Two phase flow and heat transfer
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Lecture No: 18
Condensation

Hello, welcome in the eighteenth lecture of Two Phase Flow and Heat Transfer. Here, today we will be discussing about condensation heat transfer. So, let us see at the end of this lecture you will be understanding basic difference between drop wise and film condensation. We will be predicting the heat transfer coefficient in drop wise condensation. We will be discussing elaborately the mechanisms of droplet interactions during drop wise condensation.

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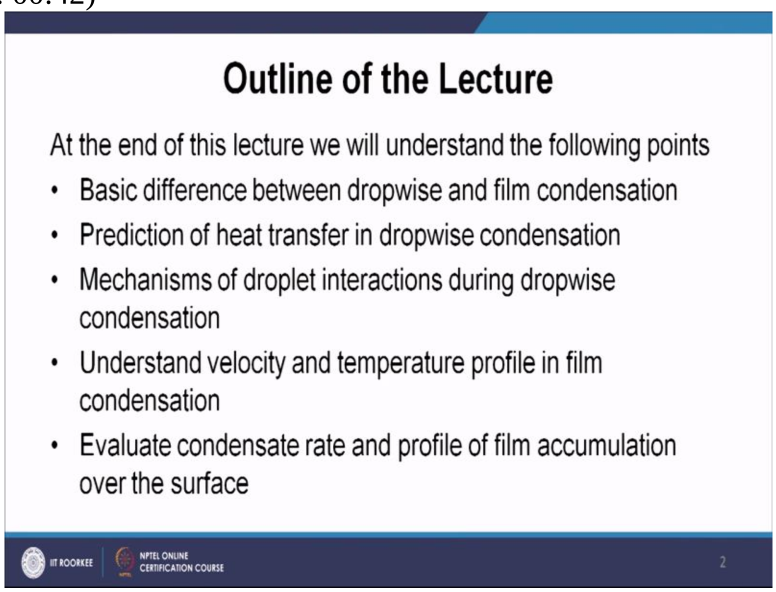

We will be finding out velocity and temperature profile when film condensation is happening over a vertical surface. We will be also seeing how to evaluate condensate rate and the profile of the film okay. Over the vertical surface, so let us start with the definition of condensation. So, condensation is 1 mode of heat transfer in which actually over the surface we will find out due to heat transfer gas will be converting into liquid okay. So here you will find out the surface will be actually having lower temperature than the saturation temperature okay.

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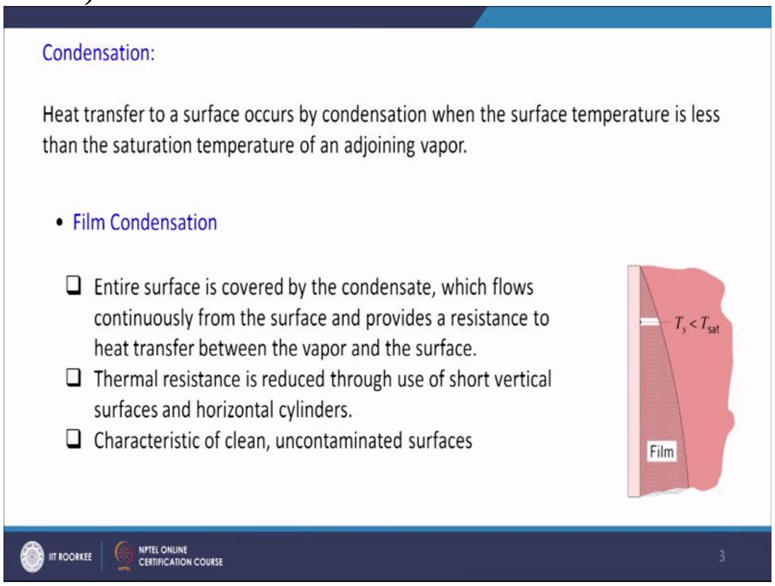

Now if we try to classify broadly, this condensation will be finding out 2 modes are there. One is called film wise condensation another one is called drop wise condensation. So first let us try to understand what is film condensation? So in film condensation majority of this type of film condensation we see over vertical surface. So here I have given you 1 schematic of the vertical surface. So let us say this is the surface, whose temperature is lower than the saturation temperature of a given pressure okay.

Now as this temperature surface temperature Ts < T saturation then you will be finding out that a liquid film is being formed okay due to the condensation. Condensation means, it will be forming liquid from vapor. So, you will find out that this liquid is forming a film over this vertical surface okay. So in case of film condensation, you will find out that entire surface is actually covered by condensate. It is not like that locally the surface is covered by the liquid, it is entirely covered which flows continuously from the surface and provides a resistance to the heat transfer between the vapor and the surface.

Because this film will be acting as some sort of resistance between you know vapor to come in contact with the cold surface. So you will be finding out this is giving some sort of resistance. So this thermal resistance okay is reduced okay through the use of short vertical surfaces and horizontal cylinders. If you want to know, remove this film boiling. So what we need to do on the surface, we need to give some sort of horizontal cylinders okay as some sort of appendage.

So that the film will be breaking down and you can once again go back to your drop wise condensation mode, where gas can come direct contact with your surface okay. And this type of film boiling you can see in the surface is where you will finding out surface is clean and you are having no contamination okay. Then let us see another version. So drop wise condensation so you see in drop wise condensation, here I have given you 1 figure in drop wise condensation.

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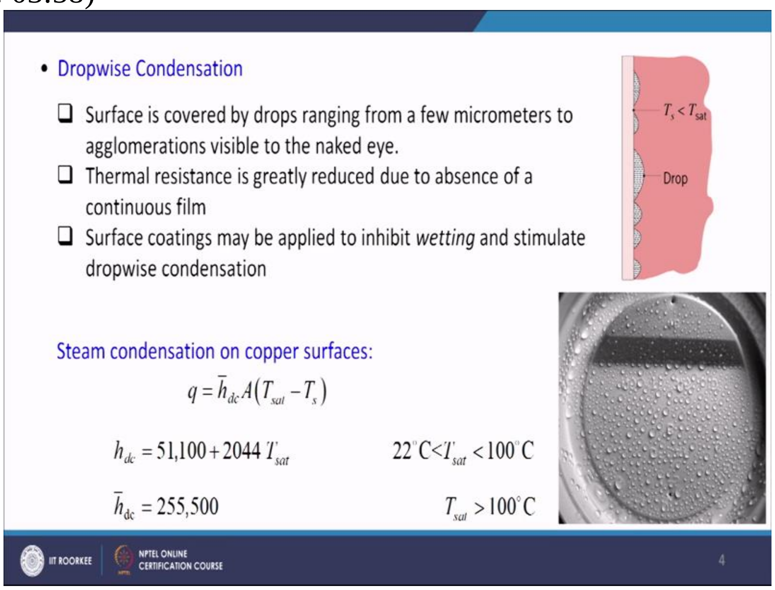

You can find out over the surface you are having lots of droplets of liquid being formed okay. Now this drop wise condensation majority of the time you will be finding out over a horizontal surface okay. But here I have given you 1 example, this to give you some sort of comparison between the previous 1 and this 1 that we are having a vertical surface once again. And you can find out lots of droplets are actually being formed due to condensation. So gas is converting into liquid.

Now in this type of drop wise condensation you will be finding out that surface is covered by drops and the size of drop will be ranging from a wide variety okay. So it will be starting from few micro meters okay. And you know agglomerations of this drops will be making this drop visible even with a naked eyes okay. Here I have shown you 1 typical example. Now this thermal resistance is greatly reduced due to this absence of continuous film whatever we have seen in the previous case. In case of film condensation and surface coating, you can apply okay to inhibit, to wetting and stimulate the drop wise condensation.

If the surface is having very poor wetting condition that means it is asking the drop to squeeze on the surface then you will be finding out the drop wise condensation is being preferred. Now let us see that how in case of drop wise condensation heat transfer can be calculated. So here I have shown you a situation where condensations, drop wise condensation is being predicted for steam over copper surface. So that can be written as q equals to heat transfer coefficient for drop wise condensation. hdc *a (Tsat-Ts) okay.

Now this hdc is very important heat transfer coefficient in drop wise condensation. It depends on the surface temperature. So if saturation temperature is in between you know 22 degree centigrade to 100 degree centigrade, we can write down the coefficient as 51,000, 100 + 2044* Tsat and if the saturation temperature is higher than 100 degree then you can write down that is actually 255,500 a constant value okay. Once you know the heat transfer coefficient once again you can go back to this equation to get the drop wise condensation heat flux okay.

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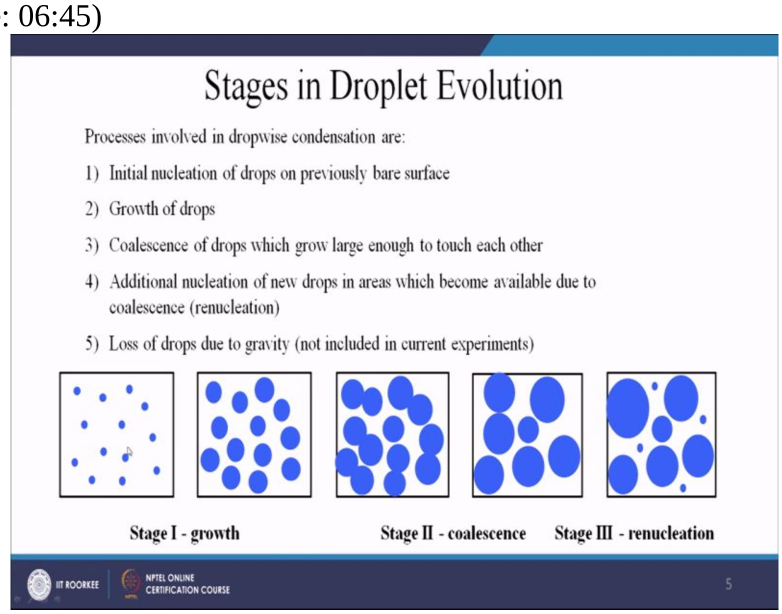

Next let us see that how these droplets in drop wise condensation will be behaving over a surface. So difference stages of droplet evolution. So you will be finding out at the beginning the droplets will be nucleating on the surface at this time the droplet will be having very smaller size in the range of a microns and then you will be finding out the initially those droplets will be growing in size due to more and more condensation around that. So it is actually increasing its size due to the condensation for that side okay.

And then after some time you will find out whenever this droplet size will be becoming considerably, we will be finding out 2 droplets side by side which are staying side by side they are actually merging or coalescences among themselves okay. So you will be finding out coalescences happens like this. Here you see the coalescences happen and the drop gets bigger and bigger in size, once again so bigger size droplets you can find out okay.

But at the same time if it is on a vertical surface then you will be finding out with the increase of size the droplet is also facing the gravitational pool. So you can find out at some time droplet is also being dislodged from the surface okay. So you will be finding out at some point of time whenever it is increasing in size some droplet you know can also dislodged from the surface okay. So loss of drop due to gravity is also very, very important.

Apart from that simultaneously you will be finding out over the surface more smaller nucleations are still continuing okay. Those are different stages of droplet evaluation and you will be finding out if you continue in this side further. Then once you will once up on a time you will be finding out that all those droplets are actually forming a film over the surface and it is turned into film wise condensation okay. Next lets us see the next subsection which already I have told as film wise condensation.

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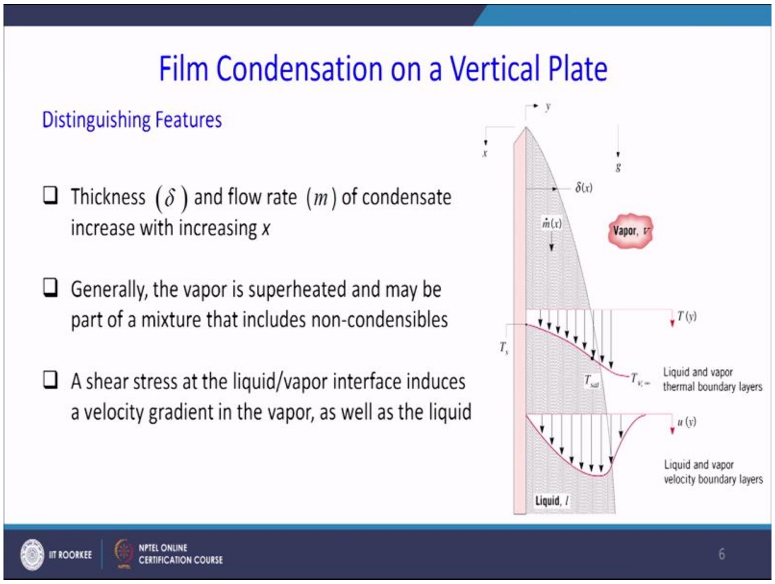

So let us try to see that how film boiling is distinguished from the drop wise condensation. So here I have shown you that vertical surface over which the film is being formed this is your liquid film being formed due to your condensation. So here in the periphery you are having vapor which is suppose to come in contact with the surface and form film okay. So this vapor I have considered as v and liquid I have considered as l. So now first if you try to find out the temperature pattern and velocity pattern over this surface then let us try to see what happens to the temperature.

All of us know that the vapor temperature will be at higher side and obviously surface temperature will be at the lower side which is necessary for condensation. So you will be finding out the temperature will be a smooth fall from the vapor side to the solid surface, where it will be attaining the Ts which is nothing but surface temperature and here it will be attaining Tv which is the Tv infinity you can say which is the free steam vapor temperature okay.

Now at the interface you can find out that there is continuous nature of the temperature also okay. Now if you think about the velocity, so obviously at the wall you will be finding out there is moistly condition. So there is no velocity over here. Obviously on the other hand you will be having no velocity when at the bulk of the gas also. So here you see once again the velocity is 0. So in between whatever film has being it has been formed that will be going in the downward direction. So you can find out a downward velocity in the film okay.

And at the interface you will finding out due to inertia you will be finding out the liquid which is falling down will be carrying some amount of gas also along with that in the downward direction. And velocity continuation is there so there is no discontinuity of the velocity so you will be finding out something like this for the velocity profile. Interestingly the highest velocity you can find out somewhere inside the liquid film domain okay.

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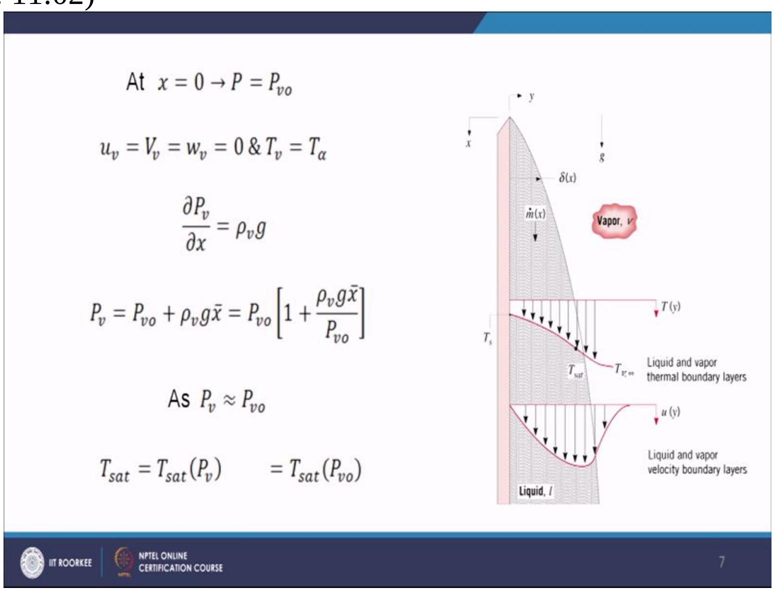

So let us now try to understand that how this condensate rate can be predicted okay. m dot can be predicted as well as how this film nature okay, delta or film thickness nature okay. Delta is the film thickness so how this film thickness varies with respect to your rate okay. So, in order to do, so we will be doing some sort of mathematical calculation for the vapor as well as the liquid. Let us start with the vapor side. So what will be doing at the leading edge that means where the film starts at this point? Let us call that 1 as x=0 where x varies in this side okay.

That means along the plate by it varies and y is actually the perpendicular direction of the wall. So at x = 0, you can find out pressure will be equivalent to your vapor pressure okay. So here we are having no liquid. So obviously the pressure will be equivalence to your Pvo okay. Next, in this position as you are not having any film liquid film. So obviously the velocities will be also 0. So we can write down that uv, vv and wv all are equals to 0 okay. And the temperature at this zone obviously will be the equivalent to your infinite temperature or bulk temperature.

So we can call Tv is = T infinity right. If you try to write down the momentum equations for the vapor now as we are having all the u's = 0. So you will be finding out only the pressure term and buoyancy term remain. So we can write down del PV /del x = Rho v*g okay. So once you integrate this one we find out that Pv = Pv not + Rho v *g x. Here we have used the integration criteria as x = 0, P = Pv. So boundary condition is at x = 0-> P = Pv not.

So if we take Pv not common form, here we get 1+ (Rho v g x / Pv not). Interestingly you see over here Rho v is there. So which is a very, very small value in case of at least for the water, so what we can do, we can neglect this term. So we can write down vapor pressure will be more or less equivalent at this zone. We can write down the vapor pressure is more or less equivalent to your Pv not okay. So we can write down your corresponding saturation pressure saturation temperature T sat, which is actually your saturation temperature corresponding to Pv that is once again equivalent to your Tsat at Pv not because Pv= Pv not. We have just now found out okay.

So and the limiting conditions for considering this Rho v very small. We can write down T sat = T sat Pv not okay. Next let us try to see from the liquid side but before going to the liquid side let us see the interface okay. So here we are having the interface between the liquid film and the vapor. So what we have taken, we have taken a small sector across the interface. So this is the small sector you see l and g okay. Liquid is there in this side in the film and gas is there in the bulk okay. So if we try to first find out the mass flow rate okay.
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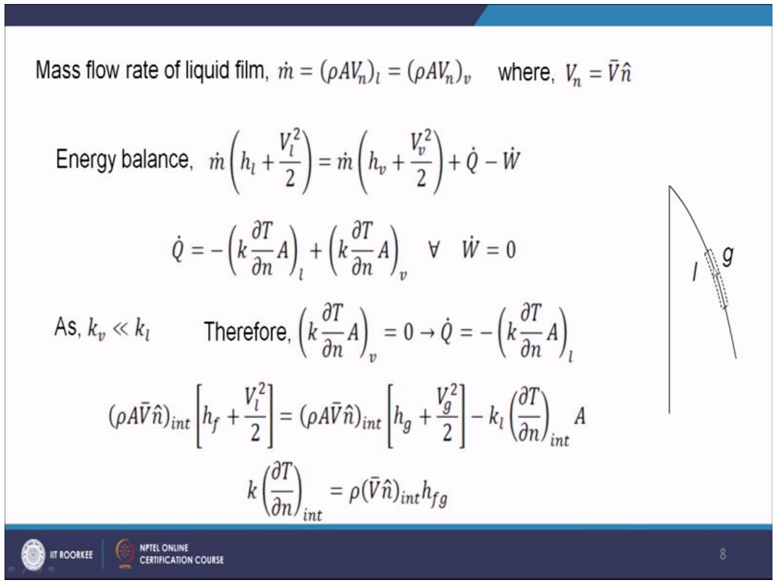

So mass flow rate for the liquid film. So mass flow rate m dot can be written as Rho a vn. Here this vn is the actually normal directional velocity of the interface. So here if you find out a normal of this one. So that directional velocity will be coming into picture over here okay. So this is actually equivalent to l and this is actually for the vapor. So because this 2 will be same because we know that whatever amount of mass will be being lost from the gas that will be accumulated in the liquid side okay.

So after doing the mass balance, let us go for the energy balance side. So if you go for the energy balance side in this across this interface then we can write down for the liquid side m dot * hl+ vl square/ 2. So this hl is nothing but your enthalpy for the liquid side. vl is nothing but the velocity for the liquid okay. So here you have added the kinetic energy portion over here okay and on the other hand side for the vapor, we can write down m dot * hv, which is the enthalpy for the vapor + vv square / 2.

Along with that we will be having the heat transfer and work done also as for the first law of thermodynamics. So you are having q dot -w dot but obviously in this case we are not having any w dot. So we can make it 0 okay. This can be cancelled out and easily this q can be written as now this q. q will be the heat transfer. Now the heat transfer will be dependent on the conduction to the liquid and conduction to the gas okay.

So conduction to the liquid if you write down then that will be -k (del t /del n A. Now this n is once again the normal direction okay. All the properties I will be taking for l that means liquid. So that means this will be kl A okay .And here for the vapor side we will be getting kv * del t/t del v del t /t del n of a right. Now you see they are opposite in sign because one will be actually accepting heat other one will be actually dumping heat okay. So q we can write down at the summation of both the conduction heats in liquid and vapor side okay.

Now if we put that this q and w in this equation then ultimately we will be getting the equation like this. Here I have also put the value of m dot from the continuity equation. So I have written Rho Av n dot. So this is v n cap is nothing but actually your normal directional velocity. What I have written in place of this vn okay multiplied by hf+ vl square / 2 equals to once again this is for the gaseous side mass flow rate. Remember what we have done over here. As this l and v are for the liquid side and vapor side in the limiting condition, we can write down there is on the interface.

So here both these l and v, we have written as int, this symbolizes the mass transfer across the liquid okay. So this will be for the gaseous side mass transfer from the gaseous side multiplied by hg+ vg square / 2 and the other hand side we are having over here the conduction part. Now see in the conduction part also. As I have shown you this conduction is actually summation of 2 conductions. So liquid side and vapor side but we know for the vapor side the thermal conduction conductivity will be very low compared to the liquid side.

So this term actually we can cancel out and this q can be written as - k del t/ del n A for the liquid side only. So that term we have kept over here as q right. So if we see this equation. So and take this first term in the right hand side to the left hand side. So I can write down that will be coming as (hf –hg) okay. Why because this is the limiting condition at the interface and at the interface already we have shown that there is no discontinuity of the velocity. So you will be finding out vl will be equivalent to your vg. So that part will be canceling out and will be having (hf-hg) which is nothing but hfg okay. So we get in this side the conduction and here in this side we get your condensation heat transfer okay involved with the hfg okay.

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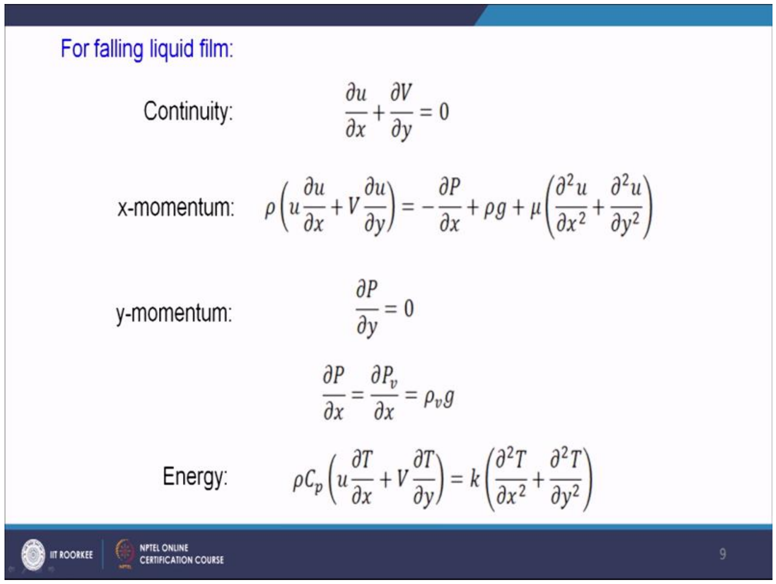

Next let us see after this 1 interfacial condition let us see what happens for the liquid side. So we have taken falling liquid film assumptions. So in falling liquid film assumptions we have written down over here the continuity, x momentum and y momentum equations respectively okay. So these are coming from your fluid mechanics already you know and here as we have already shown that del p/del x for the vapor side will be rho v * g that also you will be using into consideration, because this we have already shown for the gaseous phase momentum equation side.

And energy equation in the liquid if you write down, so in the left hand side, you are having convection and the right hand side you are having conduction okay. Next to reduce this number of equations you see over here we are having at least 1, 2, 3, 4 equations. So these 4 equations if you try to reduce the number of dependence then what will be doing, we have taken some approximations. So first approximation what you take is called Nusselts analysis. So he has, Nusselt, he has proposed this one what he has consider the assumptions are laminar flow in the liquid.

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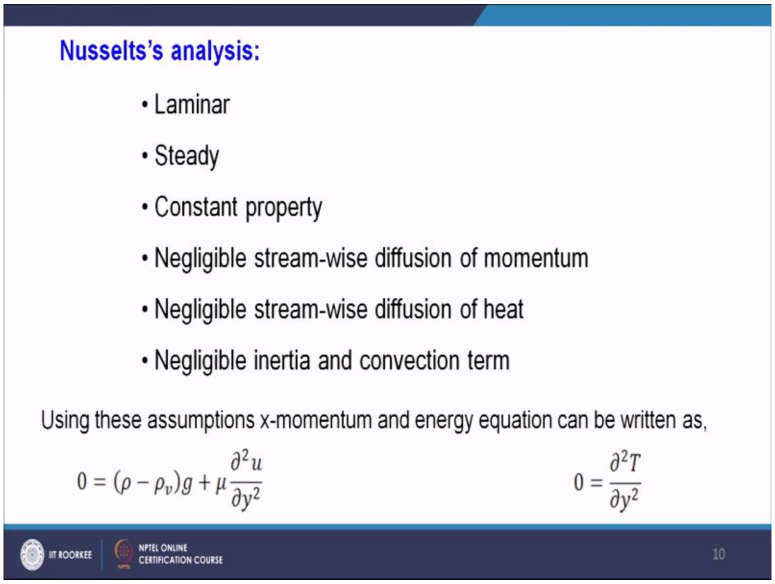

He has considered flow of liquid steady; he has considered the liquid is having constant property negligible stream wise diffusion of momentum. So negligible stream wise diffusion of momentum means in your equation del square u /del x square will be equals to 0 because x is the stream direction. So that portion is 0 okay diffusion stream wise diffusion is 0. Similarly, negligible stream wise diffusion of heat. So your energy equation you will be finding out this del square t /del x square will be also going to 0 okay.

And negligible inertia and convection term so this is very important so convection, inertia if you neglect so all these left hand side and in the energy x momentum equation and energy equation will be canceling to 0 okay. So our equation sets of equation becomes very, very simple. So this comes from x momentum equation. 0, already we have cancelled this inertia. So 0 = (Rho -Rho v) * g .Where from this (Rho - Rho v) is coming? Actually you see you are having del p /del x over here. So del p/ del x = Rho v* g we have got over here.

So we put this from this equation over here. del p/del x value will be getting a (Rho – Rho v) * g. So that term will be coming over here (Rho - Rho v)* g +. Only the cross wise diffusion is term is remaining in the momentum equation. And from the energy equation we get very simplified form del square t/ del y square = 0 because stream wise diffusion, a stream wise diffusion in energy equation and your conviction has been neglected as per the Nusslet analysis okay. Let us see the boundary conditions.

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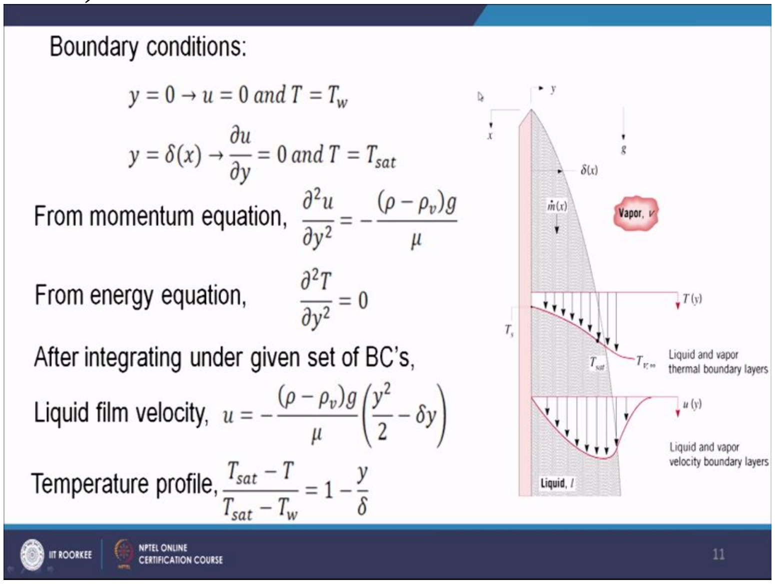

Now so at A y = 0 that means on the surface obviously the velocity will be 0 and the temperature will be Tw which is the wall temperature or you can call that one as surface temperature Ts okay. Now at interface which is nothing but y = delta will be finding out that there is no gradient of velocity because the velocity continues over that. So del u/del y = 0 as well as we find out that there the phase change is happening, so the temperature will be actually equivalent to your saturation temperature. So t = T sat, so if we now integrate your momentum equation and energy equation which already we have discussed based on the Nusselts analysis.

If we integrate along with this boundary conditions then you will be finding out u from the integration of momentum equation comes out to be – (Rho - Rho v g) * g / Mu * y square /2. – (delta y) very simplified integration we are having and we have to put the boundary conditions as y = 0, u = 0, y = del u/ del y = 0 okay. So we get the liquid film velocity in this fashion and energy equation is very simple. So 2 times integration if we do for this equation and along with the boundary condition y = 0, T = Tw, y = delta t = T sat.

We get straight forward solution for the temperature profile T sat - Tw = 1- y /delta okay. So you see this nature if you see already we have shown you over here. So this y verses u that is parabolic nature. So this is a parabolic nature and for t verses y that is actually a linear nature. So you see that is the linear nature over here. W e have seen okay. Next, let us try to find out that how condensate rate can be achieved. So here I have shown you that condensate rate m dot =0 to delta Rho u dy okay. Already we have found what is y.

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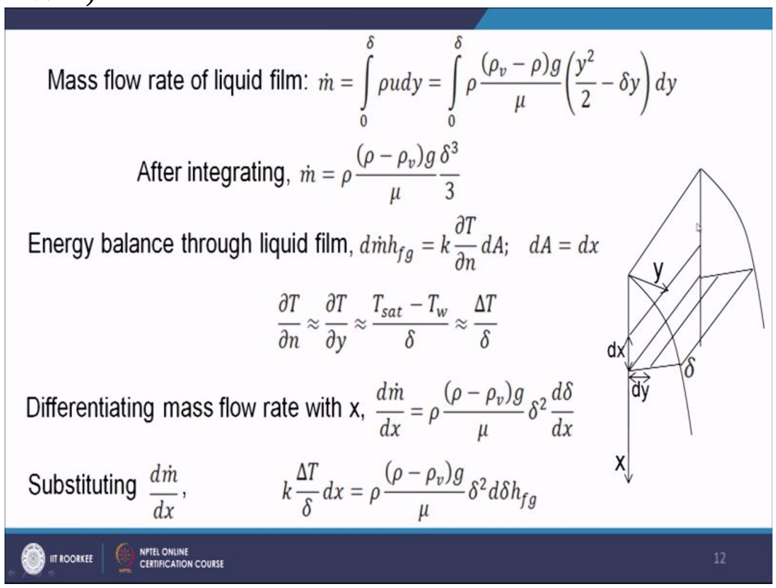

So let us put that y over here or y I have shown in the u. I have shown you in the previous slide liquid film velocity. So let us put this expression over there in integration. So if I put this over here and perform the integration then I get m dot is equals to with the obviously with the limits 0 to delta. Because, film condensation will be inside the film thickness only. So m dot becomes Rho *Rho - Rho v *g delta cube / 3 / Mu okay. So this is the condensate rate very, very important term for condensation.

And if you try to find out that the mass balance energy balance across the liquid film then I will be writing down d m dot hfg = k * dt/ dn * dA. If you remember this you have already explained across the interface earlier. We have got that d m dot *hfg d m dot this was d m dot actually d m dot into hfg was actually k*del t/ del n and the interface okay. So same equation you are using over here d m dot hfg = k*del t/ del n * dA okay. Now here interestingly if you see here dA is actually dx. So this is the area so this is rectangle.

If you see this rectangle is actually giving you the heat flux to the film. So you will be finding out that dA is actually dx*1. We have considered unitary directions in this way in this side okay z direction. So you can write down da = dx. So if I put this del t /del n over here. Del t/ del n will be once again the normal direction is y direction. Already I have showed you so del t/ del n will be del t/ del y and that can be reduced to Tsat – Tw/ delta okay. So if I put all these things over here del t/ del n will be del t / d and dA = delta x will be getting dm dot dx = Rho* Rho – Rho v * g / Mu delta square del/del x okay.

So what we can do once again m we have got over here. So if I make the derivative of m and put it over here in this equation then I will be getting this equation you see in this equation the left hand side we are having derivative of x and in the right hand side we are having derivative of delta. So we can easily integrate this one okay. So if we integrate then you find out if we integrate from you know 0 to x okay. Then we will be finding out that this is becoming delta 4 to the power 4 and in the right hand side we are having Mu k delta t / Rho * Rho – Rho v g * hfg * x plus A okay.

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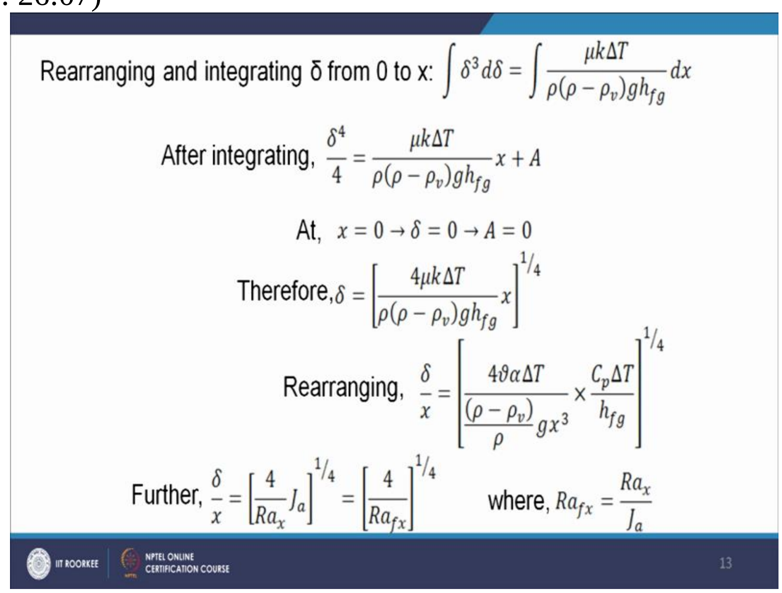

Now we need the boundary condition for finding out A. So we need the boundary condition means we know that x = 0 delta = 0 at the leading edge. So we get that value of A = 0 okay. Finally the delta turns out to be 4Mu k delta t/ Rho* Rho- Rho v ghfg * x to the power 1 / 4 okay. So if you rearrange this a term a little bit then you will be finding out this is this will be coming out as ratio between 2 non-dimensional numbers 1 is called Jacob number, another 1 is called Rayleigh number and we define the film Rayleigh number as Rayleigh number /Jacob number.

Then we can get this delta / x will be coming out to be 4 /Rayleigh number, film Rayleigh number to the power 1/ 4. So this is very, very important relationship. If I can find out the film Rayleigh number then easily the delta / x can be obtained okay. So to summarize this lecture what we have done, we have described the basic differences between drop wise and film wise condensation and where those occurs those things we have discussed. We have discussed the mechanisms of droplet growth and reduction okay in case of drop wise condensation.

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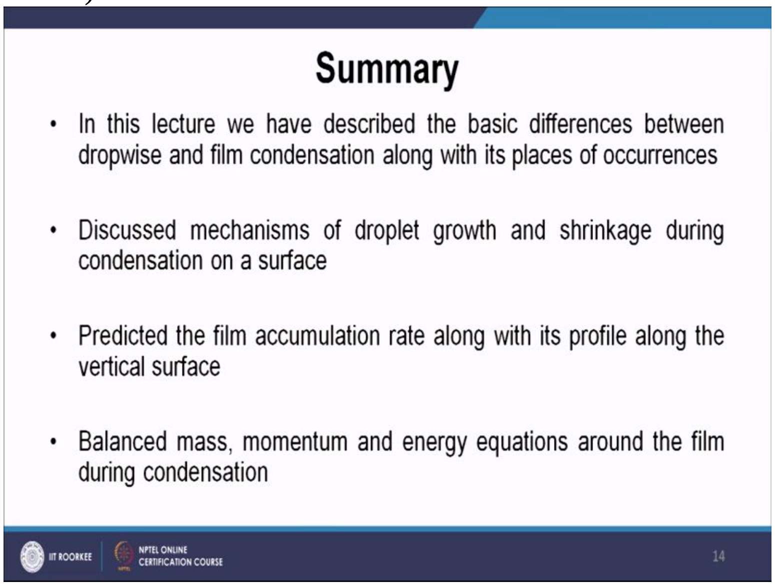

We predicted the film accumulation rate okay in case of film wise condensation over vertical surface and we have balanced mass momentum and energy equations to find out the film profile over a vertical surface okay. So let us test your understanding. So we are having once again 3 questions over here.

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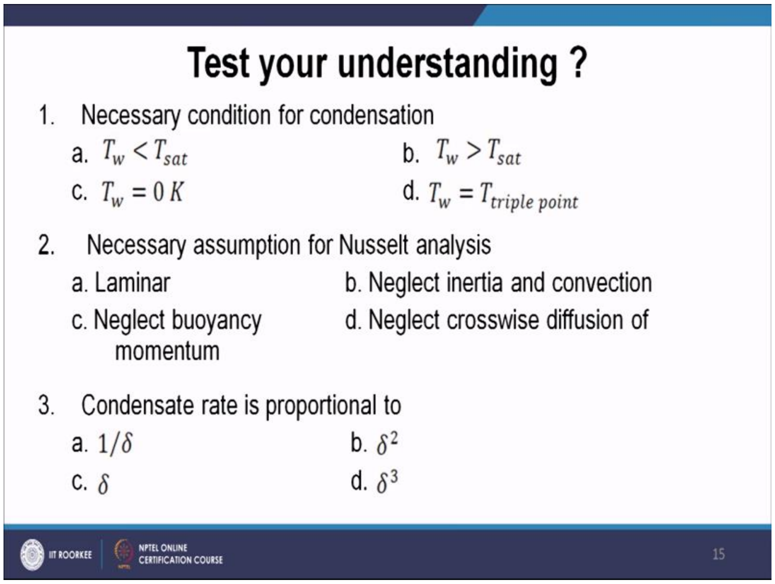

First question, necessary condition for condensation. You are having 4 answers part a Tw < Tsat, part b Tw > Tsat, part c Tw = 0 kelvin and part d Tw = t triple point okay. Answer I think all of us know answer will be part a, where surface temperature requires to be lesser than your saturation temperature okay.

Second question goes like this necessary assumption for Nusselt Anaysis. We have given you the assumptions today. So the assumptions the answers you are having as first assumption can be Laminar, second assumption is neglect inertia and convection, third assumption neglect buoyancy and fourth assumption neglect crosswise diffusion of momentum okay. So the correct answer will be obviously part a and part b because we neglect the stream wise diffusion and we and we will not be neglecting buoyancy otherwise g will not be coming into picture okay.

Let us see the last question condensate rate is proportional to very simple in the previous slide. I have shown you. So condensate rate m dot will be proportional to 4 answers you are having 1 /delta delta square/ delta is the film thickness here and part c is delta and part d is delta cube. So the correct answer is delta cube. In the last slide we have seen. So with this we will be ending this lecture, thank you.