**Renewable Energy Engineering: Solar, Wind and Biomass Energy Systems**
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**Lecture - 10**
**Practice Problems part- II**

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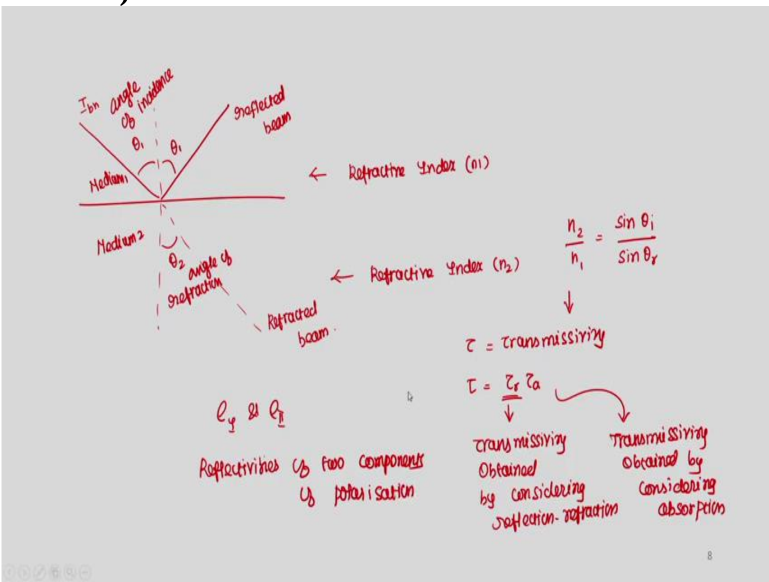


Next one is transmissivity absorptivity product of beam radiation. So, if you remember our class whatever we have discussed. So, this is nothing but the incident flux. This is medium 2 this is medium 1. So, this particular angle is theta 1 and this is reflected radiation or reflected beam. So, this angle is also theta 1 this is the theta 2 which is nothing but refractor beam. So, for medium 1 refractive index is m 1 for medium 2 refractive indexes n 2.

So, this is refraction angle or angle of refraction this is angle of incidence based on the Snell's law is derived which is nothing but sine theta i angle of incidence and sine theta or angle of refraction. So, from this we are going to calculate tau that is nothing but transmissivity. So, this is product of tau r tau a. tau r is transmissivity obtained by considering reflection refraction.

Tau a is transmissivity obtained by considering absorption. To get this particular value we use rho 1 and rho 2. So, these are reflectivities of 2 components of polarization. So, if you remember our lecture and then you would be comfortable these terminologies.

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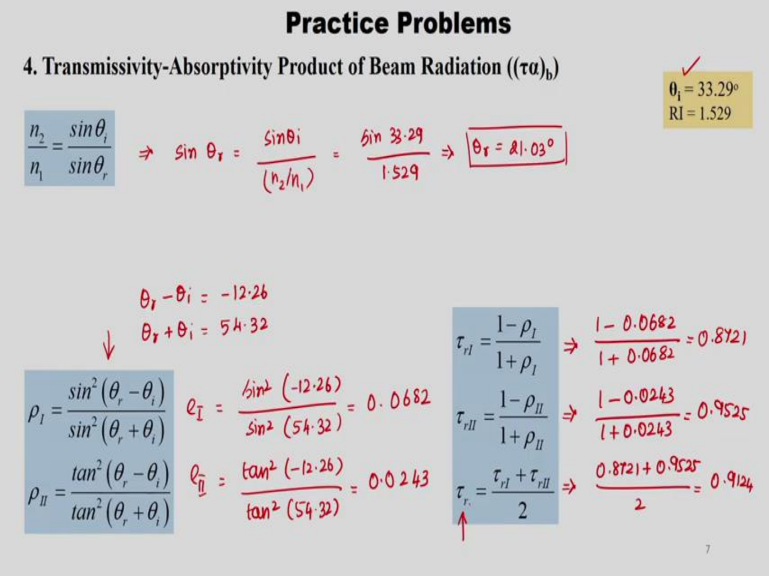


So, this is what we are going to use here. So, our angle of incidence is 33.29 refractive indexes 1.529. So, we are here calculating sine theta r which is nothing but sine theta i upon n 2 upon n 1 sine 33.29 upon 1.529. So, from this if you are calculating theta r that is 21.03 degrees and then rho 1 rho 2, we have theta r - theta I which is - 12.26 and theta r + theta i which is 54.32. Now, we are calculating rho 1 sine square - 12.26 sine square 54.32 what you obtain is 0.0682.

Rho 2 tan square theta r – theta i which is -12.26 tan square theta r + theta y which is 54.32. This value is 0.0243 from this we obtained tau r 1 which is 1 – rho 1 0.0682 upon 1 + rho 1 0.068 this value is 0. 8721 and then tau r 2 which is 1 – rho 2 upon 1 + rho 2 1 – 0.0243 upon 1 plus 0.0243 which is 0.9525. So, average of these 2 values 0.8721 + 0.9525 upon 2 this is equivalent to 0.9124. So, we have calculated transmissivity obtained based on reflection refraction component.

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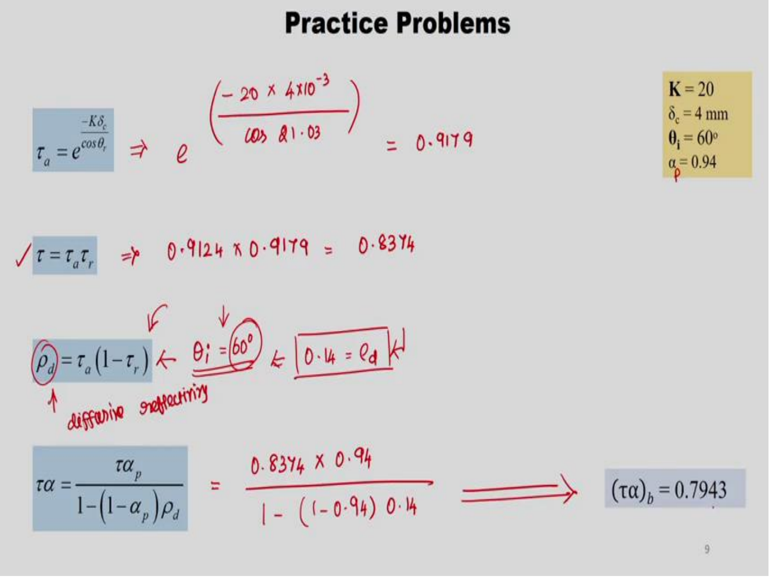


And then due to absorption, so, this is exponential power – k, k is nothing but extension coefficient for glass so, that is given in your problem 20 upon meter - 20 and the thickness of the collector 4 into 10 to the power of - 3 upon cos theta r that is 21.03. If you calculate this value is 0.9179. So, tau r just 0.9124 into tau a 0.9179 which is equivalent to 0.8374. We obtained tau then to obtain rho d. So, this is nothing but diffusive reflectivity.

So, this is obtained by this formula of tau a 1 - tau r for theta i that is angle of incidence of 60 degree. So, if you remember in our lecture, we said that diffusive radiation comes from all directions. However, we consider that is equivalent to beam radiation which is falling at the angle of 60 degree. So, if you substitute theta i is 60 and calculate tau r and tau a and substitute in this diffusive reflectivity formula.

You would get diffusive reflectivity or otherwise, for one cover system it can be taken us 0.14. So, here we have not used theta i is 60 because our angle of incidence here is 33.29. So, we are going to consider this but however, when we are calculating transmissivity absorptivity product for diffusive radiation, there we are going to take theta i as 60 degree there we will cross verify this.

So, rho d as of now, we are taking 0.14, so, and then we are substituting here tau r already we have 0.8374 alpha p which is nothing but plate absorptivity that is 0.94 upon 1 – 1 – 0.94 rho d is 0.14. So, if you calculate tau r for transmissivity absorptivity product for beam radiation is coming around 0.7943.

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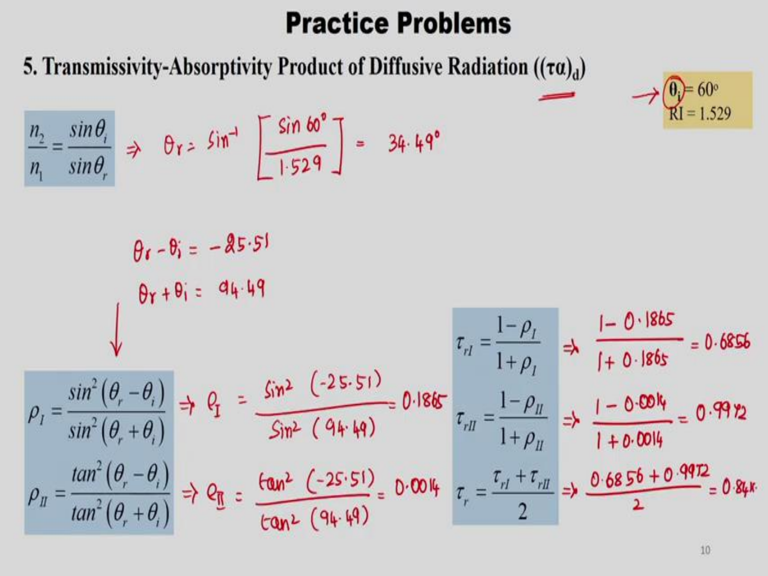


The same we supposed to calculate for diffusive radiation. So, for diffusive radiation as I said earlier, we are going to take angle of incidence of beam radiation as 60 and then proceed with the same way we calculated for beam radiation. So, sine inverse of sine 60 refractive index is 1.529. This is coming as 34.49 degree these 2 parameters of theta r - theta i this - 25.51 theta r plus theta i is 94.49. Rho 1 is sine square - 25.51 upon sine square 94.49 equivalent to 1865.

Rho 2 tan square - 25.51 upon tan square 94.49 which is equivalent to 0.0014. Tau r 1 is 1 - 0.1865 upon 1 + 0.1865 this is 0.6856. 1 - 0.0014 upon 1 + 0.0014 this is 0.9972. So, if you calculate the average of these 0.6856 + 0.9972 upon 2 this equivalent to 0.8414.

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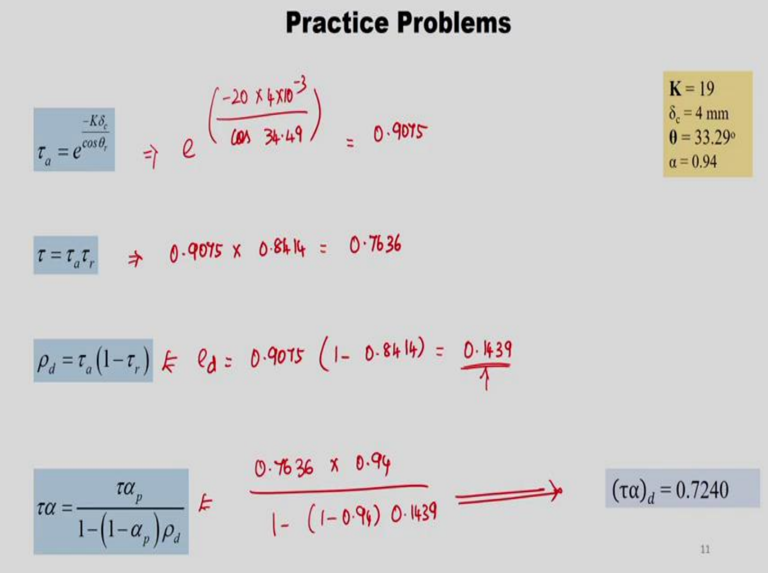


Then tau a e – 20 into 4 into 10 to the power of - 3 this is common cos of theta r here is that tau a 34.49 which is coming around 0.9075. So, tau is tau a tau r 0.9075 tau r is 0.8414. So, which is equivalent to 0.7636. So, if you remember last time, we told rho d is calculated for the incidence angle of 60 degrees. So, here for beam radiation we used theta a as 60. So, here we are going to calculate this particular parameter rho d as tau a 0.9075 into 1 – tau r which is nothing but 0.8414.

This is coming around 0.1439. So, whatever we have taken over there. It seems to be almost matching. So, for one glass cover system we can take this particular value that is assumption. So, now, our next one is tau, tau is 0.7636 alpha p which is 0.94 1 - 1 - 0.94. Rho d is 0.1439 if you calculate tau alpha d that is transmissivity absorptivity product due to diffusive radiation is 0.7240. So, we have calculated this.

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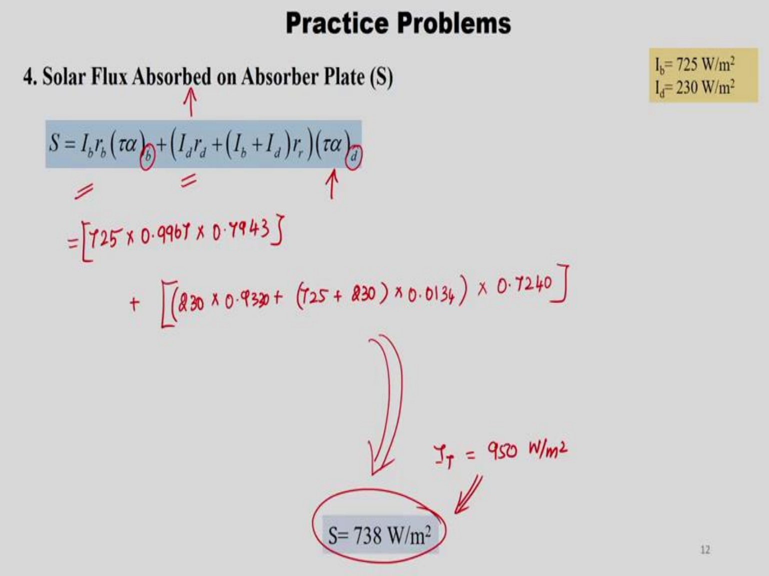


Then we are going to substitute this in beam diffusive radiation and then calculate how much solar flux we observed on a absorber plate. So, if you remember here, we have calculated I d which is nothing but solar radiation falling on that filter surface that is I d 950 watt per meter square out of which how much is absorbed by absorber plate. So, for that calculation only we have calculated transmissivity absorptivity product due to diffusive radiation due to beam radiation.

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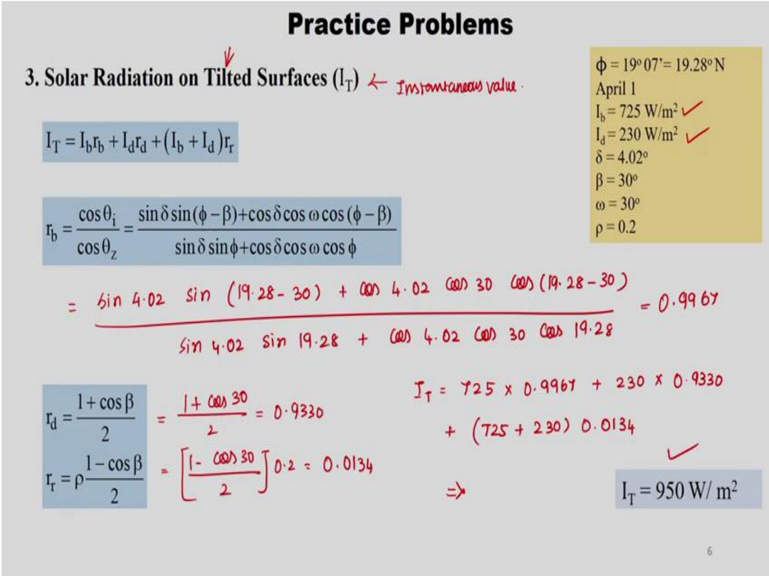


Now, we are going to substitute here whatever we calculated 725 and r b, r b is here 0.9967 tau alpha due to beam radiation 0.7943. So, this is first term, second term is I d just 230 and 2 r d + I b 725 + 230. This is global radiation into r r we will fill this value is multiplied with 0.7240. So, this is second term. We need r d and r r values, so, that we have calculated earlier itself r d and r r. So, we are going to substitute their r d is 0.9330 r r is 0.0134. So, if you substitute what you get is 738 watt per meter square.

So, total I d falling on the tilted surfaces 950 watt per meter square. So, based on the properties of the glass cover system and absorber plate, we are getting 738 watt per meter square out of 950 watt per meter square.

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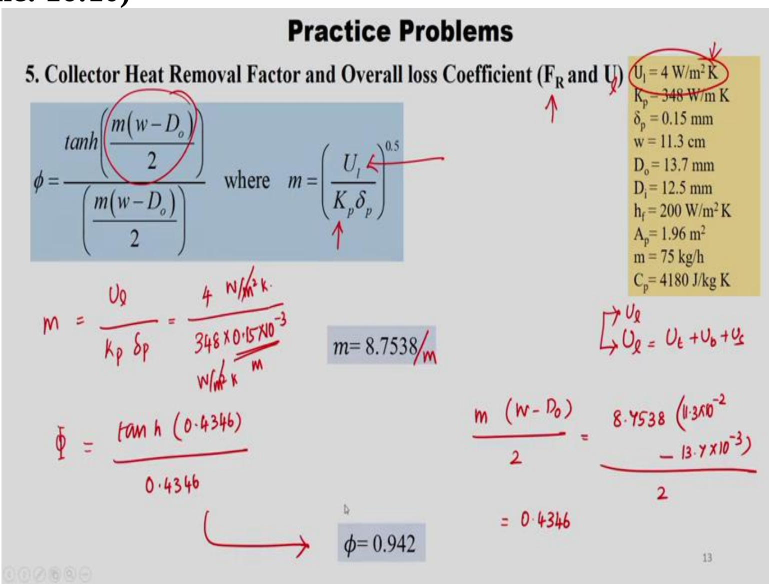


So, the next parameter we are going to calculate is collector heat removal factor and overall loss coefficient that is U l. So, to calculate F R we might require certain parameters.

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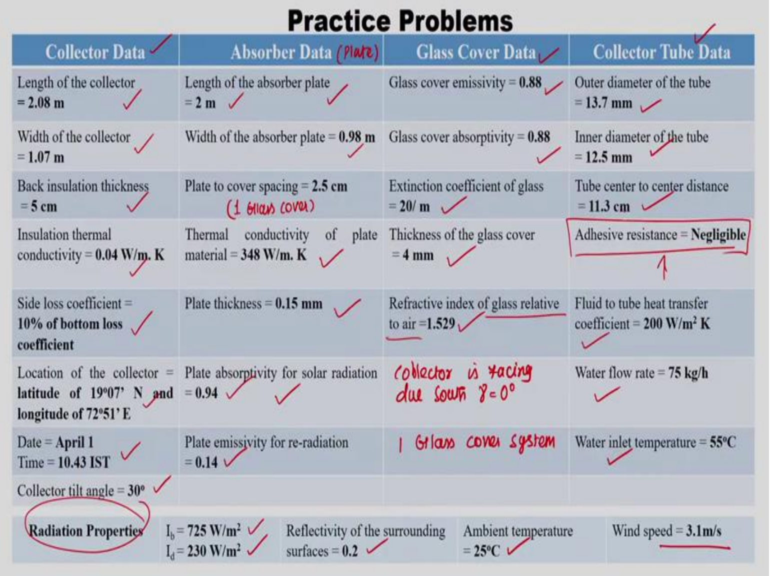

## Practice Problems

| Collector Data | Absorber Data | Glass Cover Data | Collector Tube Data |
|---|---|---|---|
| Length of the collector = 2.08 m | Length of the absorber plate = 2 m | Glass cover emissivity = 0.88 | Outer diameter of the tube = 13.7 mm |
| Width of the collector = 1.07 m | Width of the absorber plate = 0.98 m | Glass cover absorptivity = 0.88 | Inner diameter of the tube = 12.5 mm |
| Back insulation thickness = 5 cm | Plate to cover spacing = 2.5 cm | Extinction coefficient of glass = 20/ m | Tube center to center distance = 11.3 cm |
| Insulation thermal conductivity = 0.04 W/m. K | Thermal conductivity of plate material = 348 W/m. K | Thickness of the glass cover = 4 mm | Adhesive resistance = Negligible |
| Side loss coefficient = 10% of bottom loss coefficient | Plate thickness = 0.15 mm | Refractive index of glass relative to air =1.529 | Fluid to tube heat transfer coefficient = 200 W/m² K |
| Location of the collector = latitude of 19°07' N and longitude of 72°51' E | Plate absorptivity for solar radiation = 0.94 | | Water flow rate = 75 kg/h |
| Date = April 1 Time = 10.43 IST | Plate emissivity for re-radiation = 0.14 | | Water inlet temperature = 55°C |
| Collector tilt angle = 30° | | | |

| Radiation Properties | $I_b$ = 725 W/m², $I_d$ = 230 W/m² | Reflectivity of the surrounding surfaces = 0.2 | Ambient temperature = 25°C | Wind speed = 3.1m/s |
|---|---|---|---|---|



That is phi F dash, both the parameters we would require. So, first we will calculate phi. So, to calculate phi we need to calculate M which is U l upon K p delta p. So, here our aim is to calculate F R, but F R requires U l but as of now, we do not have you will that is total loss coefficient for the collector system. So, first we are going to assume that U l and proceed our calculations. So, finally, we will also calculate overall loss coefficient as a top loss coefficient, bottom loss coefficient and sight loss coefficient.

So, the assumed U l matches with the final U l which is nothing but summation of top loss bottom loss side loss coefficient if both are matching the assumed value was correct. Otherwise, we need to repeat this iteration one more time. Let us see how it works out for us today. So, U l we assumed as 4 watt per meter square and plate thermal conductivity is given as 348 and plate thicknesses given as 0.15 millimetre 10 to the power of - 3 the thickness is in meter. This is in watt per meter square Kelvin. This is also watt per meter square Kelvin.

So, M is coming around 8.7538 upon meter and then we calculate the parameter phi tan h we have this as well, which is nothing but m w D not upon 2. M we already calculated 8.7538 and then W which is nothing but tube center to center distance and outside diameter is already given the problem. So, we are going to substitute the same here 11.3 into 10 to the power of -2, -13.7 into 10 to the power of - 3 upon 2. So, if we calculate this is coming around 0.4346. Now, we can substitute the value directly 4346 upon 0.4346. So, phi is 0.942.

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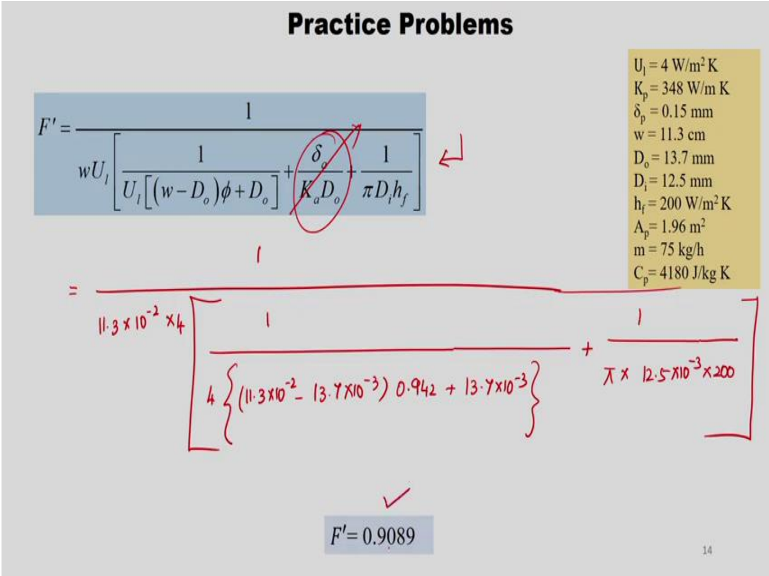


The second parameter we are going to calculate is F dash 1 upon w we already have 11.3 into 10 to the power of - 2 U l assumption value that is 4 1 upon U l is 4. w is 11.3 into 10 to the power of – 2. D not 13.7 into 10 to the power of -3 phi may calculated us 0.942 plus D not which is again 13.7 into 10 to the power of -3, close the bracket plus delta a upon K a D a not, this is the resistance due to adhesion of tube with absorber plate, but in the problem, we have considered it to be negligible adhesive resistance is negligible.

So, we are not going to take into this particular term this we can cancel it plus 1 upon by pi D i is 12.5 into 10 to the power of - 3 h f that is given us 200. So, this is whole bracket if you calculate you have F dash 0.9089.

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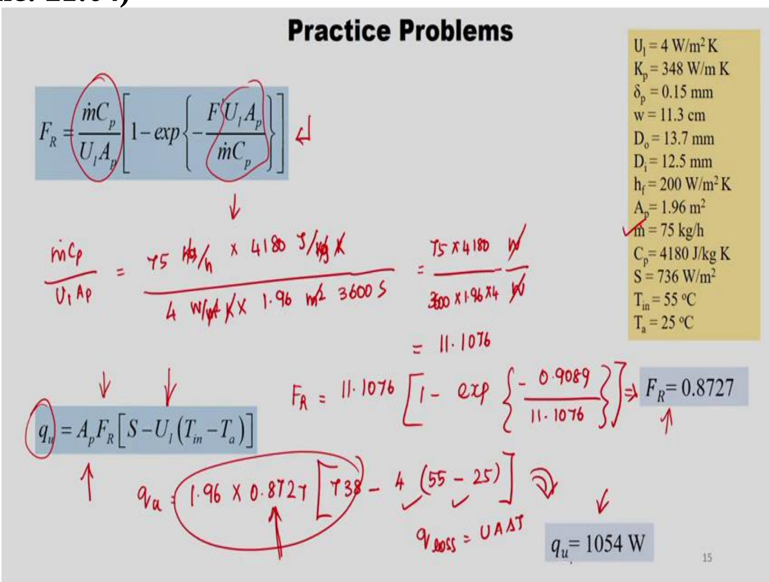


So, here F R is m dot C p upon U l A p into 1 - exponential of F dash U l A p m dot C p this term is -. So, for our simplicity in calculation first we will calculate this particular term of m dot C p U l A p m dot given here is this is dot mass flow rate 75 kg per hour. C p is given as 4180 joule per kg Kelvin U l is 4 watt per meter square Kelvin A p is 1.96 meter square meter square meter square get cancel kg kg get cancel Kelvin Kelvin get cancel joule per hour is coming.

So, if we divided by 3600 instead of hour second this becomes in watt. So, 75 into 4180 upon 3600 into 1.96 into 4 this is in watts above is joule per hour which is nothing but we divided by 3600. So, that is watt and divided by watt. So, F R this particular parameter is coming around 11.1076. So, this is unitless. This is also unitless and this is unitless and F dash is also unitless. This is a F R collector heat removal factor.

Now, we are substituting in F R m C p upon U l A p that is 11.1076 into 1 - exponential of - F dash 0.9089 upon m C p upon A p U l that is 11.1076. So, we have F R coming around 0.8727 why we calculated this heat removal factor and then heat loss coefficient is to calculate heat gain. q u is A p 1.96 F R is 0.8727 into S. S is nothing but the amount of flux absorbed by absorber plate that is 738.

738 This is assumed value of fluid. So, T in that is given in the problem 55.T a is 25. So, your q u is coming around 1054 watt remember, so, this is nothing but S into A p is nothing but the heat gain that is multiplied with collector heat removal factor that is 0.8727. So, this value is total heat gain - losses. Losses are nothing but A p F R into U l T in - T a. Normally you know how to calculate the losses q losses are nothing but UA del T.

So, del T is this U l this A p is the plate area. So, because We are not getting the 100 % here the heat removal factor is 0.8727. So, that should be multiplied. So, total how much heat is absorbed - losses that is nothing but useful heat gain that is the heat gained by the fluid.

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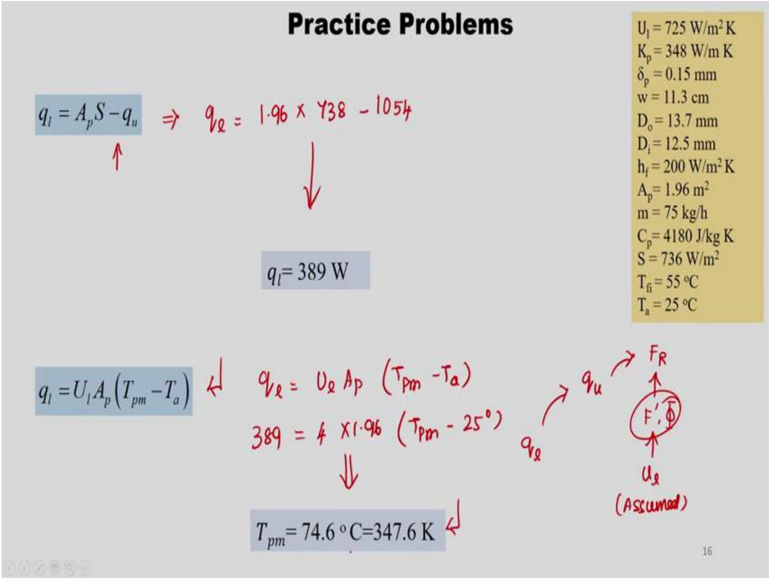


So, that is coming around q u is 1054 watts, then we are calculating how much is the exact q l. So, q l is A p S is nothing but 738 minus heat gain that we just calculated 1054 if you calculate q l is coming around 389 watts, this q l again is equivalent to as I said q l is U l A p since it is a plate, we supposed to use plate mean temperature - ambient temperature that is heat loss due to the ambient. So, U l is 4 A p is 1.96 plate temperature is supposed to be calculating T a is 25 q l be calculated us 389.

So, T pm is 74.6 degree if you convert into Kelvin 347.6 Kelvin remember this plate temperature, we calculated based on q l that was based on q u. q u based on F R in the F R we needed certain parameters phi F dash, etc. So, all of them required U l that we assumed. So, this plate temperature is true plate mean temperature or not.

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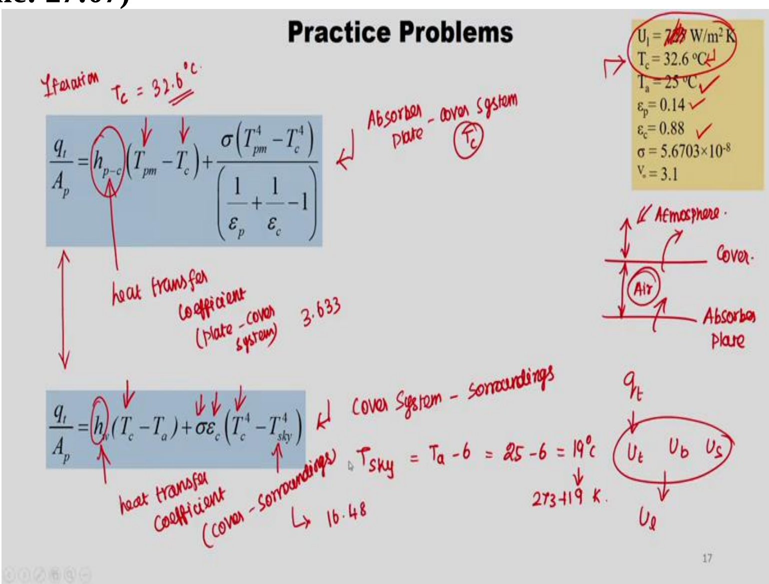

That we are going to check by further calculation to do that, we are going to check this q t upon A p between collector absorber plate. Absorber plate of the collector the cover so, in between air is filled and this is a with atmosphere. This is an contact with atmosphere. So, how much heat loss between absorber plate and cover that is given to atmosphere. This is what we are going to check q t upon A p between absorber plate and cover system the same is given to the cover to atmosphere or surroundings we can say cover system to surroundings.

So, if we check this heat balance then we would be getting q t which can be related to U t and then we can find out U b U s from these 3 quantities we can find out U l and check whatever we assumed and whatever we are getting is same if that is same then whatever we calculated us plate mean temperature that seems to be true. If not then we need to do one more iteration. So, here also this is not simple T pm we got by assuming U l, but what about c. c is nothing but cover temperature that we do not have right now. So, that also we are going to assume.

T c here assumed as 32.6 degrees centigrade. So, this is not 725 U l is 4. 4 watt per meter square Kelvin here also 4 watt per meter squared Kelvin. So, T pm calculated T c we are going to assume some temperature here 32.6 degrees assumed to get same q t upon A p between absorber plate to cover system to cover system to surroundings because the heat lost by absorber plate and cover system should be gained by cover system and surroundings.

To balance this here we have taken exactly 32.6 but it also assumption. So, we suppose to assume and calculate if q t upon A p between these 2 systems are not matching then we suppose to iterate here as well. So, again we are doing iteration here based on T c right now, we have assumed it to be 32.6 degree. So, T pm we have T c we have sigma is nothing but Steven Boltzmann constant. So, that is 5.6703 into 10 to the power of -8.

T pm T c we have and emissivity of the plate that is given as 0.14 remember this is for radiation or long wave length radiation and epsilon c is also given that is same emissivity of the glass cover system 0.88, but we do not have the h p-c this is nothing but heat transfer coefficient of plate to cover system this we need to find it out. Another thing here if you see q t upon A p for cover system and surroundings you have T c that is assumed value and T a that is atmospheric temperature that is given here 25.

Sigma is given epsilon c is given T c is given, given in the sense we assumed it to be 32.6 and sky temperature. So, the sky temperature is taken as T a – 6. T a is 25 - 6 T that is 19 degree and if you want to convert into Kelvin 273 + 19 Kelvin. But here also we have h w that is again heat transfer coefficient between cover and surrounding.

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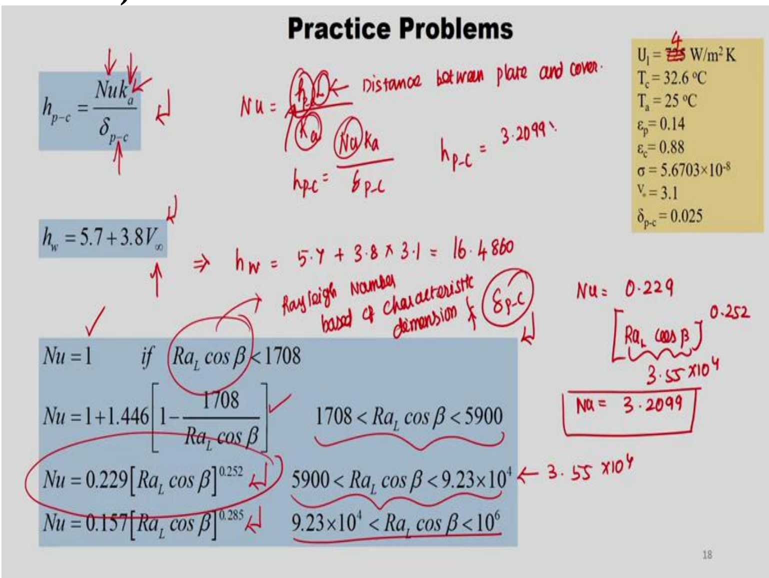


So, now, we are going to see how to calculate h w and h p-c to calculate h p-c we would require Nusselt number and thermal conductivity of the air and the distance between plate and cover system. You see here this formula is taken from N u which is nothing but Nusselt number which can be written as heat transfer coefficients upon thermal conductivity into length. So, this length is here said as distance between plate and cover we have said here that is filled with the fluid air.

So, k a here is thermal conductivity of the air and heat transfer coefficient between plate and cover system this is what our parameter of interest for that we are going to get Nusselt number and thermal conductivity of air and then characteristic dimension which is nothing but delta p-c distance between plate and cover system for h w that is heat transfer coefficient between cover system and the surroundings that is given by this correlation 5.7 into plus 3.8 V infinity.

V infinity is also given in the problem is wind speed is given in meter per second. Also remember, when you are doing the problem always check the unit consistency. So, V infinity is given this seems to be straight forward we will calculate this one first h w is 5.7, 3.8 V infinity which is nothing but 3.1 if you calculate this is coming around 16.4860. So, for h p-c what we would require is Nusselt number. For Nusselt number this correlation is given if Nusselt number is 1.

If Ra L cos beta Ra L here is Rayleigh number based on characteristic dimension L. What is this L here? That is delta p-c, because that is a distance between plate and cover system cos beta is nothing but inclination angle of the collector. So, Nusselt cos beta is less than 1708 we can take Nusselt number as 1 if it is between 1708 to 5900, we can use this formula to calculate Nusselt number, if it is between 5900 to 9.23 into 10 to the power of 4, we will use this particular correlation for calculating Nusselt number.

If this comes out 9.23 into 10 to the power of 4 to 10 to the power of 6 then we will be using this particular correlation for finding out Nusselt number.

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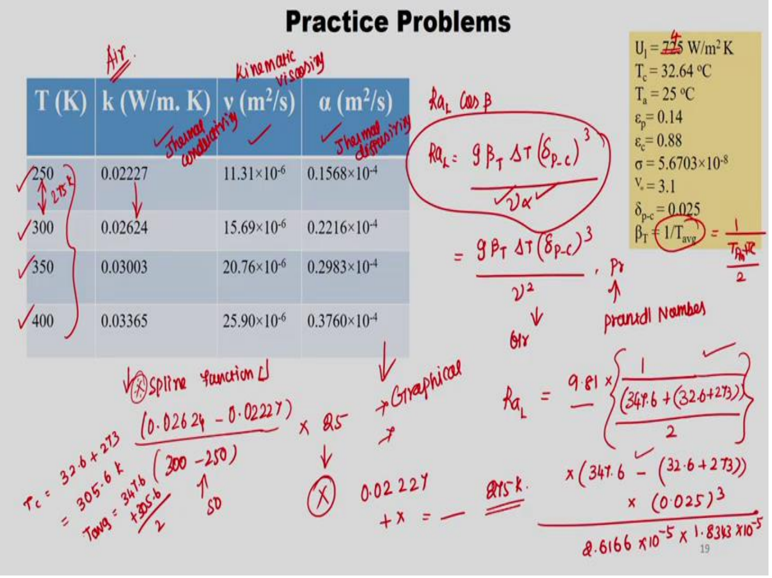


So, first thing what we supposed to do is Ra L cos beta for doing Ra L, the formula is g beta T del T characteristic dimension whole to the power 3 upon v alpha and sometimes people use g beta T del T del p-c q upon nu square into Pr which is nothing but Prandtl number this is nothing but gash of number since we have all the data with us for various temperature ranges, then we will use this formula to calculate Ra L.

So, for that what are all the parameters we require nu which is nothing but kinematic viscosity and then alpha thermal diffusivity and if you remember here, we would record k a as well that is thermal conductivity. So, you might have used this interpolation technique for example, here the temperature is given in Kelvin in the interval of 50. So, if you want to calculate any values any of these values K or new or alpha between these 2 temperatures ranges you can use spline function.

If you are good at that are if you want to calculate here this whatever the iterations, we are doing for U l and T c it is a bit tedious to do hand calculation, why we are doing so, here is to understand how to calculate if you are having proficiency with computer or programming or coding. So, I advise you to do as a computer calculation, because it is very much tedious to do 3 or 4 iterations with all these values the same way here, one can do hand calculation or if you fed the sum, computer coding then you might find out the values.

Or some of the references whatever we are going to give here in this particular lecture also would help you to get these parameters or any heat transfer book or fluid mechanics book you will find all this values. So, here the temperature interval of 50 all the parameter values are given for example, if you want to calculate for 275. How do you calculate? If it is 10, 50-degree interval 300 - 250 your value is 0.02624 – 0.02227.

If it is that then how much is for 25 because this is 50 travel. If it has this value, then how much is for 25 after getting this value, then you need to check whether if you want to do it this is increasing value. 0.022 to 0.026. If that is the case, whatever value you are getting that as a x then you are supposed to add it with 0.2227 + x. So, whatever value you get that is for this is value x, if you add it, then whatever value you get that is for 275 Kelvin.

In short for 50 difference, the difference in value of k is this, then what is for 25 k difference, so, that value is 6 if you add it with 250 then you would get with 275 Kelvin. So, here you can use as I said you can directly this data is very much available in graphical form as well. Or if you want to use any interpolation technique, I just said example a spline functions any interpolation technique you can use and get the values for hand calculation are given for air because we are working with fluid air.

So, now Ra L g is 9.81 and beta T. Beta T is nothing but thermal expansion coefficient that is defined as 1 upon T average. So, what is T average here? T p + T c T pm that is plate mean temperature plus T c upon 2 that is T average here if you calculate that 1 upon the T pm 347.6 collector temperature which is nothing but T c 32.6 + 273 because we are working in Kelvin upon 2. So, this whole term is beta T g beta T del T is 347.6 - 32.6 + 273.

This is delta t this should be multiplied with delta p-c q delta p-c is 0.025 whole cube this is nothing but average value 347.6 + 32.6 + 273 upon 2 is average value for this particular average value in Kelvin the nu and alpha parameter were found out alpha is nothing but 2.616 into 10 to the power of -5 nu is nothing but 1.8343 into 10 to the power of -5. So, what is this T c? T c is 32.6 + 273 which is equivalent to 305.6 T average is nothing but 347.6 + 305.6 upon 2 that is a T average. For this particular T average, you supposed to find out k, nu and alpha. So, here we calculated Ra L which is g beta del t del p-c q upon nu alpha.

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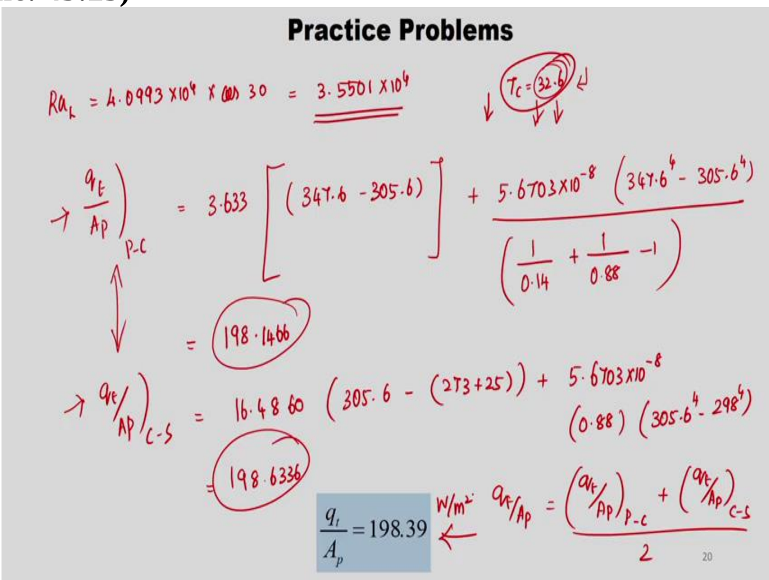


Ra L, this coming around 4.0993 into 10 to the power of 4 into cos beta is cos 30 which is coming around 3.5501 into 10 to the power of 4. So, we found out Ra now go back here. So, it is 3.55 into 10 to the power of 4 this comes in this range. Now, a Nu is 0.229 into a Ra L cos beta power 0.252. Ra L cos beta it is 3.55 into 10 to the power of 4. So, if you substitute Nusselt number is 3.2099 we got Nusselt number we supposed to calculate h p-c.

h p-c which is equivalent to 3.2099 and k a, k a again you are supposed to calculate for this average temperature what should be your K a value that is 0.0283 delta p-c. Delta p-c is nothing but 0.025. So, if you calculate h p-c is coming around 3.633. So, now, we are ready with all the values h p-c we just now calculated as 3.633 and q t upon A p this formula h w we calculated that is something 16.48.

So, we go on substituting the values q t upon A p of absorber plate and collector system h p-c h p-c is 3.633. T pm -T c T pm is here 347.6 – 305.6 that is T c. This is first term; Second term is sigma T pm power 4 – T c power 4 sigma 5.6703 into 10 to the power of -8 T pm power 4, 347.6 power 4 – 305.6 power 4 upon 1 upon epsilon p which is nothing but 0.14 + 1 upon epsilon c that is 0.88 - 1.

So, if you calculate this is 198.1466 and then q t upon A p for cover and surroundings that is h w into T c – T a. h w we have calculated here 16.48 60. T c is 305.6 - T a is 273 + 25 which is 298 + sigma epsilon c is 0.88 T c power for that is 305.6 power 4 – T a power 4 298 power 4. So, if you calculate this value is coming around 198.6336. So, if you remember what we told it is totally based on T c what we assumed 32.6.

So, if this value is not correctly assumed the parameters whatever we calculated thermal conductivity and kinematic viscosity and thermal diffusivity and then Rayleigh number everything will not be in correct value. So, there might be a problem with getting q t upon A p balanced from plate to cover system to cover to surroundings. So, to show you the calculation we have done but we have already worked on it and came up with the value of 32.6.

But if it is to be done a priory you supposed to assume T c till you get q t upon A p of same between for example, if you have 2 cover system then you need to add one more equation of c 1 to c 2 cover 1 to cover 2. So, how many ever cover system you have. So, that many equations to be added it is just that we are balancing whether we have got T c correctly to predict the or to balance the losses.

So, then q t upon A p is nothing but the average value of q t upon A p of plate to cover system and q t upon A p of cover to surrounding system upon 2. And finally, q t upon A p is nothing but 198.39 watt per meter square and stop it here. We will discuss the rest of the things tomorrow. Thank you.

**(Refer Slide Time: 49:38)**

## Suggested Reading Materials References


1. S. P. Sukhatme and J. K. Nayak, Solar Energy: Principles of Thermal Collection and Storage, Tata McGraw Hill, 2015

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4. J. P. Holman, Heat Transfer Tenth ed. McGraw-Hill Series in Mechanical Engineering, 2010