Thermal Operations in Food Process Engineering: Theory and Applications
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Lecture - 40
Boiling (Contd.)

Good Morning. So, we were discussing about the Boiling mechanism, 'right'. We had shown you that now in this 40th class, we will continue with that boiling. Maybe some problems we will solve that will give us more idea about the boiling mechanism, 'right'.

We have seen that there were 4 zones; a, b, c and d. So, first one was natural convection, 'right' and then that nucleation nucleate boiling, 'right' and in the third zone it was film boiling and fourth was no, fourth was film boiling and third zone that came down, 'right'. So, with this let us go to that class 40th and let us now look at some problem, 'right' and empirical relations.

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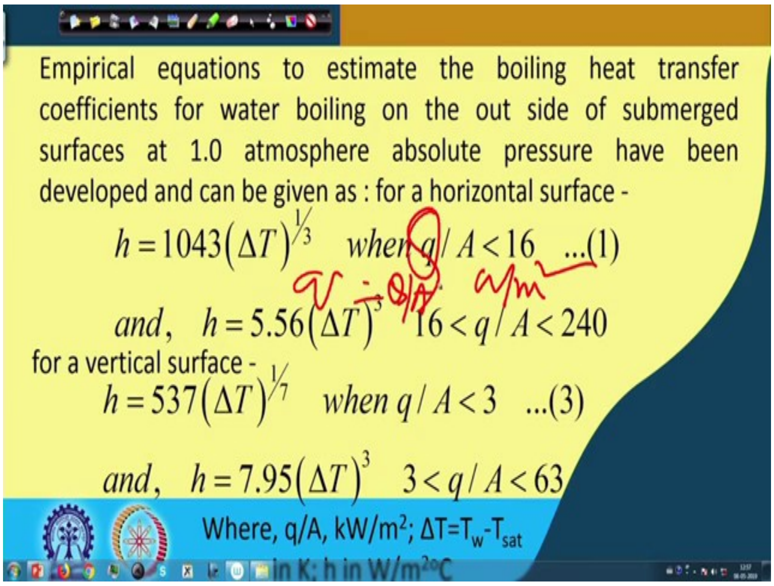

So, some empirical relations are there for estimating the boiling heat transfer coefficient. So, for water boiling on the outside of the submerged surfaces at one atmosphere pressure absolute and have been and this have been developed by some of the researchers, 'right'. For a horizontal surface that h is 1043 $\Delta T^{1/3}$, when q/A less than that is flux is < 16, 'right'. So, again q/A means this is W/m^2, 'right'. In some cases this is used capital Q, 'right' or q/A is small q normally, 'right' that is flux ok.

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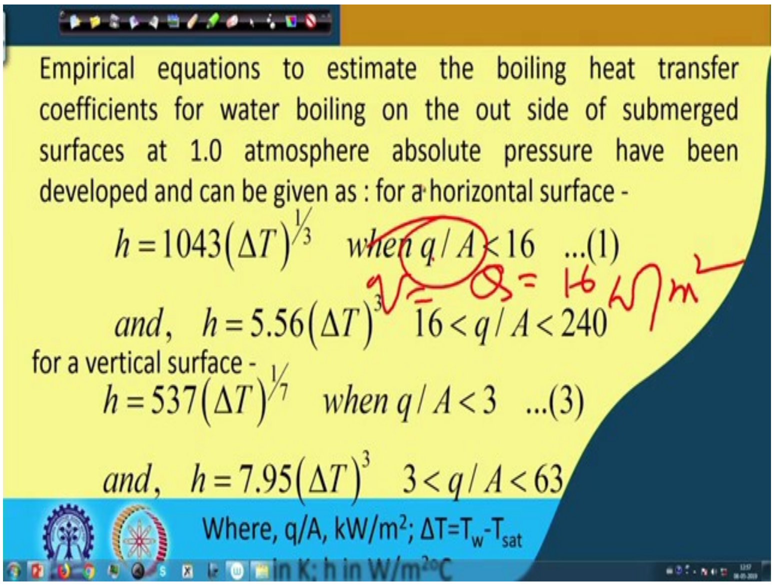

However, here we are using q/A that is Q and this is 16, not q this is q/A that is flux W/ m^2 ok. So, that empirical relation is in the horizontal surface. It is 1043 $\Delta T^{1/3}$ when it is < 16 and h is 5.56 ΔT^3 where q/A is between 16 and 240. For vertical surfaces h is 537 $\Delta T^{1/7}$ when q/A < 3, whereas, h is 7.95 ΔT^3, when q/A is between 3 and 63, 'right'.

So, q/A is the in the kW/m^2. It can be Watt or kW that does not matter, 'right'. So, kW/ m^2. And ΔT is T_w - $T_{saturated}$, 'right', T_w - $T_{saturated}$ means you have that if this is the water, so you have the vapor and liquid there at the same temperature. So, that is the saturation, 'right'.

So, there is a equilibrium between the vapor and the liquid, 'right' and that temperature is known as T saturation ok. And this is in Kelvin and h is in $W/m^{2}{}^{\circ}C$, 'right'. So, this is these are some of the relations which we will use afterwards.

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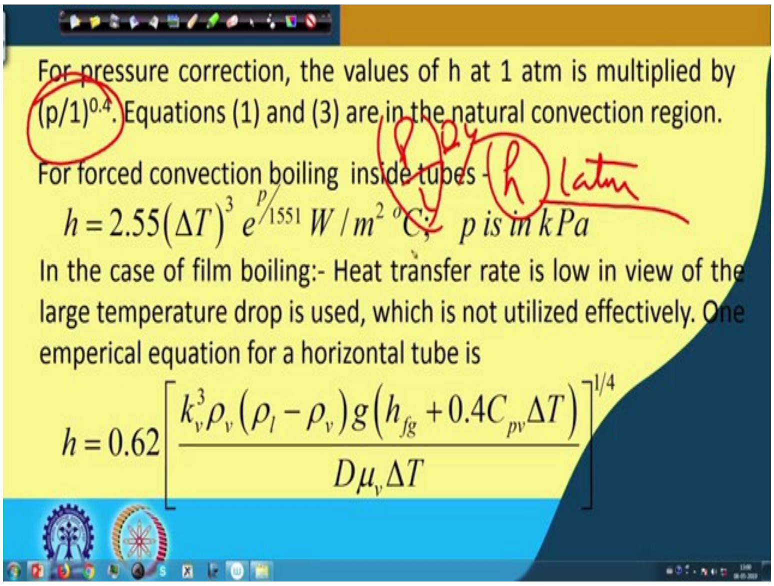

For pressure correction, if they are we because all were said in terms of 1 atmosphere pressure. So, if there is relation or requirement for pressure to be corrected, so that pressure correction is the values of h at wall atmosphere is multiplied by $(p/1)^{0.4}$. So, whatever value of h you are obtaining at atmospheric pressure if the pressure ratio that is p/1 atmosphere that is that value of h which you are giving getting that $(p/1)^{0.4}$ is taken as the pressure connection, p is the new pressure and 1 is the atmospheric pressure, 'right'.

For forced convection, boiling inside the tubes h is 2.55 ΔT^3, $e^{p/1551}$ W/m^{2}°C that is the value of h for forced convection boiling, where p is in kilo Pascal kPa, 'right'. This is not in atmosphere, this is in kilo Pascal. So, it is e power p/1551 W/m^{2}°C that is the forced convection, heat transfer coefficient, 'right'.

In the case of film boiling heat transfer rate is low in view of the large temperature drop is used which is not utilized effectively, 'right'. So, one empirical equation for horizontal tube is like this h is equal to $0.62\left[\frac{k_v^3 \rho_v (\rho_l - \rho_v) g(h_{fg} + 0.4C_{pv}\Delta T)}{D\mu_v \Delta T}\right]^{1/4}$.

So, this is for horizontal tube, 'right' the value of h. obviously, all v's are for vapor and 'ls are for liquids, 'right'. So, the relation is like that h is

$$0.62\left[\frac{k_v^3\rho_v\left(\rho_l-\rho_v\right)g(h_{fg}+0.4C_{pv}\Delta T)}{D\mu_v\Delta T}\right]^{1/4}$$

, 'right' or that is this can be said to the power 0.25, 'right'. So, if we look at the values I mean where we said b n l are for vapor and liquid, 'right'.

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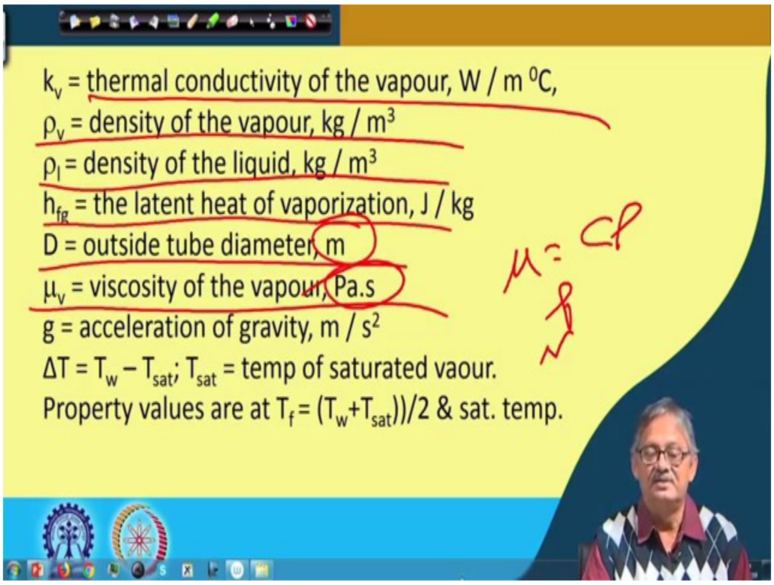

So, that is what is k_v is the thermal conductivity of the vapor in W/m°C, ρ_v is the density of the vapor in kg/m^3, ρ_l is the density of the liquid in kg per meter cube, h_f g is the latent heat of vaporization in J/kg, D is the outside diameter of the tube in meter, a μ_v is the viscosity of the vapor in Pascal seconds, this is in Pascal seconds mind it.

Mu has different units for different places earlier we had use C_p or p that is price or we have used Newton. So, wherever it is required accordingly you use it. Here it is Pascal's second, g is acceleration of gravity in m/s^2 and ΔT is T_w - $T_{saturated}$ where $T_{saturated}$ is the temperature of the saturated vapor, 'right'.

And the property values all these property values are calculated at the average temperature of (T_w + $T_{saturated}$)/ 2, i.e., saturation temperature and wall temperature average this is the temperature where the property values are evaluated, 'right'.

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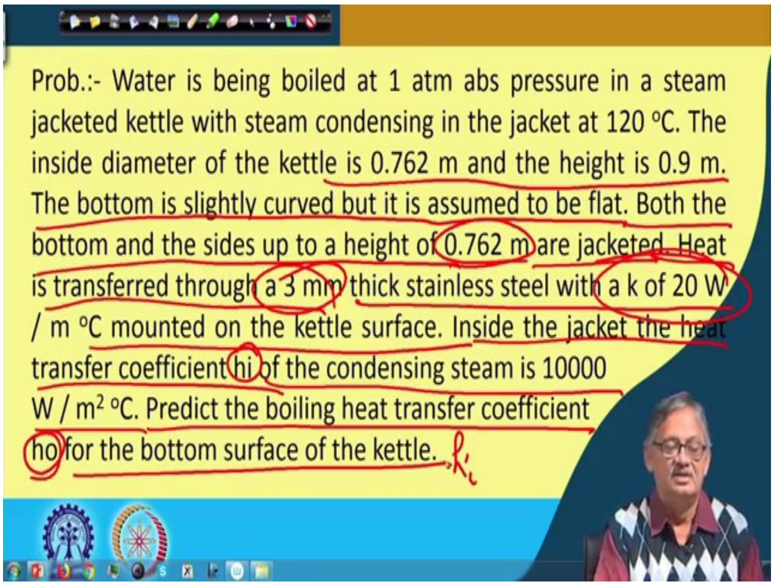

So, once we know this type of problem then we can solve once we know this type of relations that is how to find out the heat transfer coefficient though these are empirical relations, but very handful and very handy and we can utilize them effectively, 'right'. For example, in this problem this is a typical boiling problem that water is being boiled at 1 atmosphere absolute pressure in a steam jacketed kettle with steam condensing in the jacket at 120 °C. The inside diameter of the kettle is 0.762 m and the height is 0.9 m.

This type of kettle is used in food industries for making jam jelly marmalade. In many small scale industries you will see there were steam jacketed kettle in which the steam is outside the jacket and outside the kettle in the jacket and inside there is that I mean that jam or jelly the mixer or the content of that jam jelly, 'right'. So, normally jam jelly is made from either say fruit or maybe from artificial sources whatever it be. So, it is water sugar pectin and acid all these four mixture; however, that is beyond us at this moment, 'right'. So, 0.762 m and height is 0.9 m.

The bottom is slightly carved, but is assumed to be flat. Both the bottom and the sides up to height of 0.762 m are jacketed, 'right'. So, heat is transferred through a 3 mm thick stainless steel with a heat transfer with thermal conductivity of 20 W/m.°C mounted on the kettle surface. Inside the jacket the heat transfer coefficient h_i, it should be h subscript i, h_i of the condensing steam is 10000 W/m^2.°C. Now, what do you need? Predict the boiling heat transfer coefficient h o for the bottom surface of the kettle, 'right'.

So, we repeat. Water is being boiled at 1 atmosphere absolute pressure. Now, again since it has come, so absolute pressure and gauge pressure there is a difference, 'right'. If you have a gauge by which the pressures are measured, 'right'. So, fluid is coming here, this is like what we call to be like watch or similar kind of thing, 'right', dial rather. So, that there is an indicator, 'right'.

So, this indicator moves as the pressure goes up and up, 'right' and this is at 0. So, when it is at 0 that is called absolute pressure equivalent to gauge pressure. So, that one absolute 1 atmosphere absolute is equivalent to 0 gauge pressure, 'right', that you mind it. So, this since it has come we have also explain this.

So, water is being boiled at 1 atmosphere absolute pressure in esteem jacketed kettle with steam condensing in the jacket at 120 °C. The inside diameter of the kettle is 0.762 m and the height of the height is 0.9 m. The bottom is slightly curved, slightly curved means like this there is a reason also for that. Since, it is not part of this and time is also very valuable, so this curvature is made because that material which is being used they are food material, 'right'.

And if it is not properly cleaned then there may be had it been square like this there could have been that corner. This corner may contain some food material which if it is not cleaned after the process is over, if some leftover is there, so there is a chance that the microbes can invade and may contaminate. So, that is why purposefully from the engineering point of view this is made a little curvature, 'right'. Why it is that I have explained ok. So, both the bottom and the sides up to height 0.762 m are jacketed, 'right'.

We will show that in diagram. Heat is transferred through a 3 m thick stainless steel with a k or thermal conductivity to be 20 W/m°C, 'right' mounted on the kettle surface. Inside the jacket the heat transfer coefficient h_i of the condensing steam is 10000 W/m°C. Predict the boiling heat transfer coefficient h_o for the bottom surface; this of course ho has to be that o has to be suffix or subscript, 'right'.

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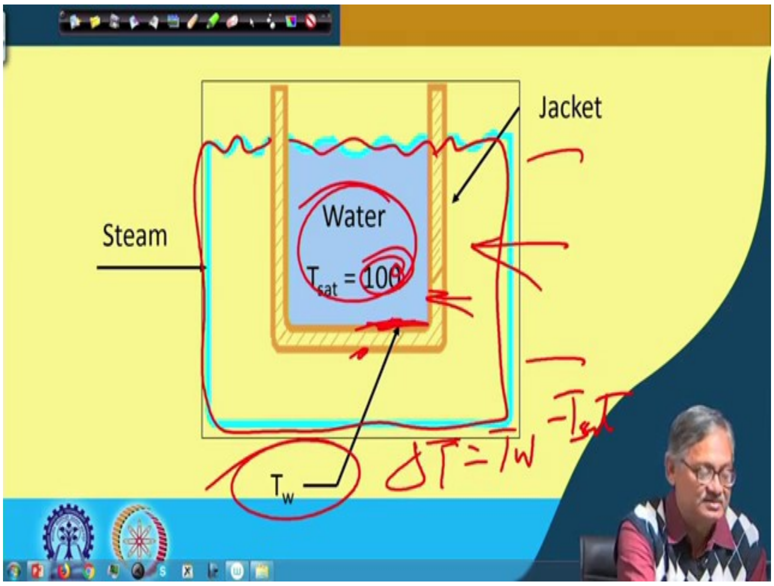

Now, if we look at the problem which has been given that looks like this, 'right'. So, this is a steam jacketed kettle, 'right'. This is how it is jacketed, 'right' and height is given and this thickness is given and water at saturation is 100 °C. Steam at 1 atmospheric pressure is there and we have to find out and this is the T_{wall}. T wall is not this outside; T_{wall} is this which is in contact with the liquid, 'right'. So, T_{wall} is that and ΔT is equal to T_{wall} - $T_{saturation}$, 'right'.

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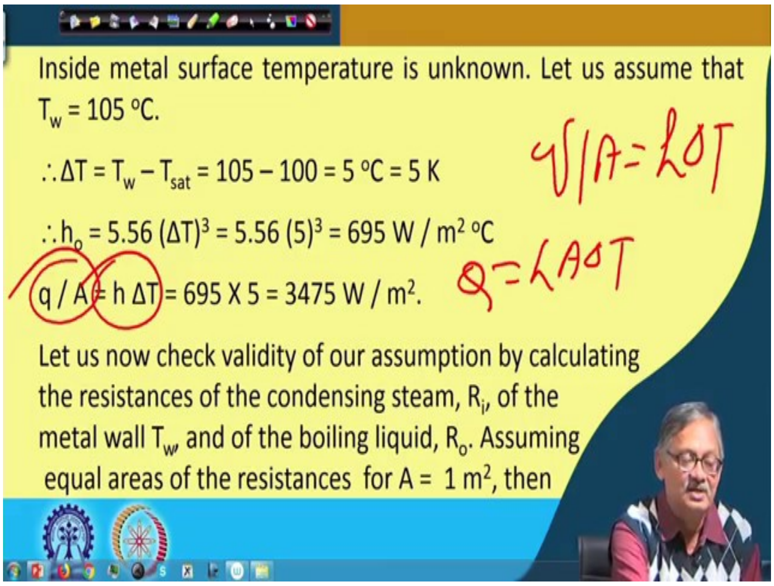

So, with this let us solve our problem let us solve our problem. And we then come to this solution like this that inside metal surface temperature is unknown, 'right'. It has not been said what is the wall temperature, 'right'. This is T wall and what is the temperature there this has not been said.

So, inside metal surface temperature is unknown. So, let us assume that the wall temperature is 105 degrees centigrade. So, ΔT is T_w - $T_{saturation}$ that is 105 - 100, so 5 °C or 5 Kelvin, 'right'. As we said that the difference in centigrade and Kelvin is same. So, h_o we can use a ration of 5.56 ΔT^3 or 5.56, 5^3 or is equal to 695 $W/m^2.°C$. So, q/A that is it flux is h $\times\Delta T$ since we know Q is equal to h A ΔT. So, that we can write q/A is equal to h $\times\Delta T$, 'right'. So, that becomes equal to 695 is h_o we have found and ΔT is 5 is 3475 W/ m^2, 'right'.

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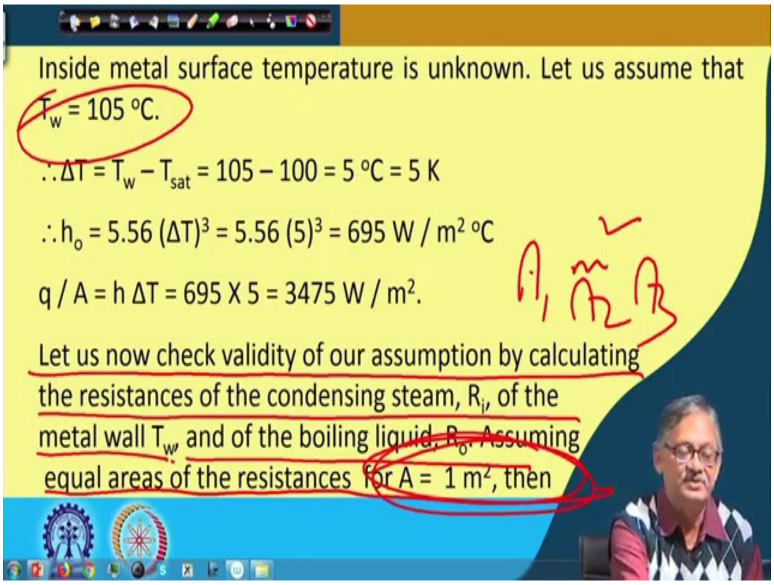

So, let us now well we have assumed T_w whether the assumption is correct or not you have to justify. Let us now check validity of our assumption by calculating the resistances of the condensing steam, R_i of the metal wall T_w and of the boiling liquid R_o.

Assuming equal areas of the resistances for 1 m^2 because if we go on changing that area meter square that A_1 then A_2 or A_3 for different cases then it will be more complicated. So, we are assuming that area of heat transfer has sin for all and that is 1 m^2, 'right'. We have to find out the resistances, 'right'.

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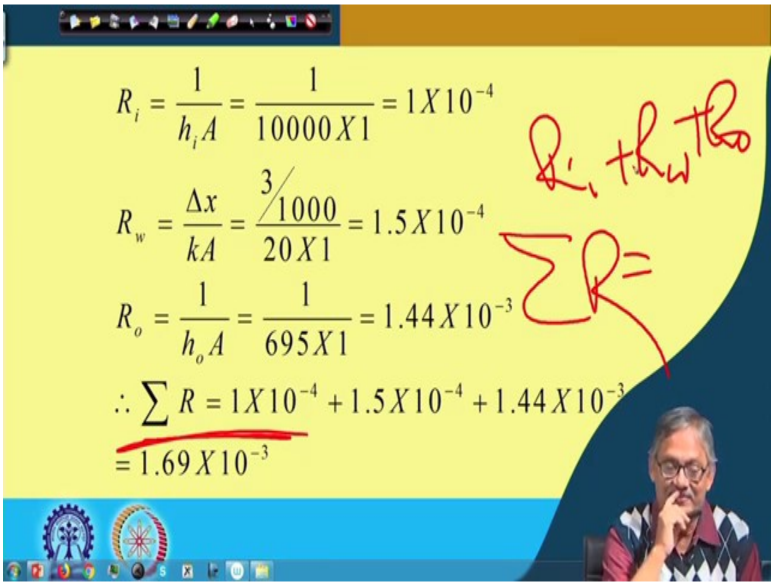

So, R_i is $1/h_iA$, R_i is $1/h_iA$ that is $1/(1000\times1)$, 'right', h_i has been given 1000; 10000. So, $1/(1000\times1)$; that means, $1 \times 1 \times 10^{-4}$ that is R_i, 'right'. What are these R_i? R_i is if you remember we had this and then we had this, then we had a jacket inside which that steam is condensing, 'right'. So, we have one resistance here with h i, 'right' that we have found out R_i . So, this is the film resistance or the wall.

Then we have to find out R_w that is this resistance that is to the wall, this is the wall, 'right' through the wall what is the resistance. So, that becomes equal to $\Delta x / kA$, 'right'. And Δx we have been given 3 mm, so (3/1000) / k is given 20 $W/m^2{}^\circ C$ and area we have assumed to be 1, 'right'. So, this has this is coming 1.5×10^{-4}. So, R_i and R_w are more or less very close, 'right'.

Then R_o and then what is that R_o? This was our material and now outside that is our condensing. So, R_o we have found out in this resistance that is film resistance we have found out this metal resistance. So, this is the R_o, that is the steam which is coming and giving heat here, 'right'. So, R_o is $1/(h_o\times A)$. R o has already we have already found out h o with that relation. So, it is $1/(695\times1)$ that is 1.44×10^{-3}, 'right'.

So, some of these resistances are $\sum R$ that is some of the resistances is equal to $R_i + R_w + R_o$, 'right'. So, this becomes equal to $1\times10^{-4} + 1.5\times10^{-4} + 1.44\times10^{-3}$, 'right'. So, that comes to be 1.69×10^{-3} that is the total R, 'right'.

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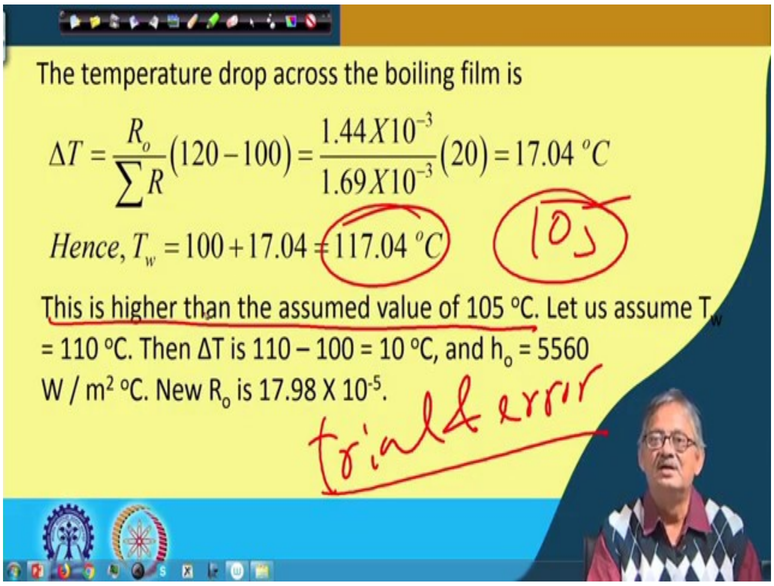

Now, if we find out again q, q becomes the temperature drop actress the boiling film is ΔT is equal to (R_o/ΔR) × ΔT that is (120 – 100) . So, R_o is 1.44×10^{-3}, summation of R is 1.69×10^{-3} and this ΔT is 20, so 17.04. So, the wall temperature becomes 100 +17.04 is 117.04 which is much above the assumed which was 105, 'right'. So, this is higher than that assumed value of 105 °C. So, first assumption it did not leak.

So, you know this is called trial and error method. When you are more than one unknown is there and you have less number of equations, then you do solve with the trial and error means you assumed one and then find out that with the assume value and if it is matching very good, if it is not matching you have to reassume, 'right'.

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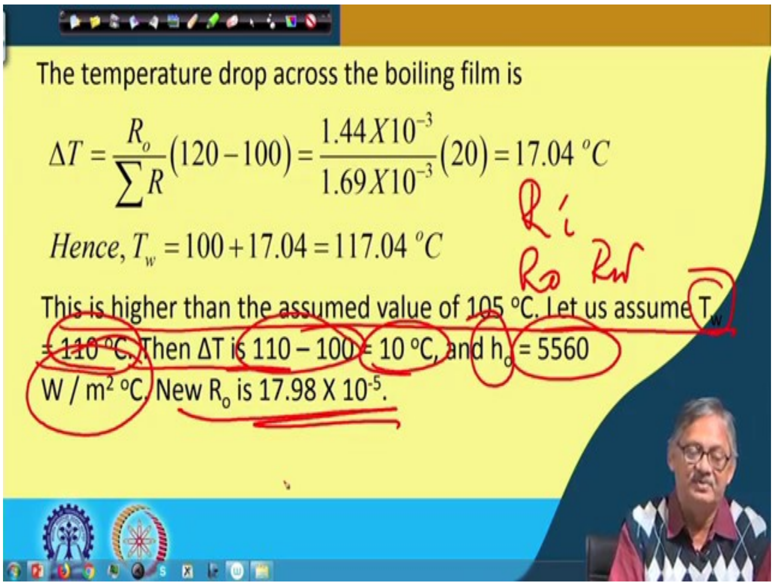

Now, reassumption will be there, 105, let us assume that 110 °C is the wall temperature, 'right'. Then delta T is 110 – 100 or 10 °C, 'right' and h_o why that equation we got 5560, 'right', 5560 W/m^2 the same equation which we have used 105 °C. And by the same way you found out R_i, R_o and R_w, 'right'. So, you can find out all of them. And new R_o is now 17.98×10^{-5} by the same process we have found out, 'right'.

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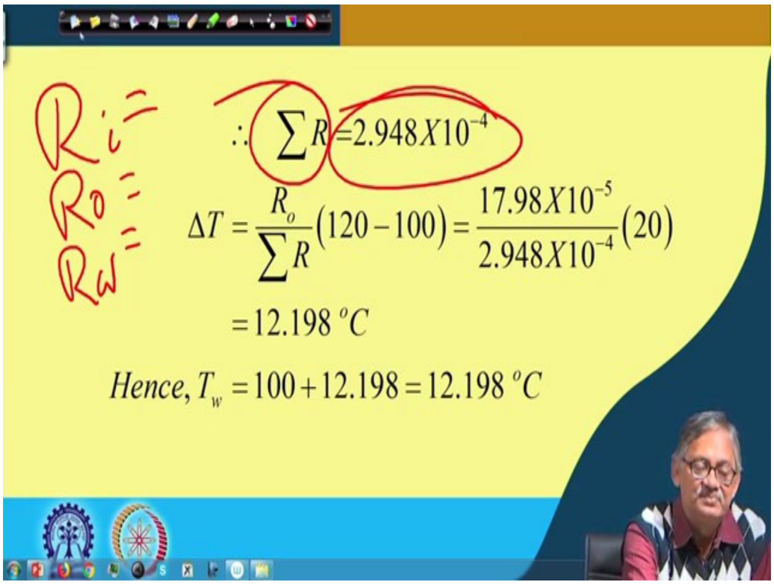

If R_o is found out like that as 17.98×10^{-5} then we can say that $\sum R$ or all the resistances is 2.948×10^{-5} again. By the same way we have found out earlier R_i, the same way now R_i

has been found out, the way R_o has found out the same way now R_o has been found out and R_w of course, R_w also by the same way, but R_w will remain same because you are not changing the material, 'right'.

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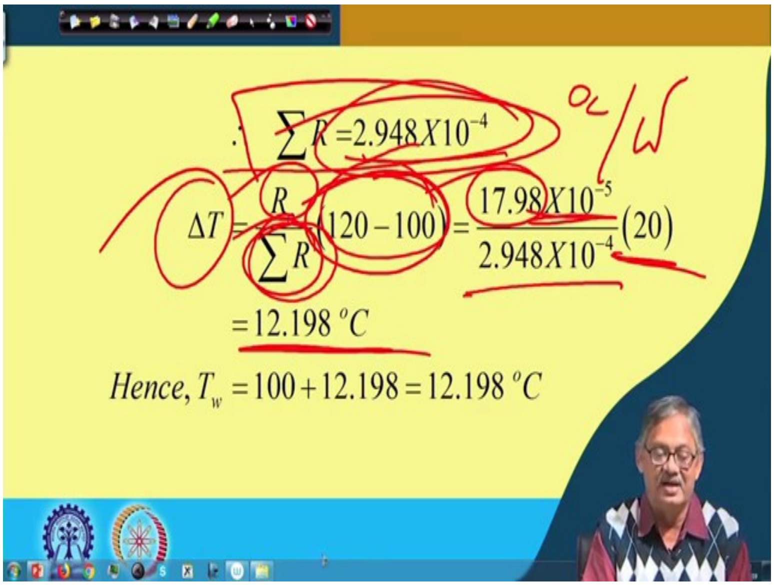

If that is not, so ΔR that is ∑R is 2.948×10^{-4}, 'right'. This is °C/W, 'right' resistance. So, ΔT, then again is $R_o/\Delta R$, ∑R, ∑R ×(120 – 100) °C which was given which means we have already found out this is 2.948, 'right'.

R_o has been found out in the previous slide 17.98×10^{-5}, 'right'. ∑R is 2 point which we have found out here 2.948×10^{-5} and this ΔT is 20. So, this comes to 10 for 12.198 °C.

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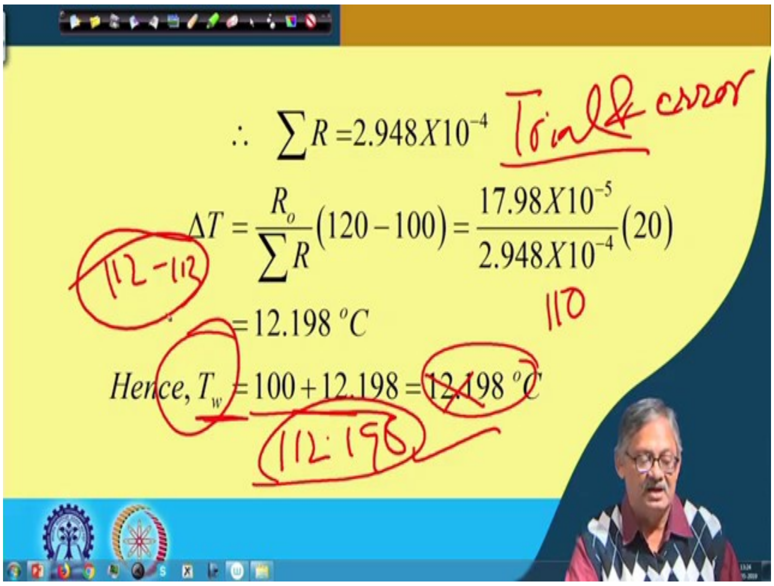

So, the T_w is 100 + 12.198 °C is 112 point, this should be 100 + 12.198. So, this is a mistake. So, it should be 112.198. So, our assumed value was 110, we got 112.198. So, next value if you take assumed value as 112.198, I hope you will get very close to 112 or 113 °C that you will be the final answer, 'right'. So, this way by trial and error you could find out, by a trial and error you could find out the value of the assumed T_w which was not given, 'right'.

Hope we have solved this and we have come to T_w as 12.198. So, the boiling expressions, boiling heat transfer coefficients and the problem solution we have done. So, we can now the time is up. So, we can close it and then we will next class we will go for the condensation ok.

Thank you very much.