Heat Exchangers: Fundamentals and Design Analysis
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Lecture - 42
In tube condensation

Hello everyone. So, if you recall that we are doing phase change heat exchangers, and in that for last a number of classes we are considering condensers. And condensers we have started with surface condensers. In a surface condenser condensation takes place outside the tubes the condensation takes place, the vapour condenses outside the tube through the tube the coolant is passed, ok.

So, surface condensers are generally liquid cooled condensers, and many of the surface condensers are of sullen tube configuration. And they constitute a very large number of condensers used in power plant, used in process industries and; obviously, in other industries also. And but that is the not the only configuration of condenser. There is another variation which is if we come to the a present slide, title slide condensers with in tube condensation; that means, inside the tube also condensation may take place. And this process is known as in tube condensation, and there could be a large number of heat exchangers with in tube condensation.

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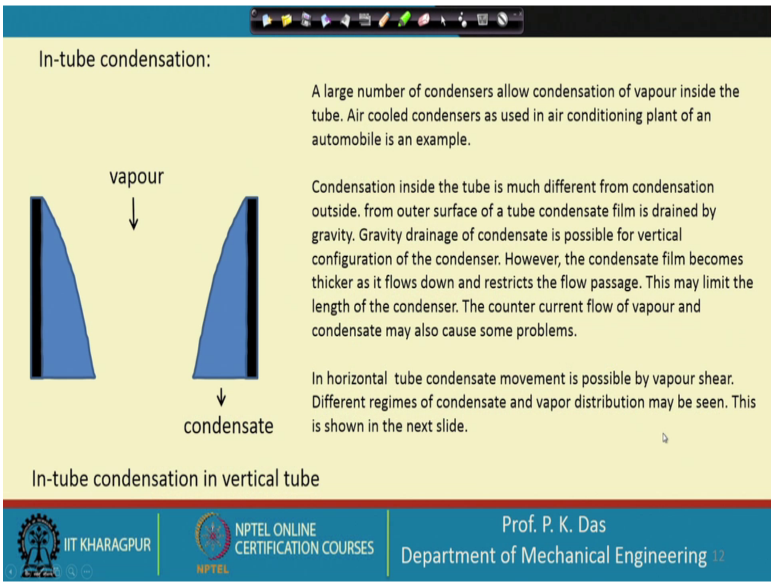

Here in this figure I have shown a vertical tube, vapour is flowing in the downward direction, and condensation is taking place on the wall vertical wall of the tube. So, this is simply a an example of in tube condensation. So, in tube condensation if this vertical tubes are there. There are in fact, vertical condensers where in tube condensation takes place, and inside the vertical tubes there will be condensation. And in the cell side there will be coolant this kind of condensers are there. Vertical tube and the type of configuration which I have shown is very good because the gravity is helping to drain out the condense set. In fact, whenever we think of film wise condensation so, then the film drainage is one of the issues and the film drainage is best done by gravity so far that is the best method.

Here in this particular case what we can find that liquid is draining in the downward direction which is good, at the same time vapour is also flowing in the downward direction. So, vapour will push the liquid in the downward direction this is good. In some cases, there could be a different kind of a design; that means, one can have the vapour going in the upward direction, but the condensate has to come in the downward direction. So, that kind of configuration though in some design it is there, it may give some problem. A large number of condensers allow condensation of vapour inside the tube. Air cooled condensers are examples where your air cooled condensers there are large number of air cooled condensers; where in tube condensation takes place.

Of course the vertical tube condensers condenser whatever I have told, the example which I have given this is probably from a sealant tube heat exchanger were cell side there will be some liquid. But there could be air cooled condenser particularly in refrigeration and air conditioning industry there are many air cooled condensers, many many air cooled condensers we are having in an automobile, in a car the air conditioning system is there and the condenser is air cooled condenser.

And if it is air cooled then outside fluid is air and tube side fluid is the condensing refrigerant vapour. If it is condensing refrigerant vapour then; obviously, you can understand that it is in tube condensing condensation taken place. Condensation inside the tube is much different from condensation outside, from outer surface of a tube the film is drained by gravity, gravity drainage of condensate is possible for vertical configuration as I have explained. However, the condensate film becomes thicker as it flows down, ok.

So, as the condensate film becomes thicker. So, it will chock the passage for vapour flow. And the if the condensate flows in the downward direction and vapour flows in the upward direction, then it will provide some sort of a counter flow between the condensate and the vapour. But there are whole lot of heat exchangers; where horizontal tubes are used for the condenser horizontal tubes are used, and the vapour is inside this horizontal tube. So, in this case also removal of condensate is needed, and generally with the vapours here we try to do this. There will be enough pumping heat supply to the vapour. So, vapour will push the liquid because it is horizontal we are not getting any advantage from the gravity.

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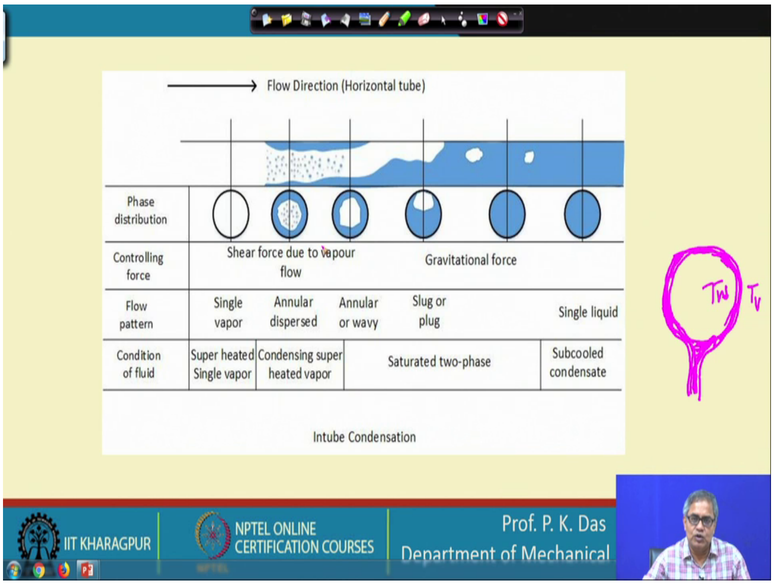

Next slide if we see, this shows the flow diagram in a horizontal tube, let me explain what is happening. So, here your this is the direction of flow. So, let us say this is the tube, and through the tube vapour is coming. Let us say vapour is coming in the superheated condition. So, then it becomes saturated and after that if cooling takes place. So, vapour produces condensate there will be droplet of liquid condensate, and there will be film at the wall.

So, here it is totally vapour, and here we will have vapour layer outside inside this liquid. Sorry, liquid condensate layer outside and; that means, at the periphery of the tube. And then the droplet of liquid that will be in the core. We can have this kind of a configuration, and in case of in tube condensation inside a tube, gravity plays a very important role. And due to gravity the heavier fluid that is the condensate that tries to occupy the bottom side of the tube and it is called stratification. So, then the vapour and liquid, they will occupy different parts of the tube, at the top side there will be vapour and at the bottom side there will be liquid. So, this is what we can see, and ultimately it will be totally liquid.

So, here we are showing some sort of a configuration; where at once side of the tube superheated vapour enters, and from the other side of the tube sub cooled liquid goes out. And obviously, the cross sectional view of the tube at different axial location will be given by this. Controlling force, here this shear force due to vapour that will be important. Here the gravity force is important, why gravity force is important? Because, we have got stratification but obviously, if the liquid has to go out of the tube then there will be pushing from the other side and the liquid will go out.

Then flow pattern it is single phase vapour. This is annular disperse flow inside the core there are disperse liquid droplet, and at the periphery of the tube inside of the tube there is annular film. Then annular wavy so, there will be wave formation. There will be slug or plug or in sometimes we can get eccentric annular kind of film distribution. And after that we will have single phase liquid.

Condition of the fluid here it is superheated in single phase, here it is condensing may be the vapour is superheated, then this would be by this time the liquid will be saturated in 2 phase condition and after that it will be subcooled condensate. So, in a horizontal tube this can take place. I was giving the example of the air condenser sorry, of the condenser of a refrigeration plant or air conditioning plant.

So, there in many cases liquid will enter in the superheated condition, and come out either in the 2 phase condition or in the subcooled condition it can come out. So, such a great variation of phases will be there and such a great variation of flow regimes will be there. Now if we consider the outside tube condensation just to recap just to remind you, what was the outside tube heat transfer configuration. So, this was the tube and on outside we had condensate film, and then the condensate film was getting drained sorry, like this. So, condensate film will get thick and up as it moves down both side it moves down.

So, you see we could have and this film is thin this also we have to remember that this film is thin. So, at this film is thin, Nusselt conduction, sorry Nusselt film condensation theory it assumes that it depends the heat transfer is mainly due to conduction. And it depends on the temperature difference let us say this is T V on this side, and let us say this is T W on the wall side. So, the heat transfer rate of heat transfer that is dependent on your, this is your T V and this is T W. So, it is dependent on T W, sorry T V minus T W, vapour side temperature will be higher.

That is one thing and analysis was simple. Only we are getting this kind of film condensation. So, there is no other geometrical configuration so, this was simple. But in the present case we can see that there are different kind of flow regimes. So, if one has to take care of this one, so; obviously, different kind of flow regimes has to be considered which is not very easy to do, ok. Some hints I will give regarding the design as we proceed, but today at least let us understand what is the difference between inter in tube condensation and condensation outside the tube. What are the critical issues of in tube condensation? So, let us understand those things.

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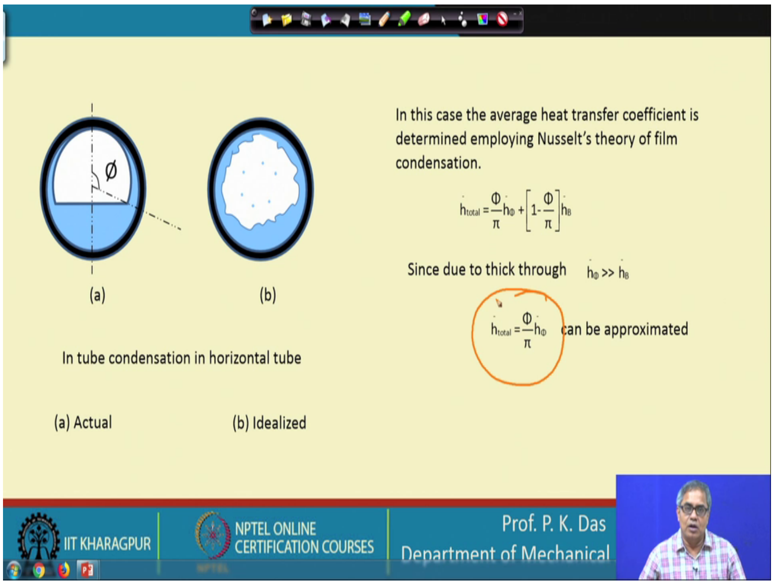

If we go to the next slide, then what we find that suppose at the initial phase we have got kind of annular, and then the annular configuration has changed because at the bottom, there is due to stratification some amount of liquid has come. So, the actual configuration of the condensate film distribution inside the tube like this. Inner core white portion is the vapour in that there are small small particles; which are the particles of the condensate.

And then if we idealize this then left side we can see the idealized representation of this kind of condensation. So, up to an angle phi; where phi starts from the top, we can see that there is a distribution of film. And it is basically film condensation that is a distribution of film, the film has become gradually thicker and thicker as it should be due to collection.

And then beyond phi what we can find, that there is a flooding of the tube with liquid ok. So, there is a flooding of the tube with liquid. So, if this is the situation, we can try to calculate the heat transfer, by some sort of by incorporating the physics of the problem. So, what we can see that there are 2 regimes. There are 2 regimes up to this sorry let us take some other colour, up to this there is this thin film. So, up to angle phi we have got one mechanism of heat transfer and then below. So, a top there is one mechanism and bottom there is another mechanism.

So, that is what has been written on the other side, the total heat transfer coefficient if we have to take average. So, up to phi we have got some sort of a heat transfer coefficient. And on the other side we have got some heat transfer coefficient h B, and then again this h phi should be taken as average heat transfer coefficient in the top portion. And h B should be taken average heat transfer coefficient in the bottom portion.

Now, this goes without saying that as this portion is totally flooded with refrigerant so, there will not be much of heat transfer. So, h B can be neglected. So, in that case our life becomes little bit simple, without occurring much without committing much error, and then h total is given by this kind of a formula; obviously, it is dependent on phi and we have to find out the average heat transfer coefficient. Now, the average heat transfer coefficient we can find out with the help of Nusselt condensation theory.

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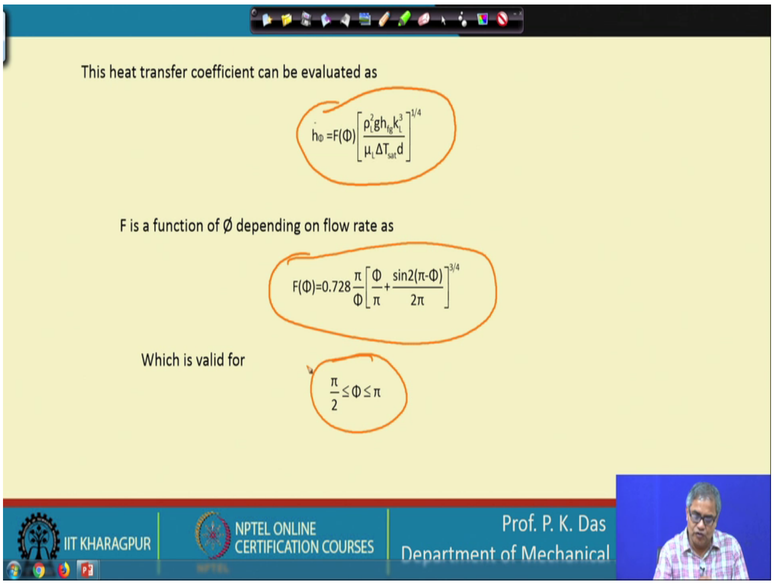

And then the from the Nusselt condensation theory we get this kind of a formula; which is which you are familiar with, this form you are familiar with the form. So, here also you see it is dependent on delta T, because the temperature difference in Nusselt equation we take that heat transfer is mainly by conduction. So, this thing comes, then there is one F phi, F is a function of phi depending on flow rate and we get F phi by this kind of an equation; which is valid for this region of angle.

So, that is also given what a region of angle it is valid. So, basically then I know the average heat transfer coefficient; which is a function of phi, the functional relationship has also been given and the validity or range of validity that has also been given. So, I am in a position to find out what is the average heat transfer coefficient. Now, let us go to the next slide.

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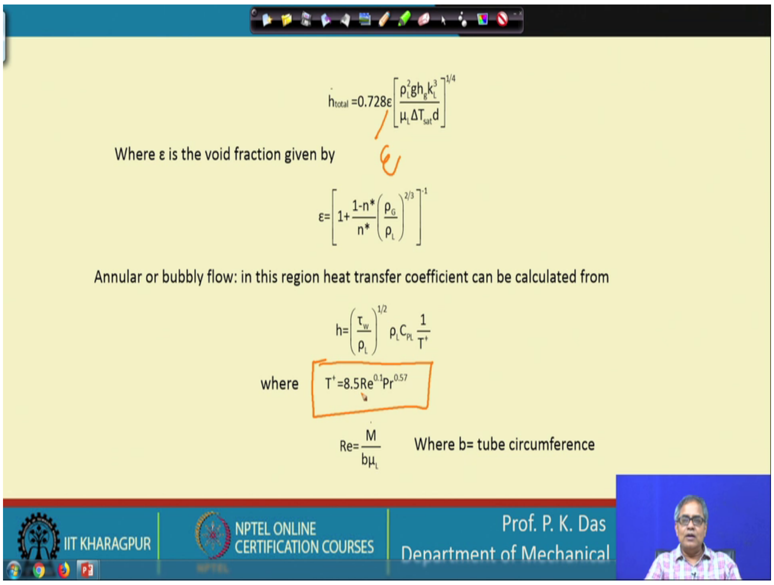

So, next slide we get the total heat transfer coefficient, but here you see we have brought a new parameter which is nothing, but this epsilon. This epsilon is nothing, but this is this parameter we have brought, and this is nothing, but your this epsilon is the void fraction which is given by this formula. And annular or bubbly flow so, this formula is for annular. Now or bubbly flow in this region the heat transfer coefficient can be calculated from another kind of a formula it has been given.

So, when there is a stratified condition which I have shown in the another the previous slide. So, we can calculate the h total, h total means considering both the bottom side and the top side of course, bottom side heat transfer we have neglected. So, average heat transfer coefficient we can calculate, and here we are using some void fraction and with the help of void fraction we can do this calculation. There are for other flow regime what we do? We try to take some sort of semi empirical formula, and in the semi empirical formula what we can do? You see some Reynolds number Prandtl number base relationship we try to use, and from there we try to find out the heat transfer coefficient.

So, this is one kind of recommendation, but we will use some other correlation and with that which is most commonly used for um condensation heat transfer. And with that we will try to solve some sort of a problem. If you problem I mean one problem at least we will try to solve; may not be as rigor as the previous problem, but at least in tube condensation how one can take care of, so that we are going to discuss. So, what we have got so far from the discussion.

That as in many heat exchanger condensation takes place outside the tube in many heat exchangers condensation takes place inside the tube. In tube condensation is difficult to analyse compared to condensation outside the tube because, there could be different kind of flow regimes. And mainly we have to depend on correlation. Outside tube we could have depended or we could have relayed on the analysis which has been given by Nusselt by modifying this analysis we could have done, the prediction of heat transfer coefficient, but the same thing is not possible in many cases in case of in tube condensation. Some effort has been made this is the kind of thing where we still try to continue with your Nusselt kind of correlation or Nusselt kind of analysis is like this.

That we try to idealize the inside condensation of the tube like this, that there is a thin film and here to some extent Nusselt correlation can be adopted. But problem is that we do not know exactly how long this Nusselt co-relation correlation can be adopted because how long will these typical type of flow regime will continue. So, this is one aspect which we have to take care of, all right. Here then there are other flow regimes; bubbly flow, plug flow etcetera.

So, plug flow bubbly flow and annular flow these 3 are the 3 main type of flow in case of power in tube condensation. And some people suggest that flow regime based heat transfer calculation should be there. But at the same time the flow regime based calculation are combustion. So, one correlation which will suffice for a large range of operate operation large range of operating condition, that kind of correlation will be good and we will gradually discuss that kind of correlation.

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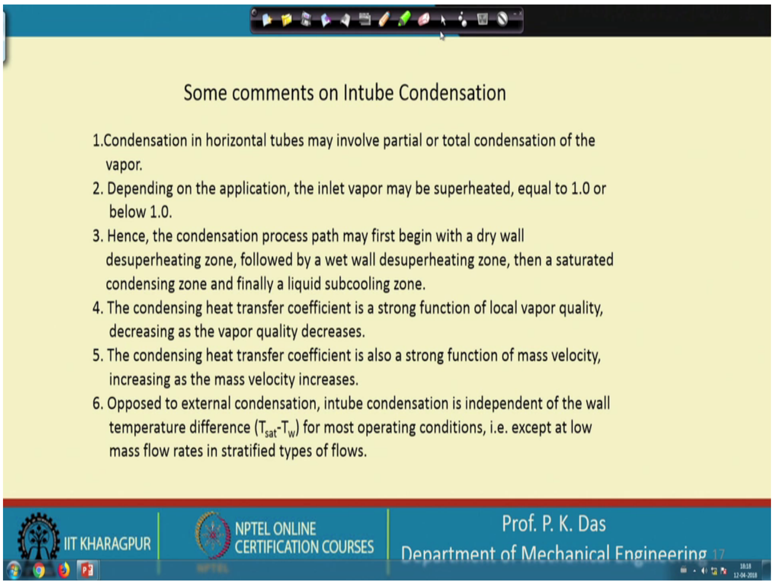

Before that let us go to the next slide. Here we get some comments on in tube condensation, after that we will see what kind of correlation etcetera can be used. What are the comments? The condensation in horizontal tube may involve partial or total condensation of the vapor. What does it mean? It means that in most of the condenser we will find the vapor is entering in superheated condition with different degrees of superheat.

Then it will condense and go out of the tube, but in many cases it may go out as saturated or sub-cooled liquid, in some cases it can go out in the 2 phase condition itself. So, it could be total condensation or it could be partial condensation ok. So, that is one thing in many of the refrigerating condenser we will find this. Not only that what happens in refrigerating condenser the refrigerate refrigeration plant or the refrigeration cycle does not always operate at the same operating point. There is change in operating point also.

Let say, let us say the condenser is air cooled and we are cooling it by forcing atmospheric air over the condenser. In case of a refrigeration plant, but a the place where the plant is situated there is a large seasonal variation of temperature of air outside. So, what we can find that depending on the seasonal variation of air temperature itself we will have different kind of condensation in inside the tube at different period of the year.

So, this is one thing so, the same condenser sometimes it may give that it is sob cooled liquid is coming out of it, sometimes it is letting out I mean it let us out this one the 2 phase mixture. Then and depending on application the inlet vapor maybe superheated, the dryness fraction could be equal to 1 or dryness fraction could be below one.

So, in at the inlet we can have 2 phase condition. Hence, the condensation process path may first begin with a drywall. So, this is also one important thing that, the first part of the condenser could have a dry wall. I have discussed this point earlier, but let me because these are important let me repeat it once again.

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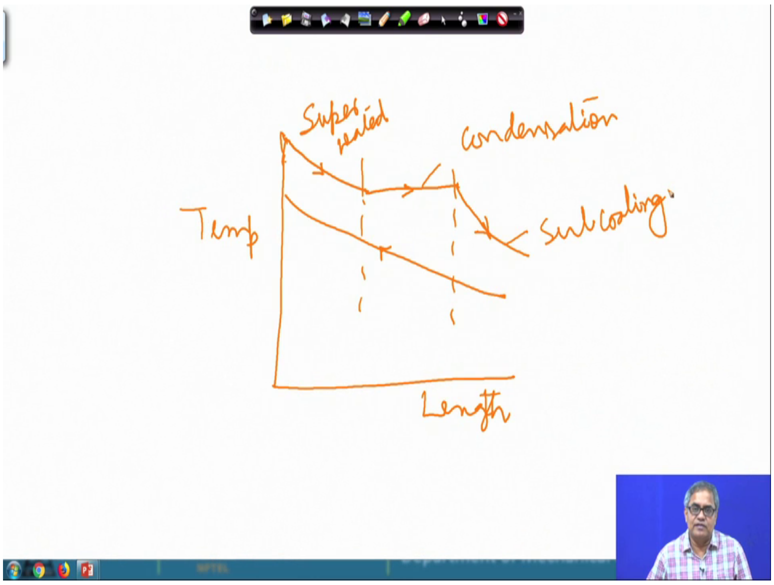

That we have got a condenser, this is the length of the condenser, and this side is the temperature. And condenser means it is giving away heat, and it is getting cool. So, initially sub-cooled liquid has entered, then there will be evaporation sorry condensation and then sorry, let me repeat it once again initially superheated liquid has enter superheated vapor has entered. And then condensation takes place and ultimately sub-cooled liquid is going out of the condenser.

And then one can have this kind of a thing also; that means, the coolant that is going on heating on this. So, up to this, we will have your superheated vapor. Then here we will have condensation and here we will have sub cooling ok. So, this is what has been told in the previous slide and many of the practical heat exchangers are of this kind.

Hence, the condensation process path may first begin with a dry wall de-superheating zone, followed by a wet wall de-superheating zone, when saturated condensing zone then a saturated condensing zone and finally, a liquid subcooling zone. So, these many zones will be there, and you can understand what is the what is the challenge for a heat exchanger designer to design such a heat exchanger; obviously, this point I have touched upon earlier.

Now also I am telling that these kind of designs are quite challenging, and without iteration this kind of designs cannot be done. So, what we do? And again I have told that let us say for a particular duty we have somehow calculated: what is the de-superheating zone. What is the 2 phase zone and what is the sub-cooling zone, but the duty or the demand or the heat load that changes. So, obviously, there will be shift of these zones.

So many cases by providing extra capacity of the heat exchanger; in this case, condenser we take care of this aspect. Otherwise if our design is very tight, then it will be sufficient for a particular operating condition for other operating conditions it will not be sufficient, ok. Then the next point the condensing heat transfer coefficient is a strong function of local vapor quality, decreasing as the vapor quality decreases. So, this is also one thing that, it is a strong function of the vapor quality and it decreases as the vapor quality decreases.

So, there are several reasons for this. One reason is that that as long as vapor is there, then condensation is taking place and some amount of heat is transferred due to latent heat. So, obviously, it is implication on heat transfer coefficient will be quite positive; that means, heat transfer coefficient will increase when there is condensation. But when it is reducing and ultimately it is producing a low, I mean sorry, the sub cooled liquid then the heat transfer coefficient will fall. Another thing when there is a when there is a large amount of vapor, locally the velocity is also high. So, that increases the heat transfer coefficient. So, these 2 effects are there that makes the heat transfer coefficient higher at higher vapor quality.

The condensing heat transfer coefficient is also a strong function of mass velocity increasing with the mass velocity increases. This point does not require much of explanation, because more the velocity more will be the heat transfer coefficient. We will see that here also we will the main mechanism of heat transfer is convection. So, in convection we know as the mass velocity increases or the Reynolds number increases we were having higher heat transfer coefficient. So, obviously, this is not difficult to understand or explain. Then oppose to external condensation, in tube condensation is independent of wall temperature difference. This is one important thing, as again let me go back and explain little bit.

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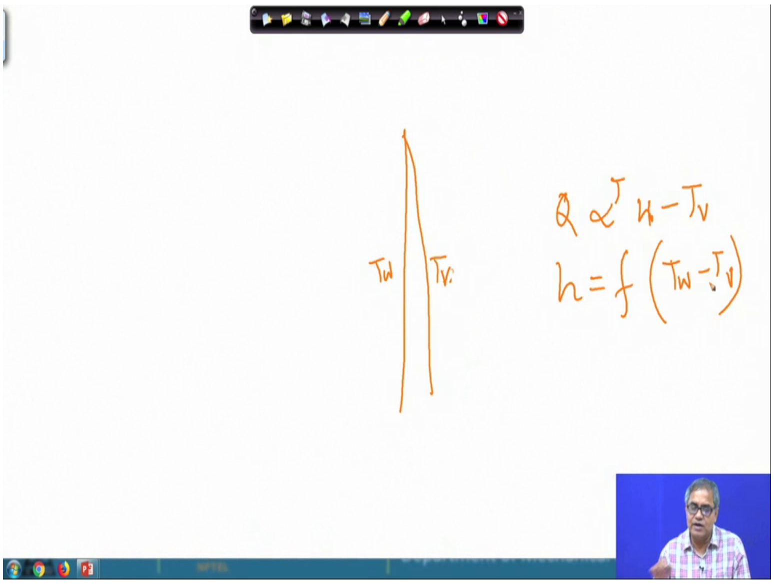

In Nusselt condensation theory as the film form; so, this side is T V, sorry, this side is T V and this side is T W. So, Q that is proportional to T W minus T V heat transfer coefficient will be will also proportional to this delta T W is a function of; that means, heat transfer coefficient is a function of T W minus T V; rather here it will be T V minus T W, because Let me write it correctly otherwise you may have a wrong conception.

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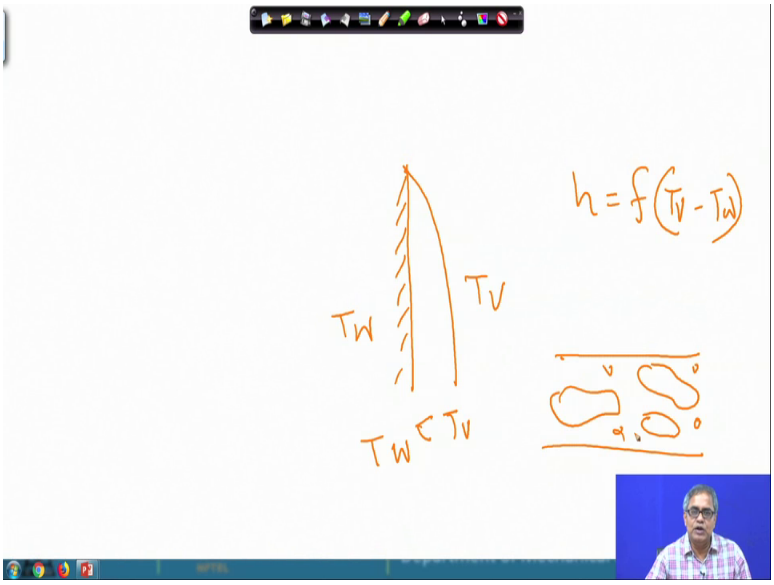

So, this is T wall and this is T V and T wall is greater than sorry less than T V and heat transfer coefficient will be a function of T V minus T W. So, this is for Nusselt's film condensation theory. Now, when in tube condensation is taking place, and we have got very different kind of flow regimes these are vapor and this is liquid. So, here the heat transfer coefficient will not be dependent on your wall temperature difference. So, this is a difference between your in tube condensation and condensation over the over the outside surface of the tube.

Once we have explained it, let us go back to our previous slide. So, except at low mass flow rate in stratified type of flow, we will not have we will not have any dependence on the wall temperature difference that is T sat minus T W which I have written as T V minus T W. So, the heat transfer coefficient will not depend on this. So, let us we are towards the end of our discussion. So, let us recapitulate what we have done; that in tube condensation is completely different from the condensation outside the tube, and in tube condensation is rather more complex phenomena due to the presence of different flow regimes.

Heat transfer coefficient can vary quiet a large along the length of the tube, and we will see how to calculate it with the help of definitely correlations are to be used and what kind of correlations we will see in our next lecture.

Thank you.