Thermal Operations in Food Process Engineering: Theory and Applications

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Lecture - 41
Condensation

Good morning. We have done already boiling, 'right'. Boiling is one of the very basic unit operations; and hopefully in many of places, it is used. I give you one more example which I already had given others. Like you have seen that in typically refrigeration units, 'right' that in the evaporator coil, these liquids they come and then get boiled off, 'right'.

Because the boiling point of the liquids is minus maybe 30, maybe 40, maybe 50 or even more so that depends on the liquid which is being used. So, there once you are boiling, I mean once the refrigerant is going in and coming in contact with comparatively higher temperature that moment it boils up, 'right'. So, that is one of the great example, 'right'. Similarly, other examples we have already given.

Now, I started with that you are making tea and for that you are boiling water, 'right'. And I gave the example that you are also putting a lead on that, and on that lead these vapors are getting condensed, 'right'. So, how that condensation is taking place, how we can do the heat transfer analysis that we will now look into. What we are now doing is that lecture number 41, and that is for Condensation, 'right'.

So, in this condensation, we will try to tell, I give you one more example for the condensation other than that tea making, this is commercially done, 'right'. So, you have a calandria, 'right' and this side you have cold fluid and this side there is a flow of the liquid coming in, 'right'. And this, this is what at a concentration of C_{A1} to a concentration of C_{A2} is being concentrated, 'right'. So, this is called evaporator. So, in the evaporator this kind of thick film they are moving in vertical desert called calandria. So, in the vertical calandria and heat transfer takes place in that. So, this is one example which is commercially applicable, 'right'.

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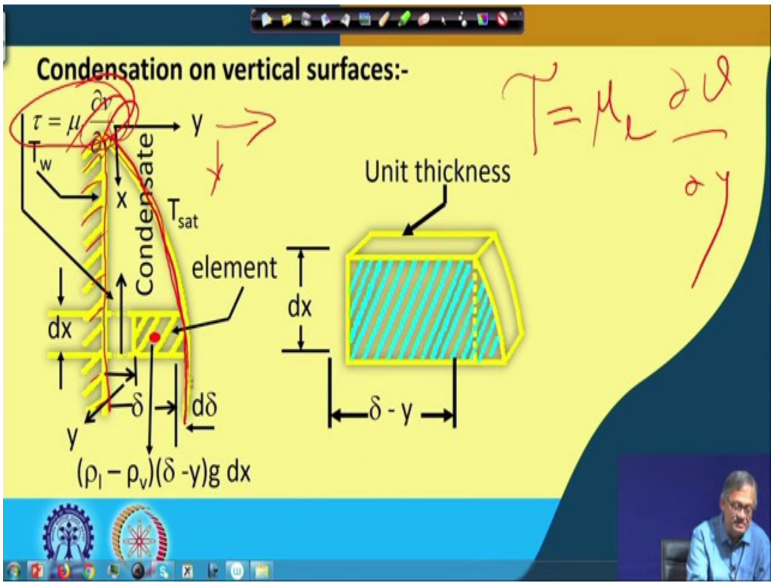

So, let us look into that how first we take picture that this is drawn with me of course that we are taking that the one which we said a vertical wall, ‘right’. So, this is the vertical wall and there is a flow of the fluid, and the flow is like a parabolic flow, ‘right’ that in pipe flow also you have seen that flow can be parabolic, ‘right’.

So, we assume that from this point and we are taking that x, y at this point ‘right’; y is in this direction and x is in this direction, ‘right’. And we tell that in this point that τ is μ_l dv dy, ‘right’. So, since it is there not visible τ is μ_l ‘right’ μ liquid δv δy, ‘right’. So, this is τ that is the shear force which is acting, ‘right’. So, at this point, this is the 0, 0, or this is the coordinate. And we are considering this flow of the fluid which is at certain concentration, and during this process it becomes more and more concentrated, ‘right’.

So, in that we have taken a volume element like this, ‘right’; a volume element we have taken and this volume element is having this also ‘right’ and that thickness is dx, ‘right’. And the condensate which is this entire thing is the condensate, ‘right’. This condensate is moving. And we take a thickness of δ, ‘right’ in the y-direction, ‘right’; in the y-direction, the thickness of the film is δ. And we take a small thickness, ‘right’ which is equivalent to dδ that is between this and this, ‘right’ that we have taken between this and that.

And we magnified this part here, ‘right’; we magnified this part here as this is the unit thickness this other dimension, ‘right’, other dimension is the unique thickness as we have seen that this is coming like this fine and we have taken that this got shifted a little bit, because this was arranged. So, this is the thickness which we are telling is δ-y, 'right' δ-y and in this, this is the dx thickness, 'right'. So, our volume element is that dx for this dimension, δ-y for this dimension, and unit thickness for this dimension.

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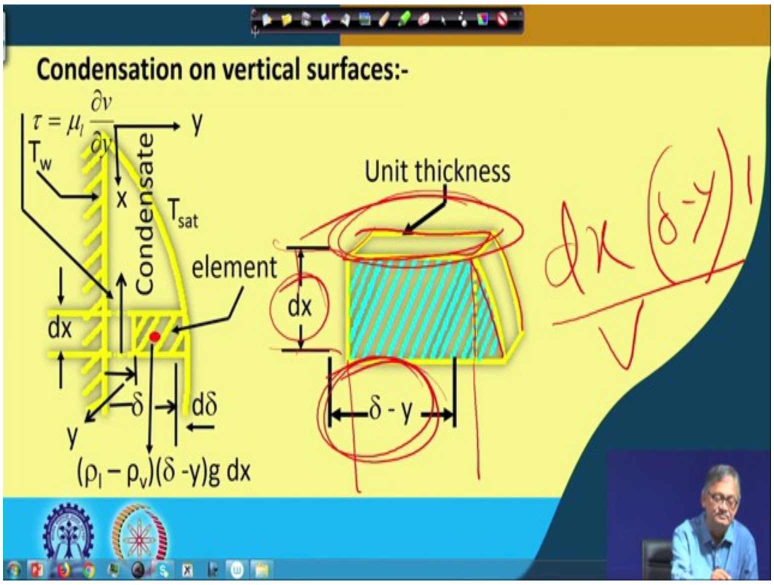

So, that is the volume element, so that is dx (δ – y) × 1, this is the volume element, 'right'. Then one more thing we have to say in this is that we assume that outside this is the saturation temperature $T_{saturation}$, 'right'. Wall of this is at T_w , 'right' and the element which we have taken is here, 'right' so, in this we can make this assumption that $(\rho_l - \rho_v)\times(\delta - y)\times g\times dx$, 'right'.

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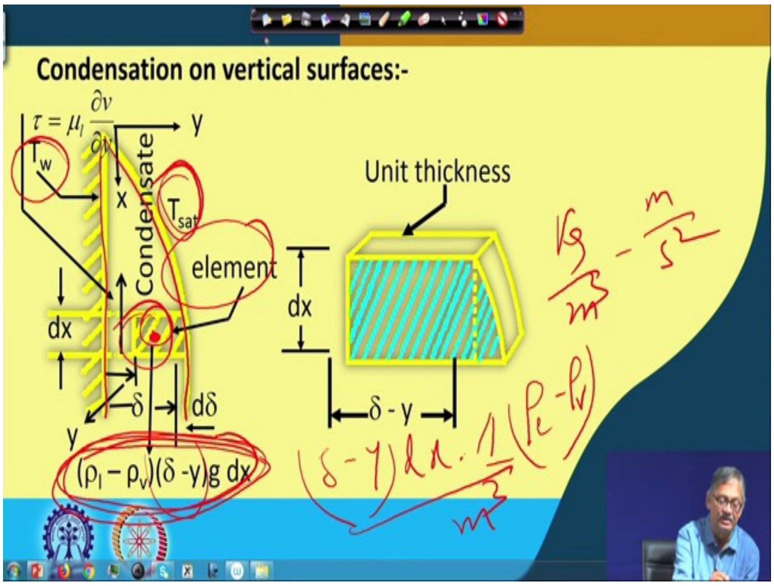

So, this is the volume element; volume is your ($\delta - y$) × dx × 1 that is the volume, 'right', and (ρ_l - ρ_v) is the density difference that is in this, this is m^3 and that is kg/ m^3, 'right', and g is m/s^2, 'right'. So, we get kg/ m^3 that m/s^2; this unit we will utilize a while and that is applicable at this point, 'right'.

So, let us then proceed to the solution, 'right'. Again our this shear stress is τ μ_l $\delta v/\delta y$, 'right'; obviously, that is - μ_l $\delta v/\delta y$ and the wall temperature is T_w that is what we have said, and the volume element we have taken fine.

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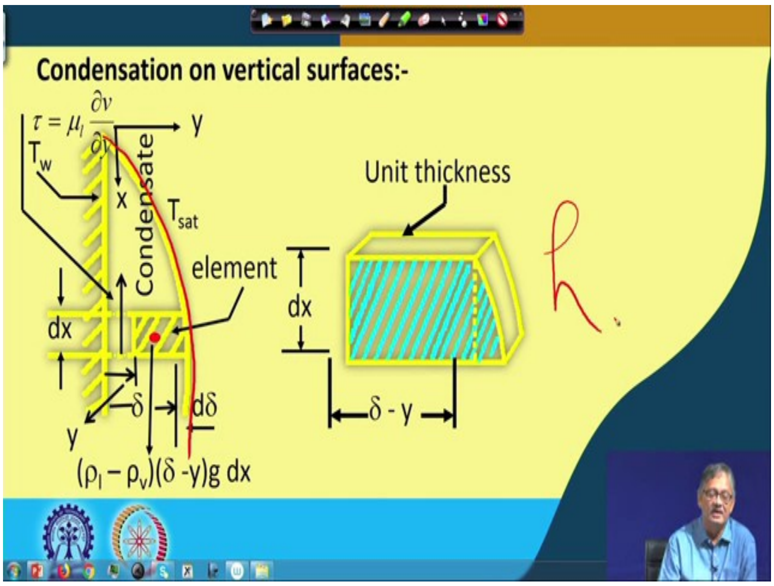

So, we know that this flow we will find out what is the temperature distribution, what is the heat transfer coefficient, etcetera we will find out. So, to do that, we keep this thing in mind that our volume element is this having (δ – y) in the y direction, in x direction dx and the third dimension is unity or unit thickness, 'right'.

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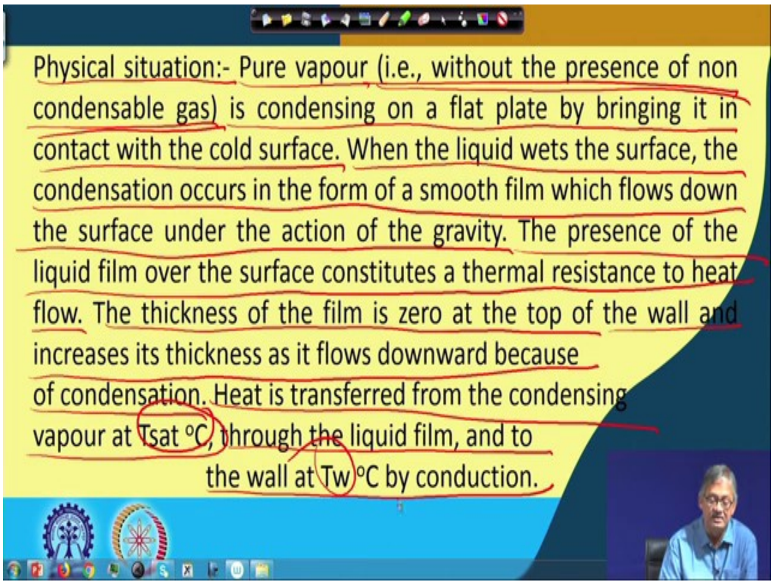

So, as we said just now that physical situation if we elaborate that the physical situation is like that. We have a pure vapour that is without the presence of non condensable gas, 'right', we have pure vapour without the presence of non-condensable gas is condensing on a flat plate by bringing it in contact with cold surface. When the liquid wets the surface, the condensation occurs in the form of a smooth film which flows down the surface under the action of gravity.

The presence of the liquid film over the surface constitutes the thermal resistance to heat flow. The thickness of the film is zero at the top of the wall and increases its thickness as it flows downward because of condensation. Heat is transferred from the condensing vapour at $T_{saturation}$, through the liquid film, and to the wall at the wall temperature of T_w °C by conduction, 'right'.

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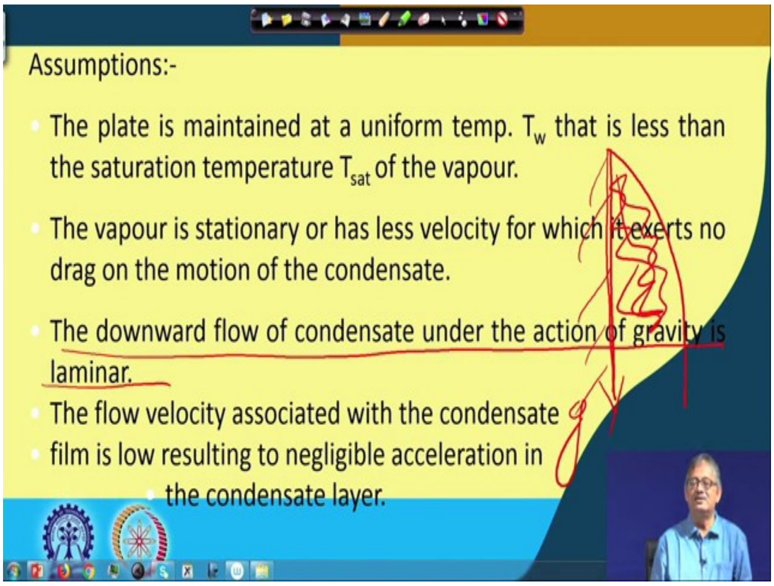

So, if this is known, then we can do the analysis like this with certain assumptions, and assumptions are valid assumptions like this. That the plate is maintained at uniform temperature T_w wall temperature that is less than the saturation temperature T_{sat} of the vapor. This is first assumption that is the plate is maintained at a temperature T_w which is less than the saturation temperature of the vapour or T_{sat}, 'right'.

Then the vapour is stationary or has less velocity for which it exerts no drag on the motion of the condensate. I repeat, the vapour is stationary or has less velocity for which it exerts no drag force on the motion of the condensate. We will make the drag force, because this was the wall, 'right' on which this was our vapour condensing, 'right'. And since the flow is very less, 'right', it can be assumed at pseudo study few things like that, 'right'. So, it has very less velocity for which it does not exert any drag force; otherwise drag force would give the opposite direction of the flow some force which we are neglecting.

Then the downward flow of condensate under the action of gravity is laminar that is also a very vital point. That you have this vertical plate and you have this flow of the condensate, 'right', it can happen. That since if it is acting with gravity g, then it can happen there could be a mixing of the condensate, 'right', and that may cause maybe a little turbulence or maybe something like that.

But we are assuming that this condensate is flowing in a laminar flow. So, the layers they are not mixing, there is no mixing of the layers, 'right', this is what we are assuming, 'right'. So, the downward flow of the condensate under the gravity is laminar. This is another assumption.

Then the flow velocity associated with the condensate, the flow velocity associated with the condensate film is low resulting to negligible acceleration in the concentrate a condensate layer. The flow velocity associated with the condensate film is low resulting to negligible acceleration in the condensate layer, 'right'.

So, there is no since velocity we are issuing to be very low, so acceleration due to the gravity that will not take place. In other word, this is also coming as per that the flow regime is laminar that is your, the fluid layers are laminar; there is no mixing of the fluid. So, with this let us go to the solution that we have assumed these things.

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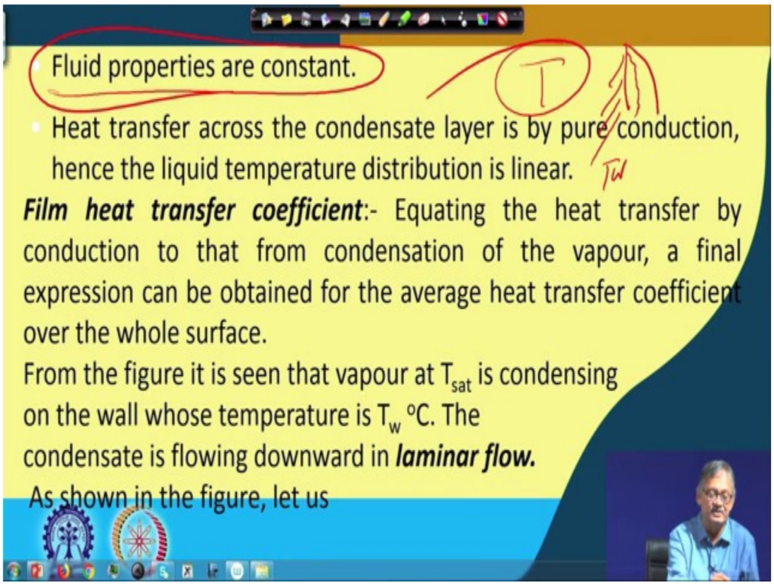

And now, one or one or two more are there that is fluid properties are constant. We have seen by this time a lot that the fluid properties is a function of temperature basically, 'right', fluid properties is a function of temperature. So, obviously, since the condensate will come from there and this T is T_w and which is constant we have said, and then it is likely that from here to there, there may be a temperature change during the flow of the fluid. And during this process, the property values are not changing that is under steady or constant those property values are constant.

Heat transfer across the condensate layer is by purely by conduction; hence the liquid temperature distribution is also linear. Since it is a liquid or fluid, we are likely to have that this wall and the condensate is flowing like this. So, there could be a convection if at all in heat transfer, but since the flow is laminar, the velocity is very low all these assumptions we have made, we also can say that the heat which is being transferred like from here to this point, this is only by conduction through the fluid, 'right'.

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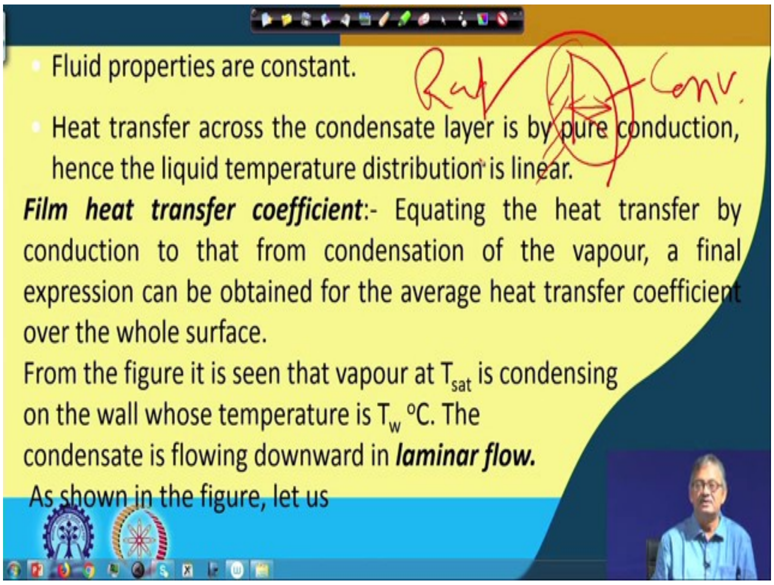

So, only conduction through the fluid, there is no convection or radiation it in this, 'right', so that is another very basic assumption.

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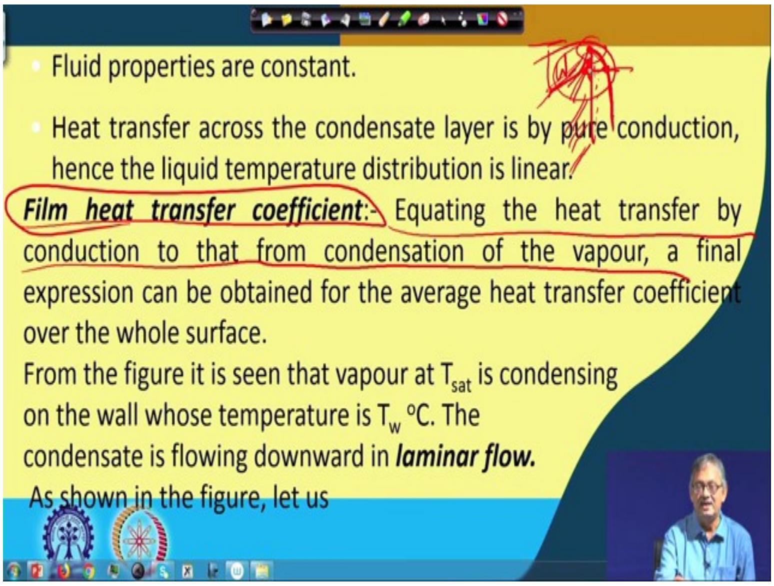

So, if these assumptions are made, and now if we look at then we can say that film heat transfer coefficient which we have to find out that can be determined like this. Equating the heat transferred by conduction to that from condensation of the vapour; basically, what is happening you had this T_w or wall temperature, 'right', and the fluid is now moving like this, 'right'. And, what is happening that because of this low temperature of the fluid of the wall, this is condensing at this point and gradually is dropping down, 'right' gradually is dropping down.

Now, while it is doing it at any moment, we have a thickness like this, 'right'. And this wall temperature has to be propagated to this upper layer or free end of the fluid, who will conduct we will transfer this, this is by conduction. So, how it is happening, at this point that fluid is giving away the latent heat of condensation, 'right' to the wall and thereby the conduction is taking place.

So, the equation will be in terms of the heat transfer by conduction to that from the condensation of the vapours, a final expression can be obtained for the average heat transfer coefficient over the whole surface, 'right'.

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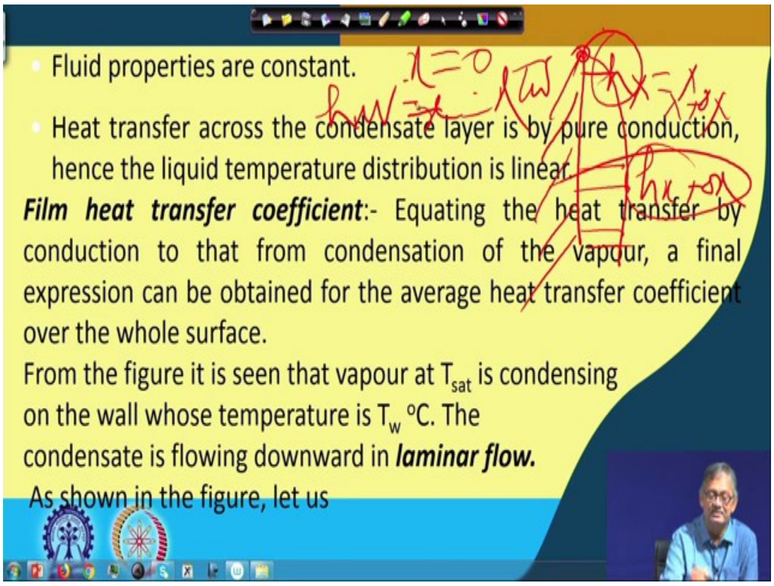

And that is obvious that again and again we are showing that this is a T_{wall}. So, the heat transfer coefficient whatever was seen here, 'right'; whatever was here that can be said as local heat transfer coefficient h_x, 'right'. And this is corresponding to that x = x, but at x is = x + Δx, this h will be then h_x + Δx at that point, 'right'. So, if we look at like this, there will be different h_s for different xx. So, we can make average of all these x, x = maybe 0 to x = x or something of that boundary we can put, and make an average h average, 'right' that is our goal.

Now, to do that from the figure which we have already shown it is seen that the vapour at $T_{saturated}$ is condensing on the wall whose temperature is T_w °C. The condensate is flowing downward in laminar flow, 'right'. So, as it has been shown in the figure let us take as we have already shown in the figure that let us assume unit thickness which you have already shown.

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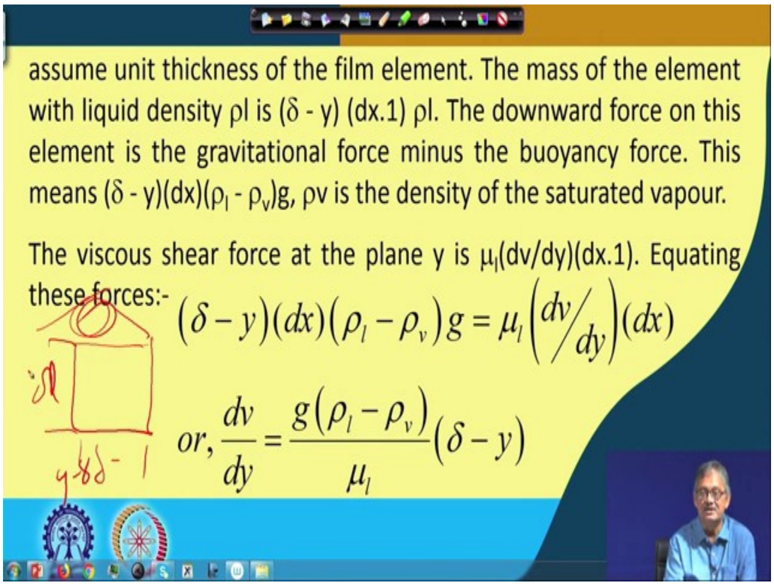

If you remember that while we said this was Δx, this was δ-δ, ‘right’, this was y-δ, this was Δx and the third dimension which we said that was unity, ‘right’. The third dimension was unity. So, we are assuring that thickness of the film element, ‘right’, unit thickness of the film. The mass of the element with liquid density ρ_1 is $(\delta - \rho) \times dx \times 1$, ‘right’.

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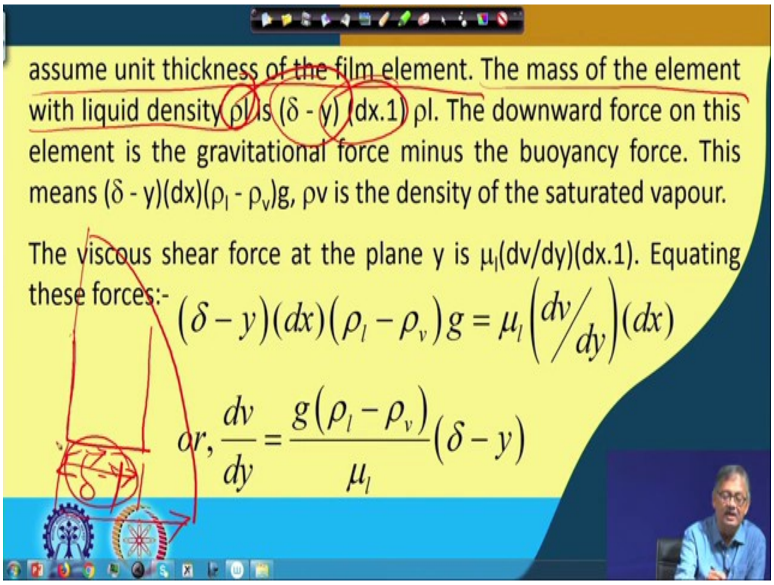

So, δ ρ y sorry not ρ δ - y because we had taken this one not y - δ δy, because y is at any point and δ is the total thickness which we had taken, ‘right’. So, this was δ and this is at a y. So, δ - and y was the entire, 'right' this was that y was for the entire thing, 'right' we so that we are assuming, that if it is so then the liquid density ρ_l and the volume is (δ – y)dx ×l. So, in that density is ρ_l, so that means, the element with liquid the mass of the element, because this is in m^3, ρ_l is in kg/m^3, so that comes to mass kg, 'right'.

The downward force on this element is the gravitational force minus the buoyancy force, 'right', because a gravitational force is acting on that and the layers which are like that that is the buoyancy force, 'right'. So, this will be equilibrium of the downward force on this element is the gravitational force minus buoyancy force, 'right'. This means that δy (δ-y) × dx × 1 × (ρ_l - ρ_v) × g, this is the thing which is acting, 'right'.

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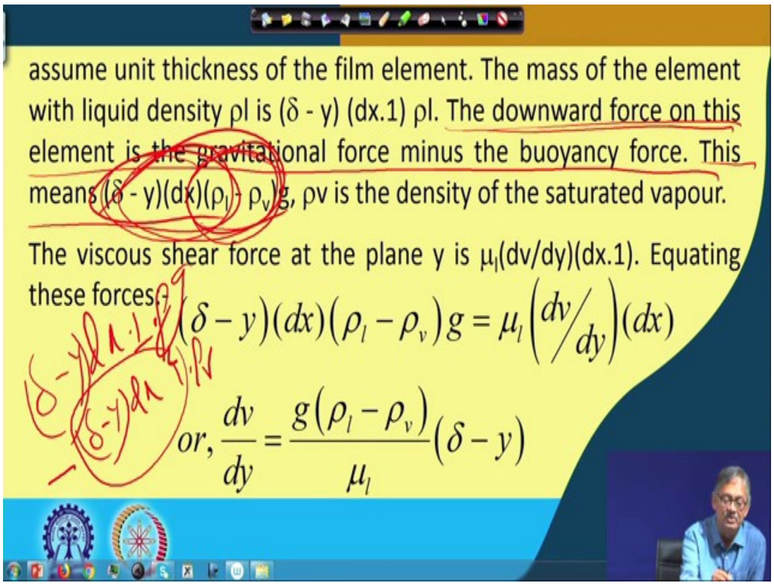

So, because the gravitational force is that volume (δ – y) × dx × 1 that times ρ_l × g that is the gravitational and minus that for the vapour it was equivalent (δ – y) × dx × 1 × ρ_v, 'right'. So, we take (δ – y) × dx × 1 as common, then we get ρ_l × ρ_v and g common so that comes to (δ – y) × dx × (ρ_l - ρ_v) × g, where ρ_v is the density of this saturated vapour.

So, we can say the viscous shear force at the plane y is μ_l dv dy × dx × 1, 'right'. So, dx × 1× dx was this, and 1 was that thickness, 'right', so that means, this 1 ok. So, this is μ_l dv dy dx × 1. So, if we equate these forces, then we can write (δ – y) dx × (ρ_l – ρ_v) × g, this is equal to μ_l dv/dy × dx into of course 1 which is not written, 'right'.

So, we get dv/dy is [g × (ρ_l – ρ_v) / μ_l]× (δ – y), 'right'. So, we have that the gradient – velocity gradient as dv dy is [g × (ρ_l – ρ_v) / μ_l] × (δ – y), 'right'. So, subsequently this velocity gradient we shall utilize 'right', but obviously for this class it is for half an hour and our time is almost over. So, we cannot proceed further.

And next class, we will start with this dv/dy, 'right' as g × (ρ_l - ρ_v) / μ_l × (δ – y). This expression we shall start within the next class and today we make it a day.

Thank you.