Process Equipment Design
Prof. Shabina Khanam
Department of Chemical Engineering
Indian Institute of Technology – Roorkee

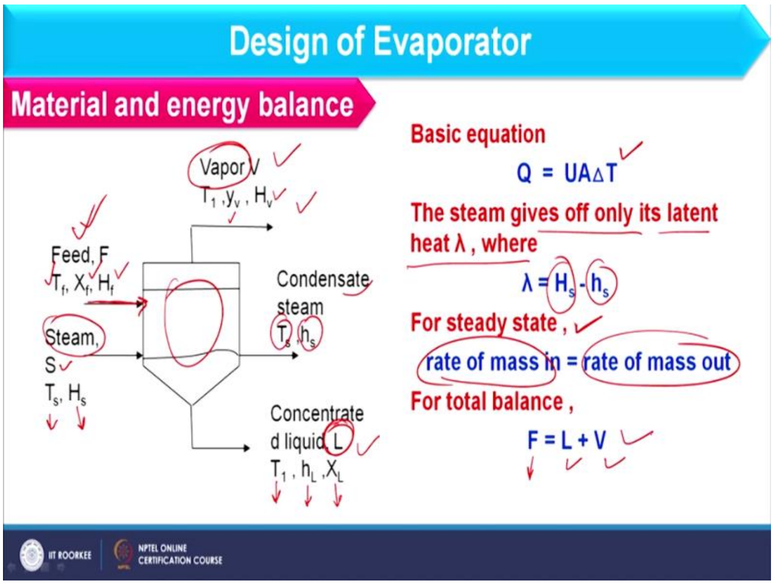
Lecture –35
Design of Evaporator-2

Hello everyone. This is the 5th lecture of 7th week of the course Process Equipment Design and overall it is 35th lecture and I welcome you all in this lecture and here we are discussing design of evaporator. So, this topic we have started in last lecture where we have introduced the evaporator, we have seen the application of the evaporator and we also have seen different types of evaporator.

And in this lecture we will discuss design of evaporator. So, as far as design of evaporator is concerned what is the meaning of this? The meaning of designing is we have to find out heat transfer area as well as we have to compute steam consumption. So, for doing this first of all we have to understand the basic model for evaporator. Basic model means how the government equations which are associated with an evaporator can be derived.

So, first of all we should focus on derivation of governing equation of an evaporator. So, these governing equations can be obtained based on conservation laws like material and energy balance.

(Refer Slide Time: 01:48)



So, let us see how to make energy and material balance around an evaporator. So, if you see here I am having an schematic where this is basically one effect. And if I am saying one effect, I am assuming that you understand that it contains heat exchanger, vapour liquid separator as well as recirculation pipe. So, in this effect feed is entering at temperature Tf concentration Xf and it contains total heat with it as Hf.

So, when this feed is entering into the effect vapour is generated which is v and concentrated liquid is generated which is denoted as L. So, vapour is available at T 1 temperature and Yv is basically the concentration of the vapour and Hv is the enthalpy of the vapour. In the similar line, liquid is also available at T 1 includes hL enthalpy and having concentration like XL.

Now, as far as heating media is concerned we used steam with the flow rate of S temperature Ts and enthalpy as Hs and condensate is coming out at Ts and it contains enthalpy Hs. Now as far as heat balance is concerned we have two equation. First is the enthalpy balance where I am using mCpdT and m lambda and second is the rate equation where Q = UA delta T mean.

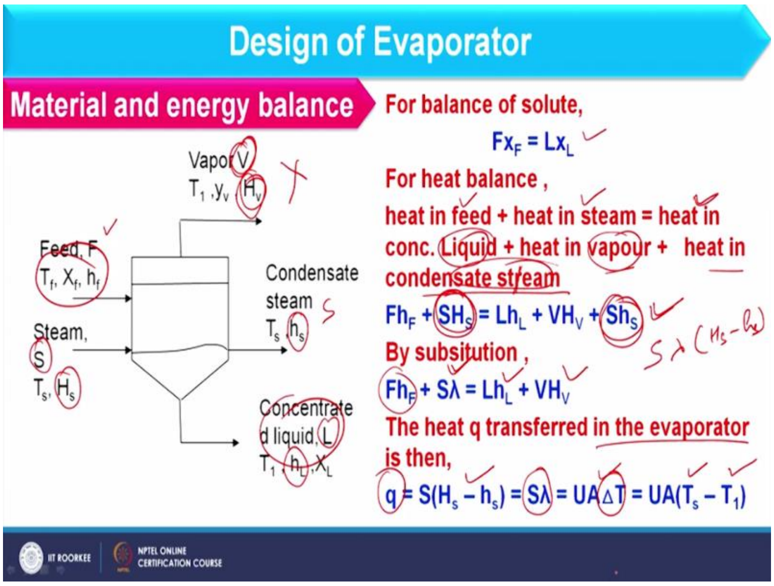
So, basic equation we have is Q = UA delta T. The steam gives off only its latent heat. So, latent heat is nothing, but the enthalpy of vapour minus enthalpy of liquid. Now, if I ask you why the enthalpy of vapour contains latent heat as well as sensible heat. So, the answer lies that how this vapour is generated. Let us say if I speak about steam, how the steam is generated? That steam is being generated using water.

So, usually water is available at room temperature. When we have to generate the steam it is initially preheated up to the desired temperature. Let us say if I am considering one atmosphere pressure so boiling point at that pressure is 100. So, first of all we have to preheat the water from 25 to 100 degree Celsius. So, during this heating up it takes sensible heat and after that phase change will occur.

So, when the phase change will start it is already having sensible heat and when the phase change will occur it also includes latent heat. Therefore, enthalpy of vapour is equal to enthalpy of liquid plus latent heat. So, further at steady state we can make the balance as rate of mass in should be equal to rate of mass out and therefore the total mass balance will be F =

L + V because whatever vapour is generated that will be the part of feed only and after generating vapour liquid L leaves the system. So, F should be equal to L + V.

(Refer Slide Time: 05:41)



Further, if I am making the component balance I am assuming that vapour is solute free whatever vapour is generated it is not including any solute so Yv value should be 0. So, if I am considering this what is the meaning of that whatever component is available in the feed the complete component is available now in the product. So, component balance says that F XF should be equal to L XL.

So, we are considering this as well as this stream and neglecting this steam. So, further for heat balance what terms we can consider these terms are basically heat in the feed plus heat in the steam should be equal to heat which is associated with the exit streams and these are liquid, vapour and condensate stream. So, heat in the concentrated liquid plus heat in vapour plus heat in condensate steam this is steam not stream.

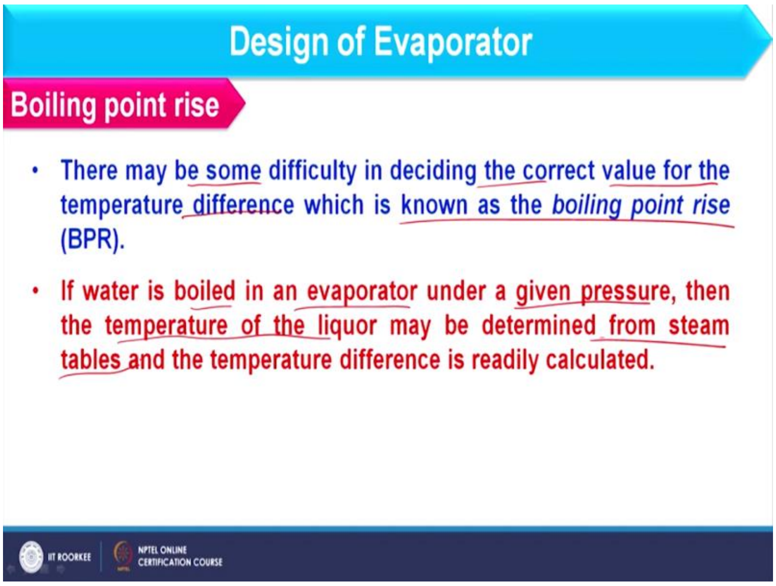
So, when you make the balance it is like F hF. So, if I make the balance that first term should be F hF plus S Hs that should be equal to V HV and S Hs and L hL. So, in this way we make the balance and we can have all 5 terms over here. Now, if I consider this as well as this we can simply write this as S into lambda because that lambda is equal to Hs – Hs. So, here I am writing that S into lambda F hF is there should be equal to L hL and V HV.

And further as far as heat transfer is concerned from steam side to liquid side we can make the balance as q which is basically the total heat duty in an evaporator. It is equal to S Hs –

small hs and that should be nothing, but S lambda and that should be equal to UA delta T and what is delta T that is basically the steam temperature minus effects temperature. So in that way we make the mass balance as well as material balance inside the evaporator.

And these balances we will use to design the evaporator, but before start design of an evaporator we should focus on boiling point rise and this point we have also discussed in the last lecture and here we will consider few more points about this.

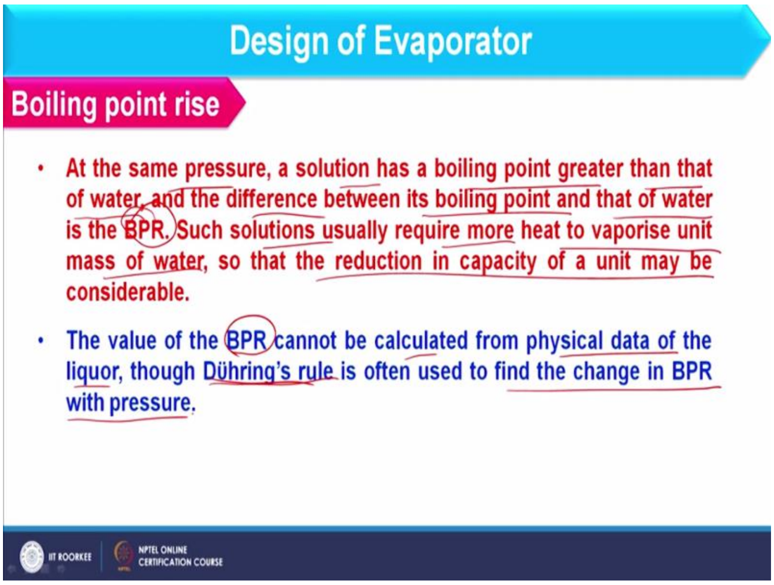
(Refer Slide Time: 08:56)



And these are basically there maybe some difficulty in deciding the correct value for temperature difference which is known as the boiling point rise. So, if water is boiled in an evaporator under a given pressure then the temperature of liquor can be determined from steam table because what is boiling point rise? It is basically temperature at which solution boils minus the temperature of pure solvent.

So, usually we consider water as a solvent in evaporator. So, pure water boiling point you can obtain corresponding to a particular pressure from steam table directly.

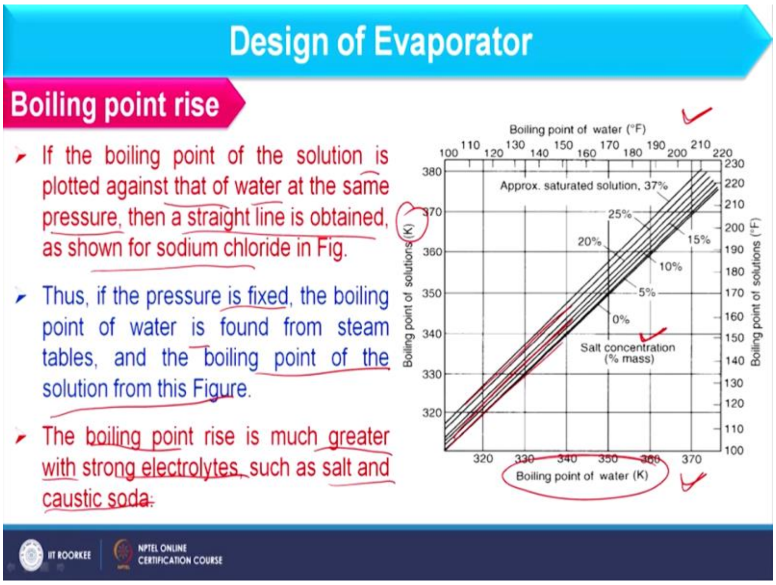
(Refer Slide Time: 09:45)



And at the same pressure a solution has a boiling point greater than that of the water and this is because the solution has lower vapour pressure in comparison to pure compound. So, it takes more and more heat to start boiling in a solution. So, the difference between its boiling and that of water is basically boiling point rise or BPR or sometimes we also call this as boiling point elevation.

So, such solutions usually require more heat to vapourize unit mass of the water so that the reduction in capacity of unit maybe considerable. So, in this way we consider the boiling point rise in a solution. So, the value of boiling point rise cannot be calculated from physical data of the liquor. Though, Duhring's rule is often used to find out the change in BPR with pressure. So, you can use Duhring's rule to find out boiling point of the solution.

(Refer Slide Time: 11:07)

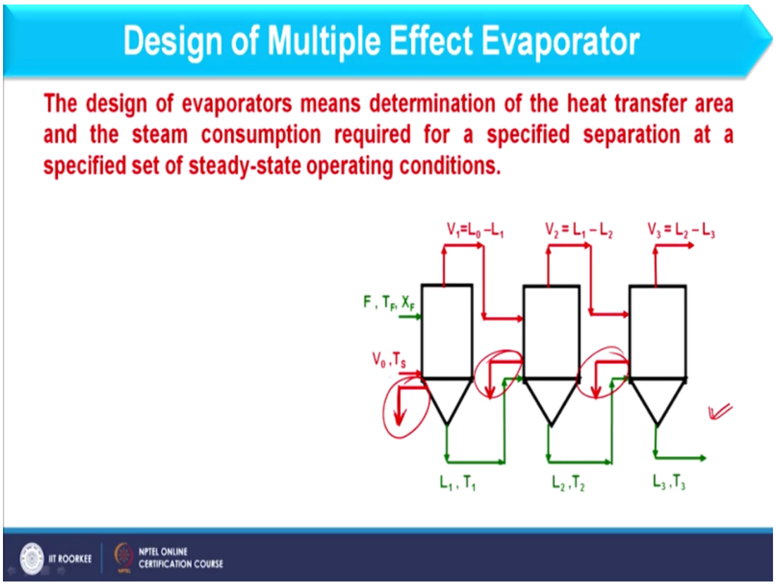


And if you consider this is basically the graph where boiling point of the solution is shown and that is in accordance with the boiling point of a pure water. So as per the salt concentration you can find out boiling point of the solution. So, if boiling point of the solution is plotted against that of water at the same pressure then the straight line is obtained as shown in this figure where sodium chloride is used as a salt.

So, you can see this image. So, here you can obtain straight lines. Therefore, if the pressure is fixed the boiling point of the water is found from the steam table and boiling point of the solution can be obtained from this figure. So, difference of these two will give boiling point rise and further we can observe that boiling point rise is much greater with strong electrolyte such as salt and caustic soda.

So, all these point you should consider while computing the boiling point rise. Now, let us start the design of multiple effect evaporator and we will start the design with triple effect evaporator. So, as far as design is concerned we have already discussed that design means we have to find out heat transfer area of effect as well as steam consumption in an effect or multiple effect evaporator. So, before start design of that let us first discuss its working.

(Refer Slide Time: 12:55)



So, here I am having triple effect evaporator and each effect of the evaporator includes heat exchanger, vapour liquid separator and the recirculation pipe this type. So, each effect contains all these three component. Now in this feed is entering into the first effect after heating up it is converted into concentrated liquid and that is entering into the second effect. And we are representing this stream as L 1 and at T 1.

So, L 1 is the flow rate and T 1 is the temperature and further whatever liquid is exiting from the second effect it is more concentrated in comparison to L 1 and we name it as L 2 at temperature T 2 and finally it is entering into the third effect and from third effect whatever liquid is exiting it is having at highest concentration in comparison to L 1 and L 2. So, in this way the movement of the feed is taking place inside the effects.

And at the same time steam is entering into the first effect with the flow V 0 and at temperature T 0. So, after evaporation in first effect the vapour is generated and that vapour is used as a heating media in second effect. So, while making the mass balance you can simply find out V 1 as F – L 1 and whatever vapour is generated in second effect it is used as a heating media in third effect.

And whatever vapour is generated in third effect it further enters into the condenser and after that we have vacuum unit. Now discus this schematic in detail. So, if I ask you triple effect evaporator how the movement of feed occur in this effect because if you see the movement of feed is basically from first effect and then to second effect and then to third effect and from third effect we get finally concentrated product.

So, feed movement is basically from 1, 2 and 3 effect. So 1, 2, 3 is the flow sequence which we also called as forward feed sequence and as far as vapour movement is concerned. Vapour movement will be from first effect then to second and then to third effect. Now the point is how this movement of feed and vapour is taking place that we can understand with the help of vacuum pump because whatever vapour is exiting from the last effect it is entering into the condenser as we have already discussed.

And after that complete system is attached to the vacuum pump. Complete system means this effect, this effect as well as this effect. So, all these effects are connected to the vacuum pump. Now, if I ask you that what are the units which are attached to the vacuum pump? So, these units are basically heat exchanger, recirculation pipe and vapour liquid separator of each effect.

However, the unit where steam is entering it is not connected with the vacuum pump. So, shell side of all three heat exchangers are not connected with the vacuum pump. So, what I am saying that vacuum pump is basically connected with the last effect. So, if vacuum pump will be started what will happen, where the vacuum will be most. The maximum vacuum can be obtained in third effect because that is nearest to the vacuum pump.

And as we keep on moving away from the vacuum pump vacuum effect will keep on decreasing. I hope you understand this. So, it means that maximum vacuum we can obtain in third effect then to second effect and then to first effect. So, if I am considering vacuum it means I am already deciding the pressure. So, maximum vacuum means minimum pressure. So, it has least pressure, it has slightly more pressure and it has slightly more pressure.

So, if we want to generate the pattern P 1 would be greater than P 2 would be greater than P 3. So as far as pressure variation is concerned that we have already discussed and usually we consider that effects are at saturation condition. So, as the pressure is there in the similar line we can observe the temperature also. So, we can consider that T 1 which is the first effect temperature should be more than T 2 which is the second effect temperature.

And that should be more than T 3 which is third effect temperature. So, as I am having decrement in pressure the natural movement of feed will be from high pressure to low pressure. So, movement of feed can be ensured when I am considering vacuum pump. So, first effect will be at high temperature then the second effect and then the third effect. Now, if I ask you what is the known temperature from all these T 1, T 2 and T 3.

As the vacuum pump is attached to the last unit we already know the reading of vacuum pump. So, it means I am fixing P 3 value and once I am fixing the P 3 value T 3 is fixed automatically. So, as far as known temperature is concerned from T 1, T 2, T 3 last effect temperature or T 3 temperature is known to me and the same pattern we follow in different effects also.

Like if I am considering 6 effect, 7 effect even sometime it is 12 effect also and that usually occur in desalination process. So, whatever is the last effect that temperature and pressure is usually known. Now further discuss this image because there are so many points about this to tell you. If I ask you that first effect is available at T 1, so whatever liquid is exiting from this effect that is available at T 1, whatever vapour is exiting from this that should also be available at T 1.

Now when this V 1 and L 1 both exits at the same temperature and at the same temperature it enters into the second effect. So, how heat transfer is taking place in second effect because both feed as well as heating media both are available at same temperature. I hope you are understanding my question. If you focus on the first effect feed is available at Tf. Effects temperature is T 1 and steam temperature is T 0.

So, what is the driving force in first effect that is T 0 – T 1. In the similar line, if I consider the second effect where is the driving force because both heating media as well as liquid both are available at same temperature. So, driving force in this case should be 0, is it so? No. So, how the driving force will be maintained? That can be maintained because as we have discussed already that it is available at pressure P 2 and P 2 is lesser than P 1.

So, when liquid comes into this effect because liquid is available at high pressure that is P 1 it will come across suddenly at lower pressure P 2. So, what will happen because of this temperature difference flashing will take place inside second effect. So, because of this flashing liquid L 1 will try to occupy pressure P 2 and the moment it will occupy the pressure P 2 it will come with the lesser temperature and that is temperature T 2.

So, when the liquid is entering into the second effect it is automatically occupying temperature T 2. When I am saying that flashing is occurring it means from T 1 it will reach to temperature T 2 and because of that whatever heat is lost that convert some amount of liquid into vapour. So, when I am considering forward feed sequence this is the advantage that vapour is generated from evaporation along with the flashing.

So, in that way more vapour is generated in second effect in comparison to first effect. So, as this L 1 acquires temperature T 2 here I am getting driving force as T 1 – T 2. In the similar line here I am getting driving force as T 2 – T 3. So, because both fluid are available at same temperature then also I am getting sufficient driving force because of the flashing action. So, this is basically happening in forward sequence.

Now, if I ask you what are the different sequence in multiple effect evaporators. You can answer this as we can have forward sequence, we can have backward sequence, we can have mixing flow sequence and finally we have parallel sequence also. So, some sequences are in series and some sequences are in parallel. Now what will happen in backward sequence? Feed enters into the last effect and concentrated liquor which is generated in last effect it is entering into the previous effect than to last effect.

So, in triple effect evaporator it is second effect. So, in backward sequence the movement will be like 3 to 1. Mixed sequence it is 2, 1, 3 or 2, 3, 1. In parallel feed is distributed into number of effects and in each effect one part of the feed enters it is converted into vapour and in that way concentrated liquid can be obtained. However, if I am considering different flow sequences either forward or backward it is with respect to the movement of feed.

Movement of vapour will never change it will always be in forward direction because of the pressure difference that is the natural movement of vapour. You can argue that natural movement of feed is also from high pressure to low pressure very right, but when I am considering backward sequence we use to pump the feed from low pressure to high pressure effects.

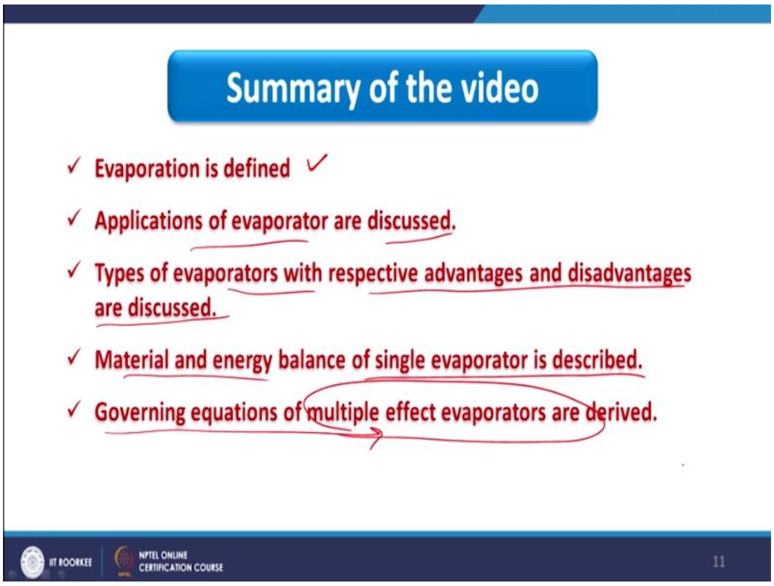
So in that case pumps will be the extra capital investment. However, feed flow sequence backward is also very useful and this sequence of the feed will depend on the temperature of feed. We try to enter the feed in the effect where feed temperature and effect temperature is more or less same. So, in that way we decide the flow sequence. So, in this way we have discussed different points about multiple effect evaporator especially triple effect evaporator.

And I hope the working of this evaporators are clear to you and here we are having another image and in which you see we also have shown the condensate flow. So, steam is entering into this, supply its latent heat to the effect and then it comes out as condensate. So, in this way you can understand the process in triple effect evaporator and as far as design is concerned first of all we need to derive the governing equation and that derivation of the governing equation we will discuss in next lecture and here I am stopping this lecture.

(Refer Slide Time: 27:11)

And here you can find the references about this and apart from this we have another book in which evaporator is discussed very nicely and that is the book of (()) (27:21) so that book you can also refer and here we have the summary of the video and this is the summary of 34th lecture and 35th lecture of this week. And in these lectures we have discussed the evaporator.

(Refer Slide Time: 27:37)



So, summary of these video is here we have defined the evaporation applications of evaporators are discussed, types of evaporator with respective advantage and disadvantages are discussed in detail. We have seen material and energy balance in single evaporator and finally we have discussed the working of multiple effect evaporators and we have not discussed the governing equation associated with these effects and this part we will cover in next lecture. So that is all for now. Thank you.