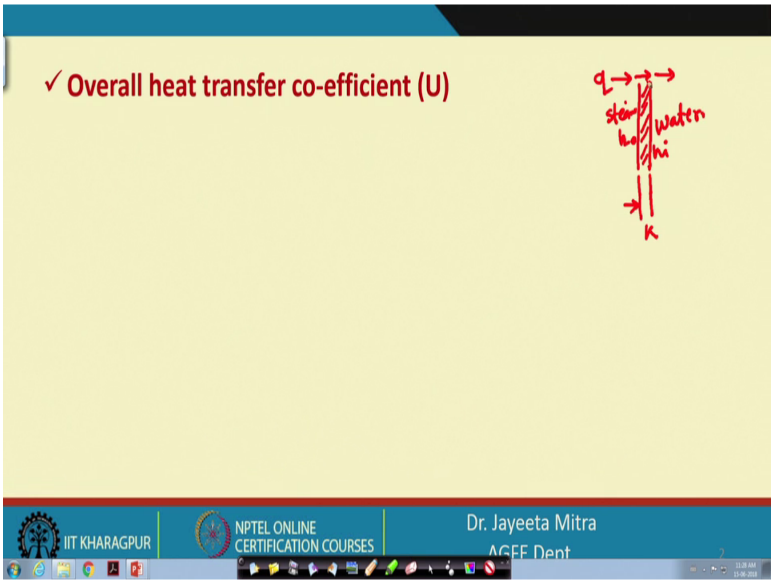

So, the first thing we need to know when we start problem solving is overall heat transfer coefficient. Overall heat transfer coefficient to give you an understanding because you might have learn this in your heat transfer courses; that if there are multiple or series of phases are there through which heat is being transferred; so, every section offers certain resistance to heat transfer right.

And when we are analyzing them together, we call them the overall heat transfer coefficient. So, overall heat transfer coefficient includes the conductive conductivity and also the effect of convective heat transfer. Say for example, if your; you know surface if you have a surface like this which is actually a metal that is the; that is separating 2 steams here let us say in one side there is steam and the other side maybe water ok.

So, in water side the heat transfer convective heat transfer coefficient will be there; let us say h o, then heat has to be conducted through this wall where the conductivity is k and in the inner side where the water is there. So, let us say there the convective heat transfer coefficient is h i, where heat q is being transferred across it.

So, we will see now how we take the value of overall heat transfer coefficient ok.

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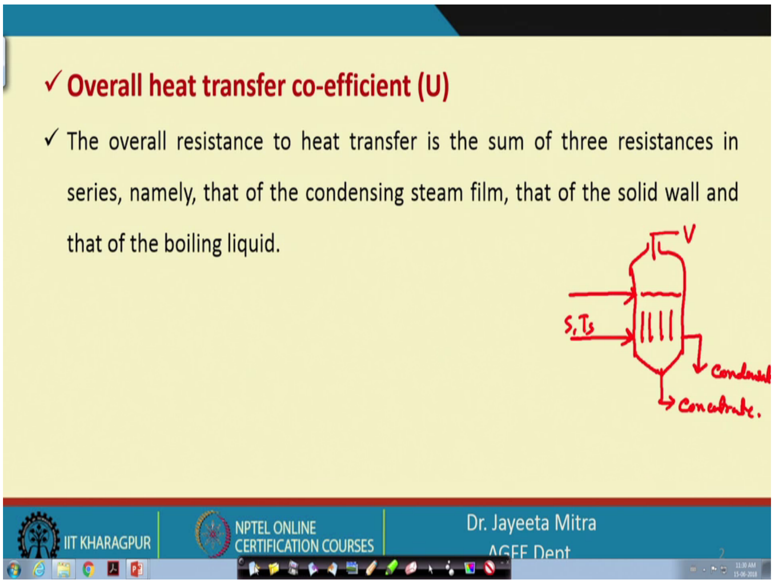

So, the overall resistance to heat transfer is the sum of 3 resistances in series; namely that of the condensing steam film, that of the solid wall and that of the boiling liquid. Because in evaporator we have we have seen that from the very starting of discussion related to evaporator; that there is if we can take this kind of an evaporator, where steam is coming and steam is getting condensed and feed which is coming into the evaporator.

So, there it is being boiled and the concentrate is coming out from the bottom, vapour is going out from the top. So, the steam which is coming it is being condensing; so, condensing over a surface we have seen that there are may be short tube evaporators or vertical long tube evaporators or simply jacketed kind of open pan evaporator.

So, any kind of evaporator there the steam condenses in one side of a surface and the liquid that is being evaporated and subsequently concentrate solution will be prepared; so, that is in the other side ok. So, that is why in series we have to take the condensing steam film and the resistance of the solid wall and that of the boiling liquid.

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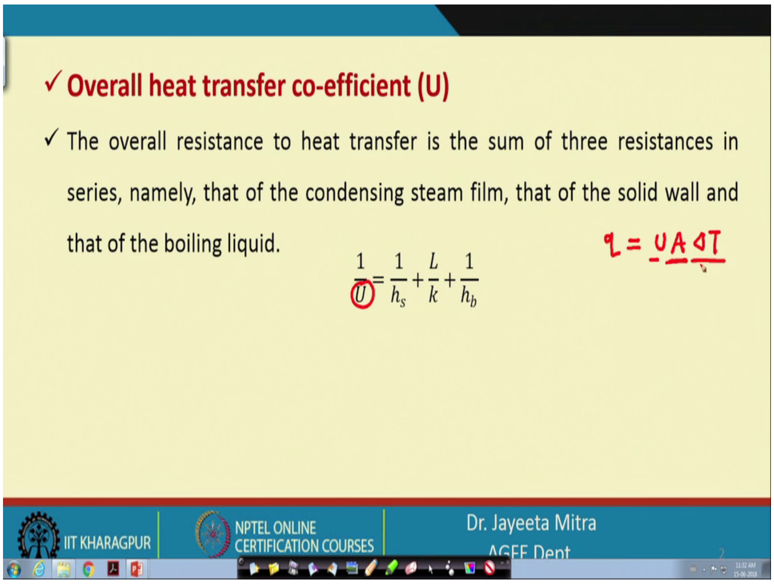

So we can write in this way that 1 by U, where U is the overall heat transfer coefficient in the combined system that is equal to 1 by h s; that is the heat transfer coefficient convective heat transfer coefficient in the steam side plus L by k.

So, L is the thickness of the surface or thickness of the wall ok, k is the conductivity thermal conductivity of the material. Suppose we are using stainless steel and the thickness is very small let us say 2 mm, 3 mm like that. So, we will take the thickness divided by the thermal conductivity plus 1 by h b; where h b is the convective heat transfer coefficient of the boiling liquid ok.

So, this is how we can calculate the overall heat transfer coefficient and ultimately we know that in the heat transfer we might have read this that q; the total heat transfer will be U A delta T where A is the area surface area of evaporator or surface area of a transfer, U is this overall heat transfer coefficient and delta T is the temperature difference that is you know across which the heat transfer is happening or occurring.

So, this is basically the difference between the steam that is condensing and the liquid that is boiling. So, that 2 temperature difference is designated by delta T.

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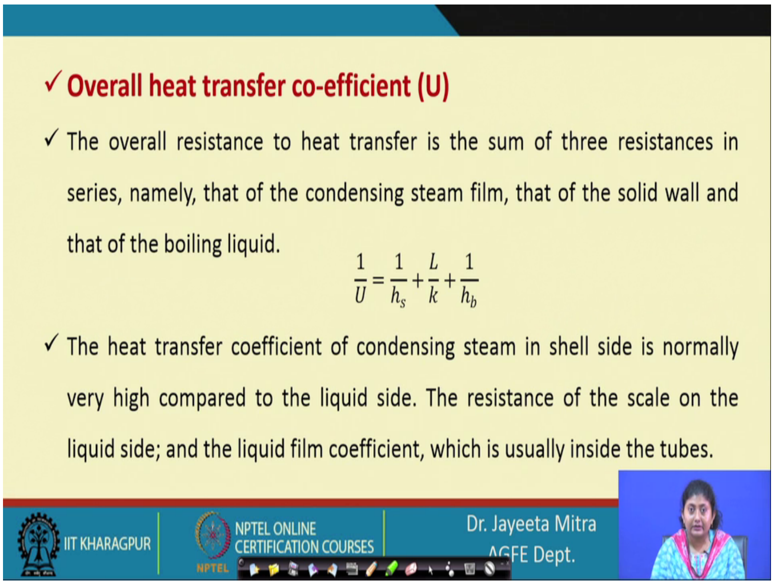

So, the heat transfer coefficient of condensing steam in shell side is normally very high compared to the liquid side ok. So, that is why because we might have; we can check this like when the steam is entering steam is coming at a temperature, let us say T S generally we use saturated steam or sometime superheated steam mostly we use saturated steam; so, at that saturation temperature the latent heat of condensation that we will measure.

So, we have seen that the heat transfer coefficient that is h S of the condensing steam is normally very high compared to h b; which is the convective heat transfer coefficient in the boiling liquid side. The resistance of the scale on the liquid side and the liquid film coefficient which is usually inside the tube; now what is this? Resistance of the scale.

Now since we are using evaporators to concentrate the dilute solution ok. So, some time what happen that these dilute solutions when they become concentrated, deposition of the solid material in the form of scale happens on the surface where the heat transfer occurs. So, because of that there is a you know resistance generate because of this scale deposition; unless we clean them properly time to time. So, that will offer a resistance in the in the liquid side of the system of the evaporator. So, because of scale deposition again the heat transfer will be reduced.

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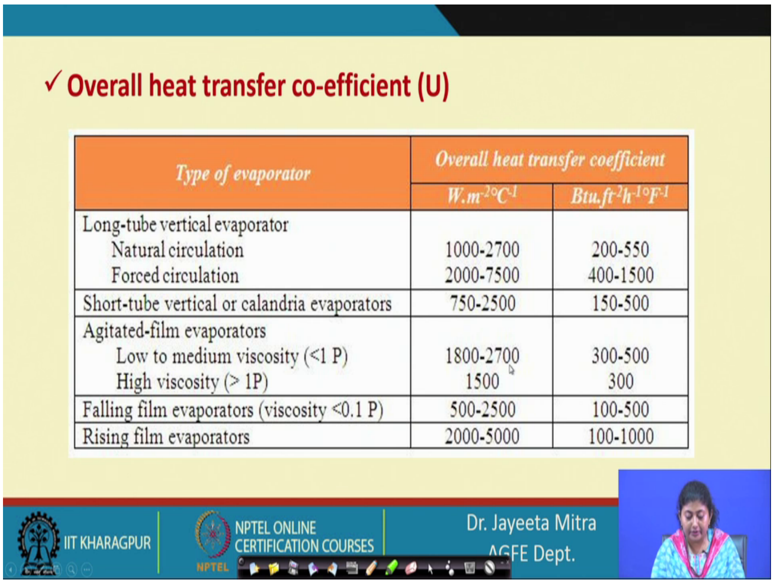

So, we will see now that few typical values of overall heat transfer coefficient; so, you will get them in the books also. So, we will see that long tube vertical evaporator; long tube vertical evaporator if we consider the, their natural circulation; that is the liquid which is coming by natural gravitational flow we are not using any pump over there.

So, in that case the overall heat transfer coefficient is 1000 to 2700 watt per meter square degree Celsius. And if forced circulation evaporators we will see long tube vertical evaporators with forced circulation, then the overall heat transfer coefficient will vary from 2000 to 7500 watt per meter square degree Celsius ok.

If we use short tube vertical or calandria evaporators, there 750 to 2500 watt per meter square meter square degree Celsius is the overall heat transfer coefficient value and again if we consider agitated film evaporators. Agitated film evaporators where the low to medium viscosity liquid we are using; viscosity is less than 1 poise. Then overall heat transfer coefficient can be used in between this range that is 1800 to 2700 watt per meter square degree Celsius. And for high viscous, high viscous solution we will use 1500 watt per meter square degree Celsius.

So, because it is obvious that in case of high viscous sample; it is very you know difficult to transfer heat; even if we employ agitation in between them to increase the heat transfer coefficient. Falling film evaporator where viscosity is less than 0.1 poise; they are 500 to 2500 watt per meter square degree Celsius. And rising film evaporators; the overall heat transfer coefficient values vary from 2000 to 5000 watt per meter square degree Celsius.

So, based on the requirement like when we use very heat sensitive liquid fruit juices etcetera. So, that time we use the short tube evaporators when we use material which is not that much heat sensitive; we can use long tube vertical evaporator. So, based on our requirement we can choose the different kind of evaporators.

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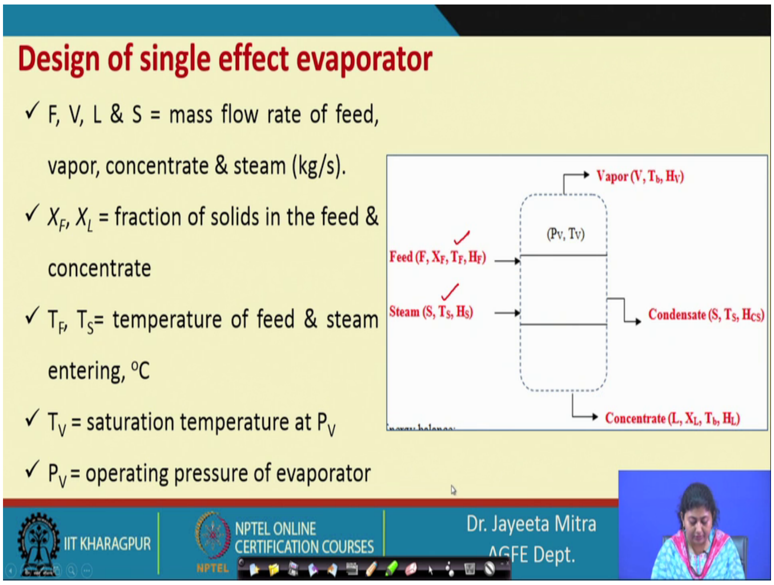

Now coming to the design of single effect evaporator; so, let us see first what is the functions or mechanism that will happen in a single effect evaporator. So, in a single effect evaporator; that means, only one evaporator effect or chamber is there in that steam is entering ok.

So, steam is entering at temperature T S and having the enthalpy H S and this steam will condense here inside the evaporator and the condensate which is coming out at a temperature T S and having the enthalpy HCS; whereas the feed which is entering at T F temperature and this feed because this is a dilute solution any maybe milk or any fruit juices etcetera. So, that will going to going to be evaporated; water will be evaporated from here and concentrated juice will come out from the bottom. So, that feed will separate into 2 steam; one is the concentrate and another is the vapor that is coming out.

Now, this particular effect; this single effect will operate at a constant pressure P V and based on this constant pressure P v; the saturation temperature or boiling point that we can see from the steam table. So, from this steam table which is the actually the property table for the saturated water vapor; we can calculate or we can see this value of temperature T V corresponding to pressure P V.

Now F which is the feed; mass flow rate of the feed in kg per second V which is the vapor mass flow rate of the vapor in kg per second, L which is the mass flow rate of the concentrate, which is coming out from the evaporator also in kg per second. And we have S which is the steam ok; so, this steam is also the flow rate of the steam in kg per second.

So, we can observe that the steam that is entered same amount of the steam is coming out; only the latent heat of condensation is being provided across the heat transfer surface in the single effect evaporator. And that heat is being taken by this feed and vapor V kg per second which is coming out and eventually the remaining steam has become concentrated. So, the concentration X F concentration of the solid in the feed was definitely lower than the concentration of solid in the concentrate that is coming ok.

So, X F X L those are the fraction of solid in the feed and concentrate then T F, T S ok. So, T F T S these are the temperature of feed and steam which is entering into the single effect evaporator; both are in degree Celsius we can have them in degree Kelvin as well T V as I said that saturation temperature at pressure P V and P V is the operating pressure of evaporator.

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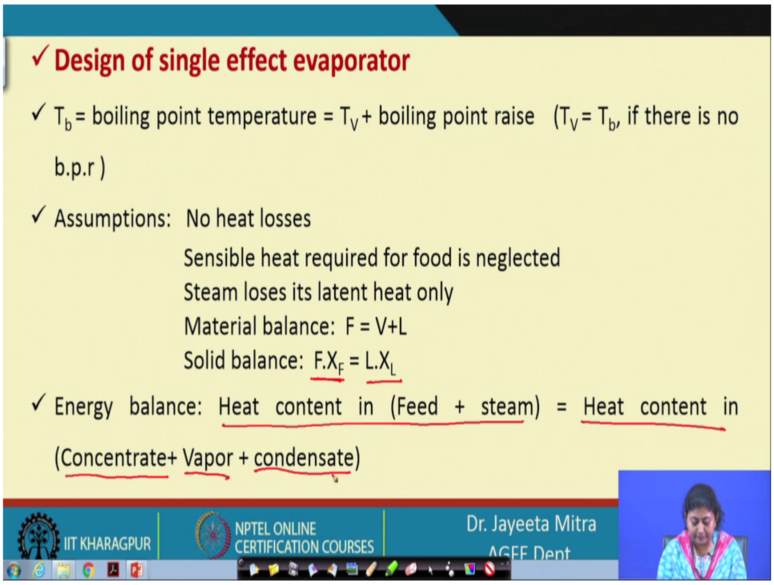

Now as I said that in the as I said in the previous slide that there will be a temperature T V that will be corresponding to the vapor pressure prevailing in the evaporator chamber that is P V. Now we have learned then there may be boiling point elevation because of increase in the concentration of the solid in the solution.

So, now we will see that what will happen if there is boiling point raise in the chamber in the in the solution. So, what will happen? That T b, T b is the boiling point temperature that will be actually T V that is the saturation temperature at P V plus the boiling point raise ok. So, boiling point will be elevated or increased ok; so, if there is no boiling point elevation then T V will be equal to T b.

So, then before solving this we will have certain assumption that we will assume there will be no heat loss; that means, whatever heat the steam is supplying by condensing. So that the total heat will be utilized by the solution that is the feed to be evaporate and to become concentrated ok; so, there is no heat loss.

And also we can consider that if the feed that is entering in the effect is close to the saturation temperature or the boiling point temperature corresponding to the pressure that is inside the evaporator. So, we can consider the sensible heat requirement as negligible; now since we have considered that steam losses it is latent heat only and first we will look into the material balance that is F the feed which will be giving us 2 steam vapor and liquid the concentrated liquid.

Now, making the solid balance over the evaporator what we are getting is F into e x that is the total; F into X F total solid in the feed that will be coming with the concentrate. So L into X L because there is no solid going into the vapor right; so F into X F equal to L into X L. Now making the energy balance or heat balance what we are getting that heat content in feed that is entering plus steam ok. So, total heat that has entered will be equal to total heat that has come out. So, that is heat content in the concentrate in the vapor that is gone out of the evaporator and condensate right.

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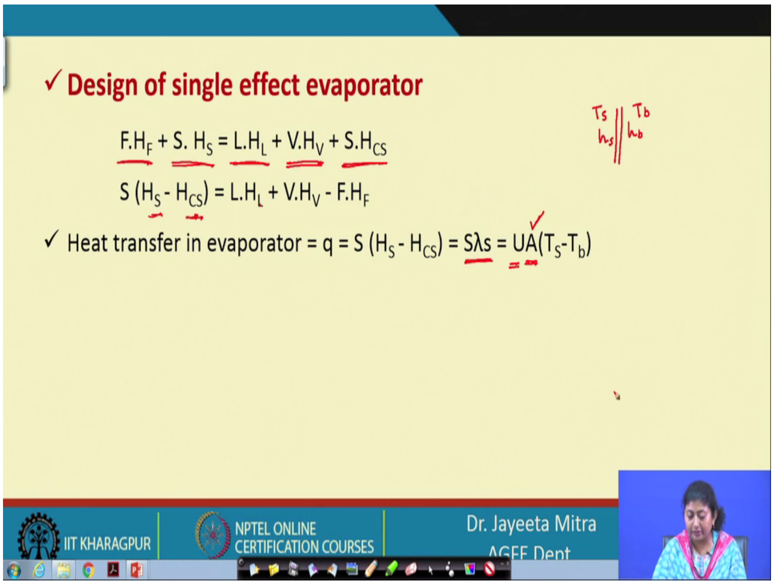

So, what will be that? F into h F that is the energy or heat content in the feed steam H F is the enthalpy and F is the feed rate; S into H S that is the enthalpy of the steam that is entered L into h L that is the enthalpy in the concentrate, V into h V that is the enthalpy of the vapor which has come out of the evaporator and finally, the enthalpy of the condensed steam ok.

So, we can again take steam in this side; so S into H S minus H CS. So, this is enthalpy of the liquid steam at the temperature of the steam at which it is entered and this H S is the enthalpy of the saturated steam at T S temperature. L into H l; so here enthalpy H L at temperature that is saturation temperature inside the evaporator V into H V again the enthalpy of the vapor at the temperature of at which the boiling has occurred, minus F into H F; so this is the this is at feed temperature T F at which it has entered ok.

So, heat transfer in the evaporator is actually q that is S that is flow rate of the mass flow rate of steam into H S minus H C S that is can be written as S into lambda S ok. Now this is the this is the heat that is being transferred in the evaporator and it is transferred through the area A in that again the series system, where there is a there is a surface which is the thickness of the heat transfer surface; one side there is steam and the other side there is boiling liquid fine.

So, we have calculated the overall heat transfer coefficient U, the surface area A and the difference in the temperature will be would be T S which is because of steam and T b which is the boiling liquid ok. So S into lambda s that is equal to UA; T S minus T b; so, calculating this A, we can find out what will be the area requirement of the evaporator; that means the size of the evaporator.

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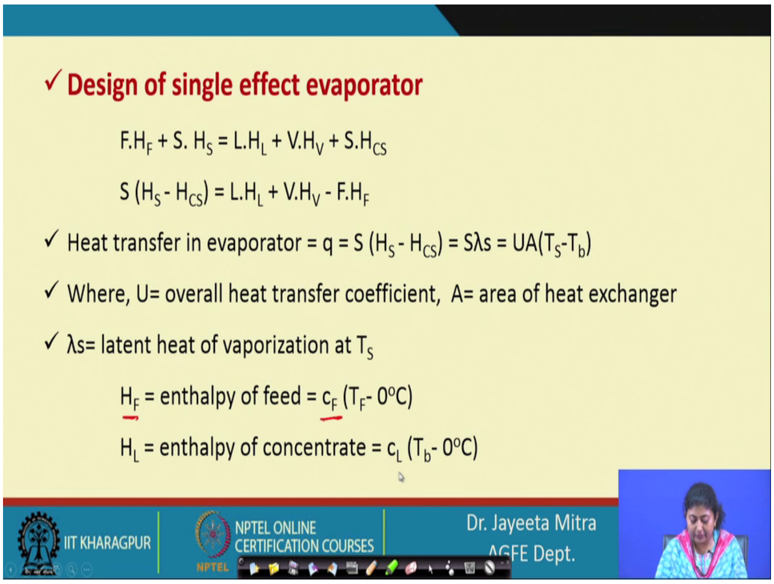

So U is the overall heat transfer coefficient, A is the area of heat exchanger and lambda s which is the latent heat of vaporization at T S ok. So, saturated; so lambda s lambda s that we are getting H S minus H CS; so, saturation vapor enthalpy is capital H suffix S and this H CS is the enthalpy of the liquid at the temperature.

So, latent heat of vaporization we are getting and enthalpy of the feed. Now how we can calculate enthalpy of the feed? We need to know another property that is specific heat ok; specific heat that is the heat required for per unit mass of the product to increase the temperature by 1 degree Celsius. So, c F into T F minus 0 that is giving me the H F or enthalpy of the feed; H L is the enthalpy of the concentrate.

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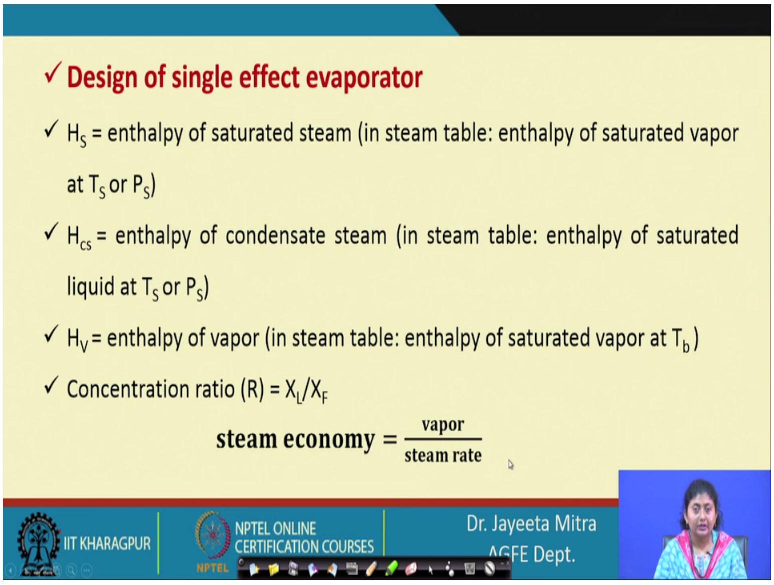

So again we will calculate the c L that is ; sorry. So, we will calculate the we will calculate the specific heat of the concentrate and T b minus 0; we have taken we are taking here 0 as the base temperature or data. So, T F also we have taken with the base of 0 and T L that is the concentrate we also take with reference to 0. So, this is the enthalpy of both the steam and yeah H S and H CS we have already explained; H V is the enthalpy of vapor ok.

So enthalpy of saturated vapor at T b that is the boiling point corresponding to the pressure inside the evaporator; now concentration ratio R; so, concentration ratio; that means, how much we have concentrated from the initial concentration? So, X L divided by X F; so this is the concentration ratio.

Now steam economy that is how much steam we have utilized and what amount of steam we have generated ok; that means, we have evaporated that much water from the liquid ok. So, economy or effectiveness we always calculate based on what we are getting divided by what we have given to the system or what is the input to the system ok. So, the vapor that is been evaporated from the liquid steam divided by the steam, the rate of steam that we have entered into the evaporator will give us the steam economy of the evaporator.

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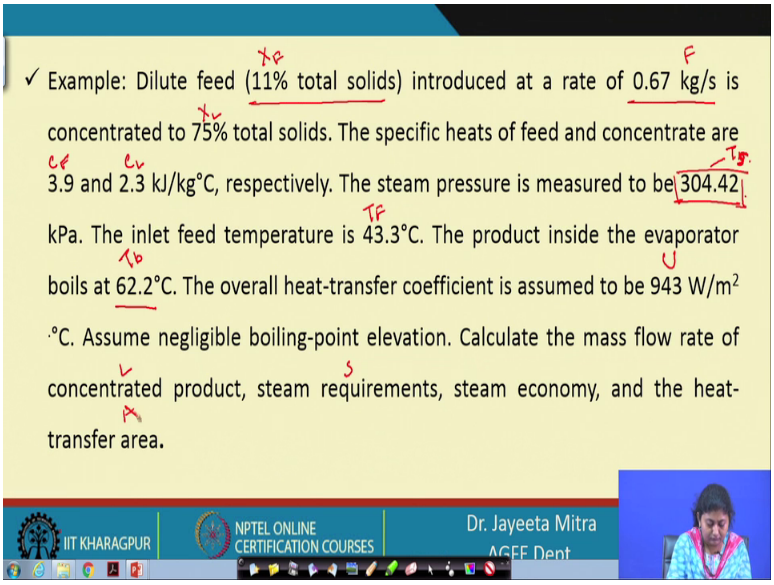

Now, we will quickly look into one problem that is single effect evaporator problem; dilute feed 11 percent total solid ok; 11 percent total solid introduced at a rate of 0.67 kg per second; this is the feed F which is the feed rate, concentrated to 75 percent solid.

So, this is our X L, this is our X F the specific heat of the feed and the concentrate are 3.9 and 2.3 ok. Feed and concentrate; so this is feed, so this is c F and this is our c L specific heat of feed and concentrate 3.9 and 2.3 kilo joule per kg degree Celsius respectively; the steam pressure is measured to be 304; 304.42 kilo Pascal. So, we what we need to know is at 304 kilo Pascal we will refer steam table to identify what will be the T b or saturation vapor saturation temperature at this pressure.

The inlet feed temperature is 43.3; so this is our T F, the product inside the evaporator boils at 62.2 degree Celsius ok sorry. So, here we have we have to do one correction where 304; this is actually T S steam pressure. So, steam pressure are given; so T S is not given. So, this is actually T S right T S and here the feed temperature is given and the evaporator temperature is 62.2.

So, this will be our T b overall heat transfer coefficient is assumed to be U that is 943 watt per meter square degree Celsius; assume negligible boiling point elevation. Calculate the mass flow rate of concentrated product steam requirement; S. So, we need to calculate L, S steam economy and heat transfer area a ok.

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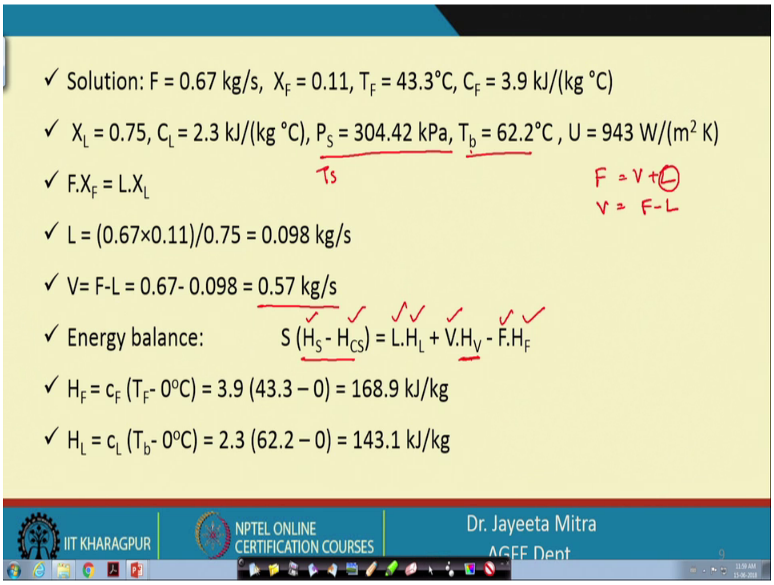

So, what we will do is; first we have noted down what we have already have this data ok. Now this is important that pressure of the steam is given; so from the steam table we will find out what is the saturation temperature T S; T b is given that is the you know inside the evaporator what is the temperature; boiling temperature U is given also. So, F into X F, L into X L this balance we need to know to find the L that is the mass flow rate of the concentrate ok.

Because feed is given to us X F and X L that is the concentration of the solid in the feed and the concentrate is given. So, we can calculate L first; so L is coming 0.098 kg per second. So, what will be V then? Ok s we know that F this steam is equal to V plus L we have calculated first L; so V will be simply F minus L; so, that is 0.57 kg per second.

Then coming to the energy balance or heat balance; so, we know that the latent heat of the steam into S that is the steam mass flow rate of the steam that will be equal to L into H L plus V into h V minus F into H F. So, all the mass flow rate multiplied with their respective enthalpies. So, H F will be what? We know that c F into T F minus 0 c F is the specific heat that is given 3.9, T F is also given 43.3 minus 0; so 168.9 joule per kg.

Similarly we will calculate H L, c L into T b minus 0; 2.3 into 62.2 minus 0; so, 143.1 kilo joule per kg ok. So, we know F, we have calculated H F, we know V and we know L and H L right, we also know this H V from the steam table we can get this one and we can also get this and this from the steam table. So, putting all the values here because this is coming from the latent heat of condensation and this is coming because vapor is generated at a temperature of T b. So, what is the enthalpy at the temperature, we can get from the steam table.

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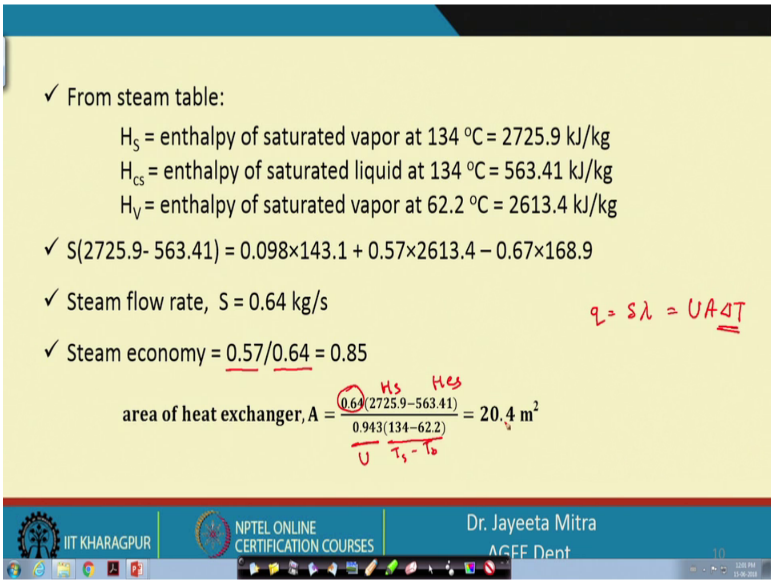

So, H S is the enthalpy of saturated vapor at 134 degree Celsius that is 2725.9; enthalpy of the saturated liquid we are getting H V is the enthalpy of saturated vapor at 62.2 that is T b. And also putting all this value we can calculate the value of S that is 0.64 kg per second.

So, steam economy will be what? The vapor that is evaporated is 0.57 kg per second and the steam that is being used is 0.64; so, steam economy is 0.85 ok. So, we can see that since it is a single effect evaporator, we cannot get economy higher than 1; however, if we use multiple effect evaporator; that means, the same vapor if we used to evaporate liquid from the concentrated solution in the next effect and eventually in the third effect as well ; so, the vapor that is the water evaporated from the liquid from the same amount of steam utilization will increase. Therefore, steam economy for the multiple effect will be always greater than 1..

Now area of the heat exchanger will be; so, we know that the equation that we have seen q is equal to S into lambda that is equal to U A delta T ok. So, here the delta T that is this one, the steam that is entered minus T b that is the boiling temperature inside the evaporator ok, this is the value of U, A we are calculating. And here rate of mass flow rate of steam is 0.64 kg per second and this is the value of H S minus H CS; so we are getting the area as 20.4 meter square.

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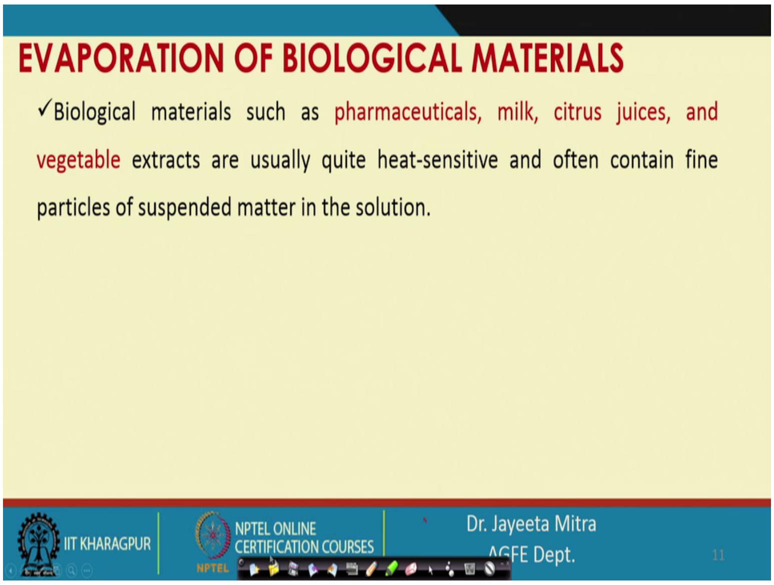

So we will stop here; we will continue in the next class.

Thank you.