# Heat Transfer
**Prof. Sunando Dasgupta**
**Department of Chemical Engineering**
**Indian Institute of Technology, Kharagpur**

## Lecture – 47
## Boiling, Evaporation and Evaporators

This would be the last class on Convective Heat Transfer. What we have covered in convective heat transfer so far or when we have flow outside of a plate or a tube which is external flow, internal flow, the concept of fully developed flow the relations and correlations which are applicable both in laminar flow and in turbulent flow for flow outside as well as flow inside. And, we have seen what is, how to design a heat exchanger based on the log mean temperature difference method and if both the outlet temperatures are not known then a better method known as epsilon NTU method or effectiveness NTU method can be adopted.

And, we have solved a number of problems and you would be it be given more problems in the tutorial sheet which you try should try to solve and if there is any difficulty we will discuss about it, but will close the convective heat transfer today with something that we have not discussed that much in our previous studies this is about evaporation boiling heat transfer. The utility, the importance of evaporation and boiling heat transfer would be more apparent in the next half of this class when we talk about the evaporators.

As you are probably aware of evaporators is one of the major equipment, major unit in many heat transfer, many chemical plants were a solution a dilute solution is going to the concentrated by evaporating part of the solvent there be making it more concentrate. So, the applications of evaporators, the types of evaporators and the reason for concentrating a specific product in a dilute solution you discuss about it.

So, the first starting point is to know a little bit about evaporation and boiling in we are I am also going refer to a specific experiment which is a very famous experiment where we would see how the boiling curve that is what the heat flux removed from a wire which is submerged in water how does it vary when you change the temperature difference between the wire which can be heated electrically and that of the surrounding water which is assumed to be saturated.

So, at any given point of time you can control the amount of heat which passes through the which is generated due to the passage of current through the wire and at steady state the amount of heat which is provided to the thin wire most of the cases it is a nichrome wire of high resistance. So, the joule heating is we would see how the joule heating or how the dissipation of heat from the wire follows the specific trend with delta t which is the temperature difference between the wire and the surrounding liquid that has been imposed on the system and will get some interesting or interesting idea out of that boiling curve.

The evaporation is also known as quiet boiling in which case most, let us say you take a beaker of water and you place it on a hot plate. So, near the near the interface with the hot plate the temperature is going to be almost close to that of the hot plate, but this temperature would change drastically if you just move up a little bit. So, a large change in t can be observed in a region very close to that of the heater. Beyond that point the temperature more or less remains constant and when you come close to the interface it is assumed that the interface is at equilibrium with its vapour.

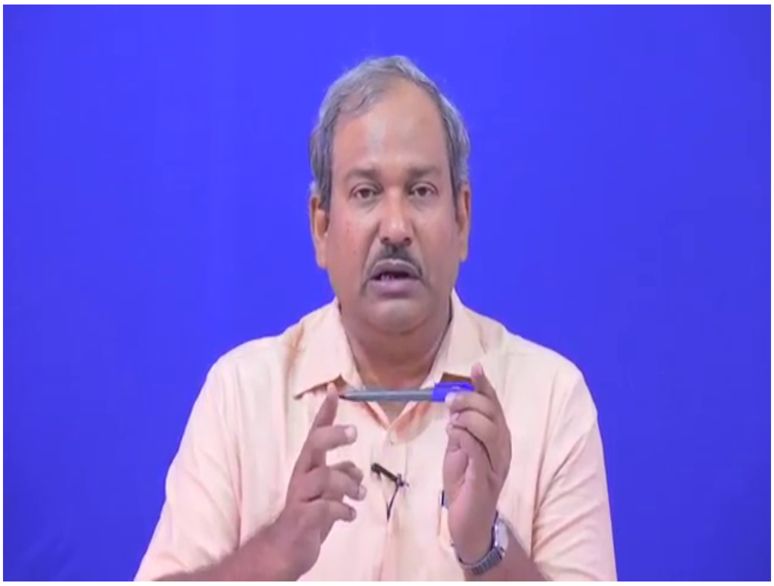
So, interface temperature is for the case of evaporation the interface temperature most of the times is approximated as the saturation temperature of water or the liquid that we are using or for the given conditions. So, the temperature profile if you could draw it as a function of the distance from the heater in the beaker then it is going to be very short near the region of the hot plate then it more or less follows a constant pattern and there is a small temperature jump which most of the times it is neglected. So, t sat is going to be equal; t sat is going to be equal to t naught that is the temperature of the on the liquid side of the interface.

So, this is how the evaporation is perceived and evaporation is a slow, as you can understand evaporation is a slow process it is totally different from that of the boiling, where in the case of boiling you have phase change taking place everywhere in the liquid column that we were just discussing. But, in the case of evaporation phase change is taking place only from the top of the liquid and there are numerous relations and correlations which connect the heat which is dissipated from the heater as a function of delta t.

So, these relations and correlations are available in the text that is the book Fundamentals of Heat and Mass Transfer by Incropera and David and also on any other book or text book on heat transfer. So, we can take look at the relations and whenever you have to find the heat transfer coefficient for such processes go to the go to the reference, find out which relation or correlation is appropriate for the specific situation and use it.

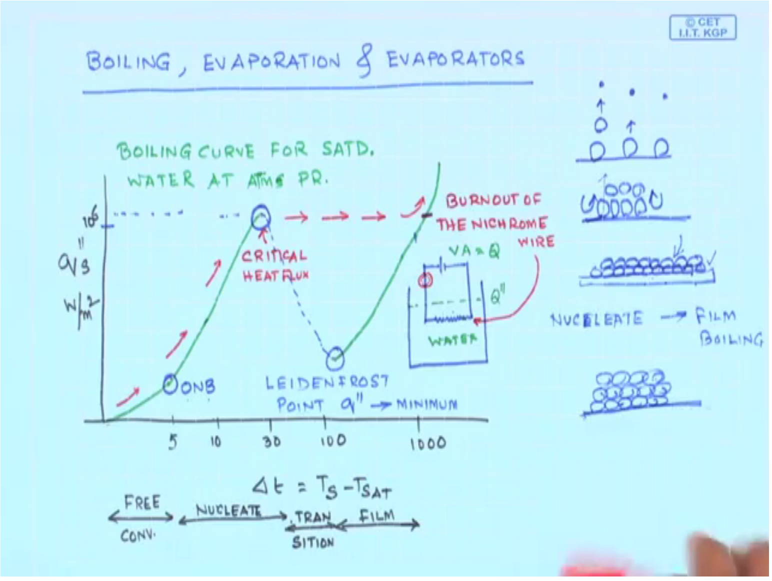
But, we are going to now talk about the case of boiling curve where a wire which is submerged in water the current is being passed through the wire which heats up and you can measure what is the, you can find out how much of heat is being lost by the thin wire to the surrounding fluid. And you can calculate, you can measure the variation of this q as a function of delta t and we would like to see how it changes and this has given us the boiling curve of what of boiling curve for the case of water.

(Refer Slide Time: 07:05)



So, near the vicinity of the wire, if this is the wire then near the vicinity of the wire what are the different steps that we can encounter, that we will encounter as the temperature of the wire is progressively increased. This is what we is going to give rise to the boiling curve.

(Refer Slide Time: 07:21)



So, let us look take a quick look at the boiling curve for saturated water at atmospheric pressure. So, we can see on the left hand side I have plotted the heat flux which is q double prime s in watt per metre square and delta t is the x axis the independent variable, where delta t is defined as T s minus T sat. So, temperature of the surface minus T sat. So, initially up to a delta t of above 5 degree the heat flux gradually increases; slowly increases with delta t. So, this kind of relaxed increase of heat flux with delta t this region is mostly governed by free convection. So, up to about 5 degree centigrade temperature difference it is a free convection which is which takes which is responsible for heat transfer.

So, you have the setup could be like this it is just a schematic of the setup. So, you have a specific wire of high resistivity high resistance which is connected to a power source and this is submerged in water. So, you pass a current through it and from the voltage and the current V times A is going to give you the amount of heat that is being dissipated by the wire in the water. And the T sat is the saturation temperature and the q this divided by area would give you can also find out what is Q double prime that which has been plotted over here.

So, when the temperature difference is about 5 degree it is free convection, but as the temperature difference is increased the first bubbles will start to appear on the wire and it is going to be the onset of the nuclear boiling nucleate boiling. So, over here what you are going to get is onset of nucleate boiling. So, this point is where the first bubbles will appear, but the bubbles are going to be detached from one another. So, bubbles going to form and the bubbles will get released and they will try to move towards the top because of (Refer Time: 09:48).

But, since they heat super heat content of the bubbles are not that great specially at low values of delta t they will disintegrate and collapse back to become the liquid once again. So, this formation of bubbles and the movement of the bubbles will ensure that your q, the slope of the q double prime s versus delta t increases more rapidly with delta t as compared to the free convection. So, as you increase it beyond that as you increase the current through this even more.

Then what you are going to have is bubbles which are going to form and the bubbles are going to get detached and they has going to be a lot of mixing in over here. So, disturbances near the interface should increase and as the disturbance is mixing or and the interference between the bubbles increase at this point. So, you are going to get higher and higher values of heat flux as a function of delta t. So, it is going to increase rapidly, but as it is doing so a point would come where the wire will see, will be covered by almost like a blanket will start to get covered with a blanket of the vapours. So, this is your wire which is going to be covered going to start to getting covered with a blanket of the vapour.

So, therefore, there would be the problem of the liquid reaching the surface changing it is phase and forming the bubble. So, the additional resistance provided by the low thermal conductivity vapour bubbles clinging to the surface accumulating on the surface. So, there are two competing mechanism; one is the bubbles are taking the vapour bubbles are change I mean it is liquid is changing phase creating the liquid bubble. The liquid bubbles will take the latent heat and will rise in the liquid there by creating the keeping the surface cool.

The other competing mechanism would be, the competing mechanism would be the bubbles forming an additional layer of resistance on the wire. Therefore these two are acting at cross purposes formation and release of the bubbles and formation of a blanket of the vapour over the solid which increases the heat transfer. These two are the competing mechanism and they will balance out resulting at some point in the maximum heat flux which you can obtain for such cases and the point where this happens is known as the critical heat flux.

So, in critical heat flux is the which takes place when these two more or less cancel out each other and this is what is known as the as the critical heat flux and from the nucleate boiling you start. So, this is the onset of nucleate boiling and over here in critical heat flux you are going to go from nucleate boiling nucleate towards film boiling. So, critical is the transition between the nucleate and the film boiling.

If you go beyond that the this region is marked as dotted because in most of the cases it is very difficult to get this region which is an unstable region and there as the temperature difference increases the thickness of this vapour layer will simply be more. It keep on increasing and the resistance due to the entire wire is going to get blanketed by a layer of the vapour with very low thermal conductivity. So, with increase in delta t more bubbles are formed and the heat flux keeps on decreasing.

So, the point where you are going to get the minimum heat flux for such a situation is known as the Leidenfrost point. So, Leidenfrost point which simply says that this q double prime is going to be minimum. Once you cross this the mode of heat transfer is going to be I am mean that radiation would start to play a role. So, the increase in delta t the heat flux will start to rise again because your t delta t is more. So, therefore, the change in delta t the increase in delta t will start to compensate for the lower heat transfer coefficient resulted because of the formation of this. So, it will start to increase and beyond certain point the radiation is going to take place, take over and it is going to be very very steep curve from there.

So, somewhere around this point; somewhere around this point you are going to get the burn out of the nichrome wire which is this one the wire over here. So, when that happens this is roughly a measure of what is the heat flux. So, this is connected to a voltmeter to a power source. So, is slowly increase the power and you see how this is changing and when at certain point the wire brakes that is the point which is known as the critical which is known as the critical heat flux.

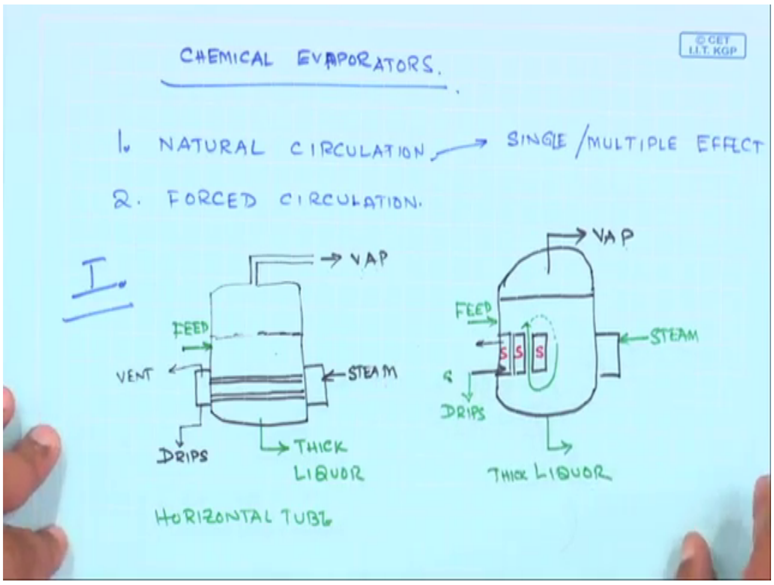
So, the knowledge of critical heat flux is extremely important in the design of equipments which involve boiling. So, whenever you have a boiling situation for a in a heat exchange equipment for example, in an evaporator you need to know what is the maximum heat flux that this surface can handle without going to a going to a point where which change if increase in delta t your heat flux will decrease. So, we are going to be on the other side of the boiling curve rather than with change in delta t heat flux is increasing if you are at or near the critical heat flux a change in delta t can be counter productive instead of getting more heat flux you are going to get less heat flux.

So, the limitation of your boiling equipment in order to in order to evaluate the point up to which your system, your equipment, your designed equipment evaporator can work you really need to know what is the critical heat flux for such as such a point. So, the important points here are that through this experiment you have an idea of the different modes of heat transfer starting from natural convection to forced convection. And, in forced convection you are going to get the onset of nucleate boiling, where the bubble or vapour bubbles are going to form detached from the surface rise towards the top, but will probably assimilate once again by a face change process with water.

So, more number of bubbles means more heat transfer. So, with the change in delta t in the nucleate boiling region your temperature your heat flux keeps on increasing, but has that happens there is going to be formation slowly that is going to be formation of a vapour blanket on the wire. Therefore, these two competing mechanisms would try to make it try to come to come to a balance. And, the point where the maximum occurs is known as the critical heat flux beyond that with change in delta t the heat flux will keep on decreasing or at the most will remain more or less a constant. So, you are not utilising anything, getting anything new out of your equipment by having it operating near at or near the critical heat flux region.

So, designing of heat exchange equipments specially which those which involve boiling would require that you have a fair knowledge accurate idea almost what is going to be the critical heat flux for such situations. And again there are relations and there are correlations available which would give you the value of the critical heat flux for some of the substrates liquid combination and you can look at your text to find out what they are I am not going to write all of them down. What I am going to do next is to show you some quickly little bit about the evaporators their designs and so on.

(Refer Slide Time: 18:57)



CHEMICAL EVAPORATORS.

1. NATURAL CIRCULATION → SINGLE / MULTIPLE EFFECT
2. FORCED CIRCULATION.

So, let us move on to evaporators and we will just deal with chemical evaporators and in chemical operators are of two types one is natural circulation, it can be a single or a multiple effect; I will talk about what is single and multiple effects are. And the second obviously, is going to be forced circulation where you require higher throughput, higher values of heat transfer you are going to get you are going to use this.

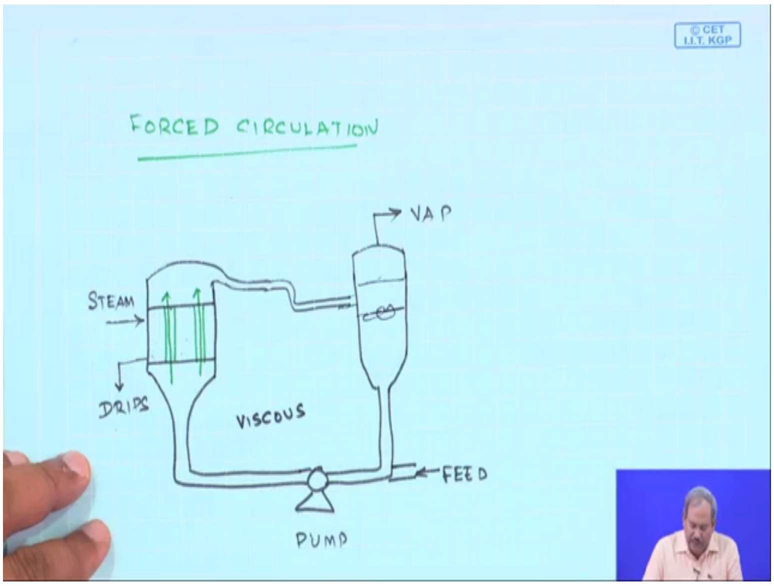
So, the natural convection type I, if we starts working with natural convictions some of the possible exchanges are going to be this is the simplest one, where you have a liquid up to this point and then there are steam which is coming in and you have pipes or tubes like this. So, steam is going to pass through this tubes come to the other side and whatever is remaining it goes out of the vent, whatever condense is the condensing steam is going to come out as drips. The feed comes in here at the top and the concentrated product which is known as the thick liquor come can be collected at the end.

So, this is a horizontal tube this is the horizontal tube heat evaporator you can also haves as a name suggests you can also have tubes like this where steam is going to be go in and out and so, the same thing is on this side. So, this is filled with liquid, it is for the vapour to go come out of this. So, you have steam which is going so, I will write this the s team will is going to pass through them and you have the same thing on the right hand side and the liquid is going to come down rise due to natural convection reach over here change its direction and come back again.

So, this kind of circulation will go on in the intervening space between the tubes and therefore, you have the feed which is coming in here and the thick liquor would be collected from the bottom and you have steam which is in here. So, steam comes in here and this is obviously, going to be the drips and any remaining vapour can come out of this. So, these two examples of natural circulation evaporators and in many of the cases the vapour which comes out from these streams, these vapours can then be used in another evaporator which is in series which is after this one.

So, instead of instead of having just one evaporator which is also known as the single effect evaporator you can have multiple effect evaporators, but more number of evaporators 2 3 4 are going to be in series and the vapour from the evaporator 1 is going to be used to heat that of that of 2 and so on which I will draw, I will show you.

(Refer Slide Time: 23:47)



So, the forced circulation; when we look at the forced circulation one you simply have the design construction would approximately remain the same. So, in a forced circulation type of evaporator you still have the steam and the liquid is forced by a pump which goes through the space between them, goes over to over here to another chamber where the vapour is collected.

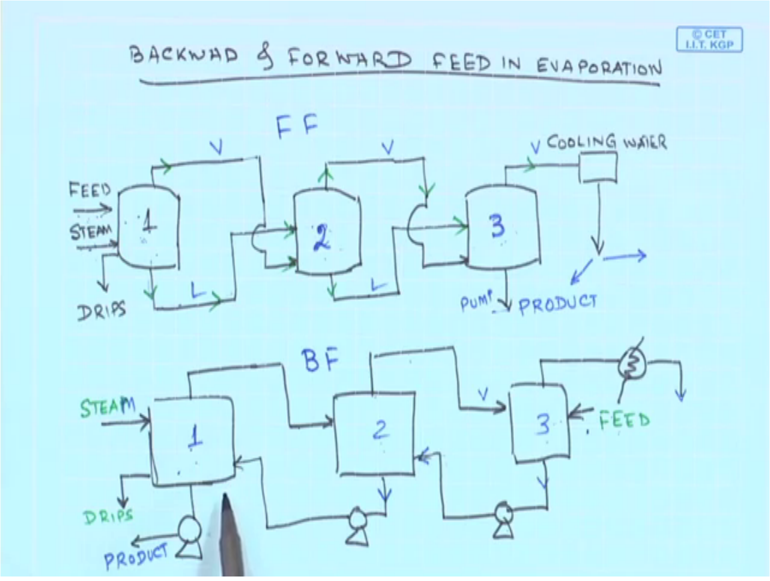
So, you have the liquid over here and you keep on circulating; you keep on circulating; you keep on circulating this and it gets more and more heated. The vapours are going to be collected this is a drip from the feed or any you can give some you can provide the feed from over here and these kind of systems are used where the concentration problem involves a solution with poor flow. And it may have a it may form scales it may have a thermal undesirable thermal characteristics or it is highly viscous. So, you really need to force the liquid through the spacing where it is in connect in contact with the steam through these tubes.

So, for highly viscous fluids this kind of poor circulation would be an ideal evaporator where you force the feed to go through this collect the vapour and you can continuously reduce the solvent content of the material and therefore, you can have a system in which it will automatically start reducing the water content of this. So, as I said you can have multiple effect evaporators as well. So, one reactor, one evaporator after the other, so, you get a feed and the feed comes in contact with steam. The feed temperature has also increased the vapour which is generated from the feed contains some significant amount of energy. So, vapour from the feed is in going to go as the heating material into another evaporator which follows the first one. So, where the feed from the where the vapour from the first evaporator is going to come in heat the material and so on.

So, in that way you can utilise more and more heat the heat efficiency of the entire system will enhance. And, you can have a system in which both the feed and the steam will come in the same direction will travel in the same direction or we can have a system of the evaporators. So, series of evaporators where the feed is going to come from one the feed is going to come to the first evaporator where the steam is going to come to the last evaporator. So, you can have a forward feed or a backward feed.

So, I will quickly draw the pictures of the figures of these two forward feed evaporator, backward feed evaporators and talk about their merits and demerits and once I draw the pictures I think the concept will be very clear to you what is known as what is the multiple effect evaporator and what is going to be forward feed and what is going to be the backward feed. So, let us quickly draw these pictures and try to see what we get out of this.

(Refer Slide Time: 28:37)



So, this one is as you can see it is the forward feed and this is the backward feed. So, let us see what happens over here the feed and the steam both come in evaporator 1. The concentrated product which is slightly heated because since it is come in contact with this steam goes to the next evaporator. The vapour generated out of this contains lot of energy. So, it goes to heat up whatever is coming at this point and it goes into number 2. The same way the product is going to go as the feed to the third evaporator and the vapour which is generated in 2 goes as the as the heating stream into 3.

So, finally, what you get out of 3 at the bottom is the final product and any vapour which leaves 3 is going to be cooled using cooling water and then it can be either it can be brought back to the product or it can be stored elsewhere. So, once again in forward feed both the in what in forward feed both of them travel in the same direction and the liquid feed flows in the same direction as that of the vapour it is a forward feed.

So, the vapour and the liquid; the vapour and the liquid are travelling in the same direction. So, it is known as the backward feed the forward feed. In the backward feed this steam comes at 1, the feed comes at 3 and there can be more such evaporators in one after the other. So, when the feed comes it is cold it is first going to get it is first going to encounter the vapour which is coming from. So, this is the vapour which is coming from 2. So, the feed gets slightly concentrated, you are going to it is going to loose some amount of some amount of vapour which can be condensed and collected.

So, the feed then slightly heated now it is pumped through 2, 2 as the new feed. The heating one comes from the vapour of 1. So, into the concentrated part from 3 is the feed and the vapour from 1 is the heating medium even more concentration being done at 2 and then it is pumped to 1. So, when it goes into 1, the new feed it has the maximum concentration and there in it comes in contact with live steam it gets further concentrated and it is this is going to be the final product.

So, let us see the relative advantages and disadvantages. First, backward feed: the feed which is coming is the feed which is coming is at all it is talk about the forward feed first. The forward feed a vacuum is maintained in the last effect this affect and the liquid flows itself from 1 to 2, 2 to 3 and so on in backward feed you need a pump to make the liquid flow towards from 3 to 1, and in order to remove this feed at the final, at the product you probably need a pump at this point, whereas you required pumps after every effect in the case of backward reactor.

If the feed is at a higher temperature is higher than the, if the feed liquid itself is higher than the saturation temperature then some evaporation some flashing will take place automatically as in 1 and this flashing will take place in every effect thereby reducing the steam requirement. So, if your feed is at a higher temperature than the saturation temperature the moment it enters the first effect it is going to flash and that is going to be part of the vapour which is going to evaporate and then the rest is going to condense and the same thing will happen in 2 and 3 and since the feed is at a higher temperature than that of that saturation temperature your steam requirement would be less the problem that we. So, that is advantages.

The problem that you see in forward feed is as the product from 1 becomes the feed of 2 the product of 2 becomes the feed of 3 and then ultimately you are going to get the final product, the concentration keeps on increasing between 1, 2 and 3. So, the liquid starts to become more and more viscous therefore, it is difficult to make it slow. So, the last ones is it has the highest viscosity liquid the it will have the least overall heat coefficient since the liquid is going to be very concentrated at this point.

On the other hand in backward feed the dilute liquor enters at the last at the last end and leaves concentrated from the first which is the hottest one which is at the highest temperature. So, here the liquid must be heated in each effect and you would require more steam in backward feed, but if the feed is initially hot therefore, if the feed is initially hot then it is there is no point in letting it enter into 3 in backward feed. So, if the feed is initially hot use forward feed, if the feed is initially cold and or if the feed is viscous introduce it here.

So, as the liquid becomes more and more concentrated the temperature is also increasing so, therefore, the effect of increase in viscosity, the detrimental effect of increase in viscosity is compensated in backward flow as compared to that in forward flow. So, steam cost will be less for backward feed if the feed is cold and less for forward feed if the feed liquor is approximately at the operating temperature the first effect of higher.

So, depending on the condition of the feed you have to choose whether you are going to use a backward feed or a forward feed. So, if your feed is hot at a high temperature relatively high temperature then by all means use forward feed, where flashing is going to take place inside evaporator one and that vapour is going to be utilized in 2 and so on. Therefore, the steam requirement at each of these effects will be lower because of vapour flashing which can take place only when the liquid feed liquid is at high temperature.

But, as the in forward feed as you move from 1 to 2, 2 to 3 it is becoming more and more concentrated viscosity increases and therefore, your heat it heat transfer will keep on decreasing. So, if you are dealing with dealing with a liquid which when it is concentrated, when it is when the solvent is evaporated it becomes highly viscous do not use forward feed. In that case if it use of a backward feed would be justified because as it goes from 1 to 2 to 3 in the reverse direction the temperature keeps on increasing and therefore, and the concentration keeps on increasing as well.

So, the increase of viscosity due to concentration increase will be offset by an increase in temperature. So, use of a backward feed would be justified in such a case. So, this is in a very the nutshell is about evaporated, we spoke about boiling, we spoke about evaporators, the type of operations the natural convection the evaporators which are which depend on natural flow, natural convective flow. And in some cases you have to have forced flow forced convection effects forced convection convective evaporators and the arrangement of multiple evaporators either in forward flow or in backward flow with their advantages and disadvantages. The relations and correlations are available in the text which I am not reproducing over here, so, you can simply see those in your text and use them whenever appropriate.

So, this concludes our discussion on convection and from next class we will move over move over to Radiative Heat Transfer.