Solar Energy Engineering and Technology
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Lecture 31
Tutorial: Solar Pond Power Plant Design

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Tutorial

Solar Pond Power Plant Design

Dear students, today we will be discussing a tutorial on Thermal Energy Storage. In the tutorial, we will be specifically discussing on the Solar Pond Power Plant Design.

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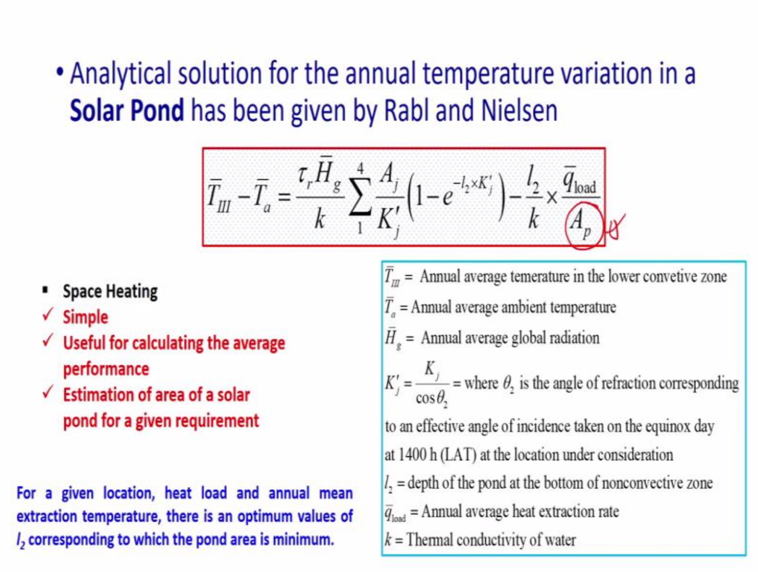

So, straight away, we can take the analytical solution for the annual average temperature variation in a solar pond, which was given by Rabl and Nielson. So, this is the relationship like $\overline{T}_{III} - \overline{T}_a$. So, what does it mean, $\overline{T}_{III}$ which is equal to annual average temperature in the lower convective zone and $\overline{T}_a$ which is nothing but annual average ambient temperature.

And $\overline{H}_g$ is nothing but in annual average global radiation then $K_j' = \frac{K_j}{\cos\theta_2}$, where θ_2 is the angle of refraction corresponding to an effective angle of incidence taken on the equinox day, at 14:00 hours local apparent time at the location under consideration. And l_2 is the depth of the pond at the bottom of the non-convicted zone and $\overline{q}_{load}$ is nothing but annual average heat extraction rate and k is nothing but thermal conductivity of water.

So, this is the area, so we need to find out the area, if we know other parameters. And K_j values are already discussed and we will be using those values in solving one of the numerical problems. A_j values also given to us at different wavelengths, so straight way we can use it. And τ_r values has to be calculated at incidence angle, which is specified for the particular location.

So, this analytical solution is normally used for space heating applications and this analytical solution is one of the simplest solution and is useful for calculating the average performance and also, it is useful for estimation of area of a solar pond for a given requirement. So, for a given location, heat load and annual mean extraction temperature, there is an optimum value of l_2 corresponding to which, the pond area is minimum. So, that we need to calculate, because it is one kind of optimization problem. At what blend we will get the optimized parameters, okay? So, if we can fix it up, then accordingly we can design other parameters.

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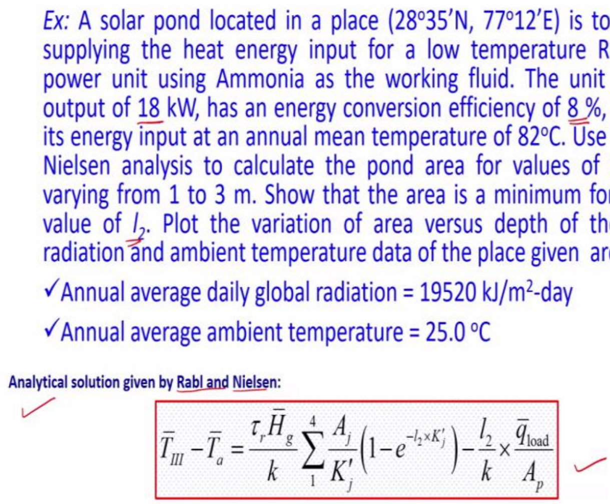

So, without delay, we can start a numerical exercise. The exercise goes something like; a solar pond located in a place having latitude and longitude are 28° 35′ North and 77° 12′ East, is to be used for supplying the heat energy input for a low temperature Rankine cycle power unit using ammonia as working fluid. The unit develops an output of 18 kW, has an energy conversion efficiency of 8 %.

So, Rankine cycle efficiency is given as 8 % and requires its energy input at an annual mean temperature of 82 °C. So, I will draw the pond and I will designate which location we want 82 and what is 8 % efficiency. Use the Rabl and Nielsen analysis to calculate the pond area for values of the depth l_2 varies from 1 to 3 m. And we need to show that area is a minimum for a particular value of l_2 and we need to plot the variation of area versus depth of the pond.

The radiation and ambient temperature data of the place given are as follows like, annual average daily global radiation is 19520 kJ/m^2-day and annual average ambient temperature is given as 25 °C. So, we can use the analytical solution given by Rabl and Nielsen. So, this correlation we can use.

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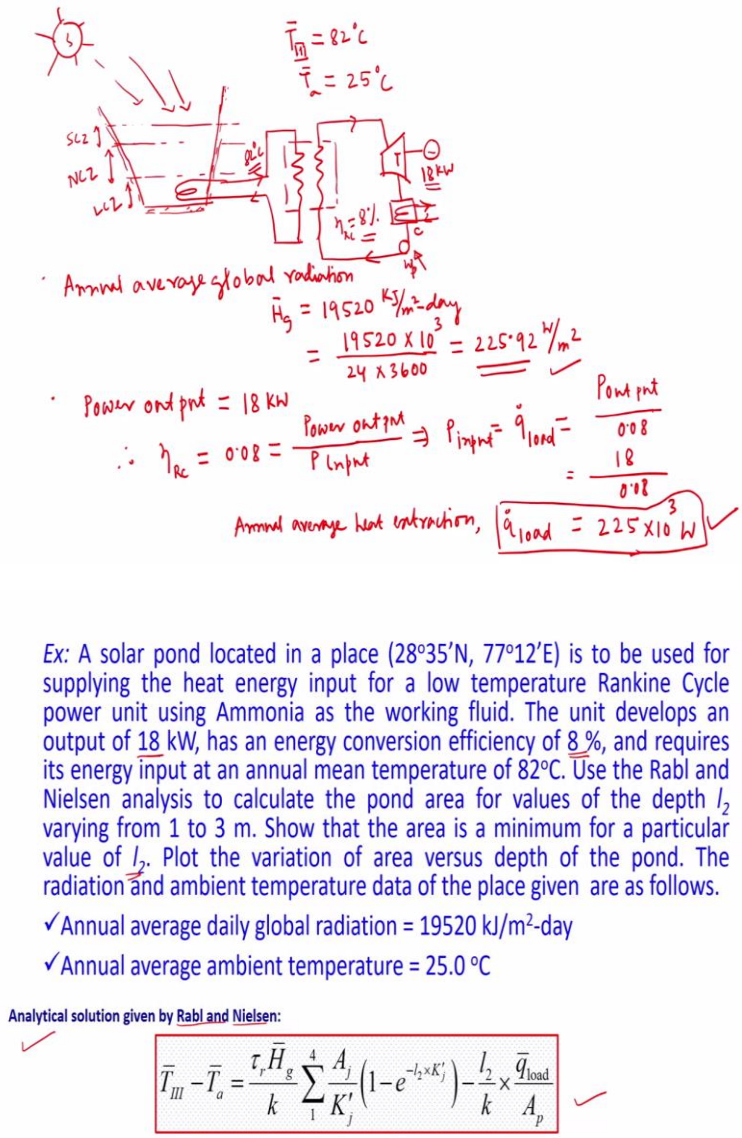

So, first let us draw the solar pond. So, we will have sun here, sun ray will fall and we will have this kind of pond. So, there are 3 layers already we have known. So, this first layer is known as surface convective zone and second layer is known as non-convective zone and third layer is known as lower convective zone. And this is applied to reduce the heat losses, of course, this has to be some kind of insulation kind.

So, solar radiation is falling here and data given to us is something like $\bar{T}_{III}$, which is nothing but 82 ºC right. So, what is this temperature? So, maybe we can think of this kind of heat exchanger here. And we will think this kind of heat exchanger okay. And this is connected to here and here we want 82 ^oC okay. So, already this is given and we will have this Rankine cycle.

In the Rankine cycle, what happens, we need some kind of working fluid, ok. Since, this is a low temperature operation, then we need some kind of refrigerant or organic fluid. So, what we will get, this is 18 kW. So, this is turbine, this is condenser, this is pump W_p, so pump work is neglected here and this is the heat exchanger. So, this hot water goes in the heat exchanger and exchanges heat with this organic fluid and then fluid will be evaporated or refrigerant will be evaporated like ammonia, what we have used in this setup or maybe other refrigerant R22 can also be used.

So, it will evaporate and pressure will rise and will expand in the turbine and electricity will be generated. So, it is given that 18 kW electricity is generated in this setup and this is a condenser and pump and it circulates again and again. So, I will now write down, what are the information given to us. So, this efficiency, Rankine cycle efficiency, so η_{RC}, which is given as 8 % and ambient temperature, which is average of the air, it is 25 ^oC.

And also we know, the annual average global radiation which is given to us, annual average global radiation global radiation, which is designated by $\overline{H}_g$ which is given as 19520. So, what is given, we can see here 19520 kJ/m^2-day. This is kJ/m^2-day. So, we can convert it to W/m^2. So, if will do that, then what we need to do?

So, 19520 $\times 10^3$, it will be J now, then it is in days so, it is 24 hours and then 3600. So, this will give H_g in W/m^2. So, this is something like 225.92 W/m^2, right. So, this is important, we need manier times this information and also we know power output, which is equal to 18 kW, right and efficiency of the Rankine cycle is also given it is a 8 %. So, η_{RC} which is equal to 0.08, which is equal to, this is power output to the input energy.

So, input energy or power input or I will write it as P input. So, this is nothing but q_{load} or annual average heat extraction. So, this P_{in} or P input which is equal to, q_{load} will represent, which is nothing but P output, which is power output and this will be something like 0.08. So, if we substitute the value of power output to be 18 kW and this is 0.08, so this will be equal to 225 $\times 10^3$ W.

So, this is nothing but annual average heat extraction. This is annual average heat extraction. So, this, we can represent like q_{load}. So, q_{load} is known now and H_g in W/m^2, is also known to us.

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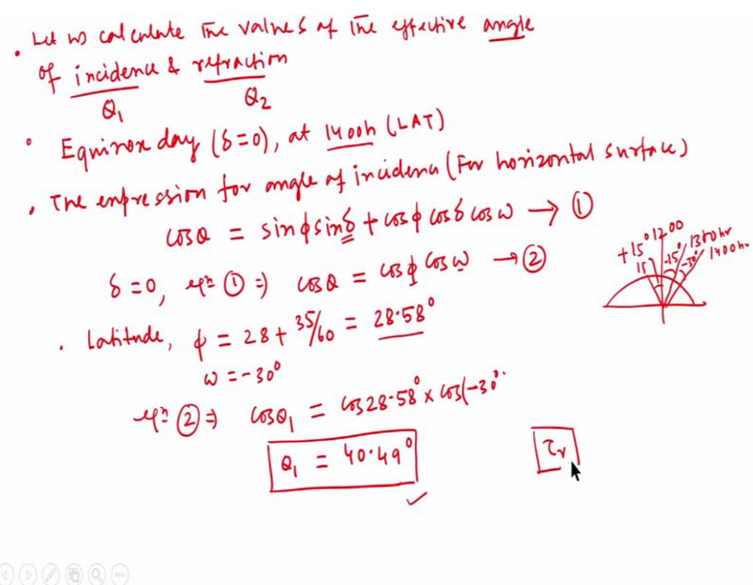

Now, what we will do, we will calculate θ_1. So, that means, let us calculate the values of the effective angle of incidence and refraction. So, this angle of incidence which is represented by θ_1 and this is represented by θ_2. And these two values, have to be obtained on the equinox day. So, equinox day, equinox day, that means $\delta = 0$ and at 14:00 hours, okay 14:00 hours which is LAT, local apparent time.

And also we know the expression, expression for angle of incidence for horizontal surface and that has to be for horizontal surface. So, this is something like $\cos\theta = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega$. So, if we substitute, say maybe, one we can write, the value of $\delta = 0$ then equation 1 implies, cos θ is equal to, so here sin 0 is 0, so this expression will be 0, then this will be cos ϕ then cos 0 is 1 so, it will be cos ω. So, this may be equation 2.

Also, we can calculate the latitude, the latitude ϕ, we can calculate from the given data, (28+35/60). So, which will be equal to 28.58° and what will be the ω? So, this has to be calculated 14:00 hours local apparent time, so that means, every 1 hour so, if we consider this and this is solar noon so, this is 12 hours. So, every 1 hour so, this side means 11 o'clock if we consider then this will be 15° and this will be positive.

So, other side, so it may be 13 hours so, it will be 15°, but it is minus; because afternoon. And at 14:00 hours, so it will be -30. So, that is how, it is -30°. So, ω is also known, then ϕ ω is known and we can use the equation to find out what is θ and this θ is nothing but θ_1. So, equation 2 implies, then cos θ, this θ is nothing but θ_1, okay.

So, cos 28.58 ×cos (-30). So, if we do the calculation, then θ_1 is found to be 40.49°. Now, what we need to do? We need to find out τ_r, at this condition.

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Ex: A solar pond located in a place (28°35'N, 77°12'E) is to be used for supplying the heat energy input for a low temperature Rankine Cycle power unit using Ammonia as the working fluid. The unit develops an output of 18 kW, has an energy conversion efficiency of 8 %, and requires its energy input at an annual mean temperature of 82°C. Use the Rabl and Nielsen analysis to calculate the pond area for values of the depth l_2 varying from 1 to 3 m. Show that the area is a minimum for a particular value of l_2. Plot the variation of area versus depth of the pond. The radiation and ambient temperature data of the place given are as follows.

✓Annual average daily global radiation = 19520 kJ/m²-day

✓Annual average ambient temperature = 25.0 °C

Analytical solution given by Rabl and Nielsen:

$$\boxed{\bar{T}_{III} - \bar{T}_a = \frac{\bar{\tau}_r \bar{H}_g}{k} \sum_1^4 \frac{A_j}{K'_j}\left(1 - e^{-l_2 \times K'_j}\right) - \frac{l_2}{k} \times \frac{\bar{q}_{load}}{A_p}}$$

So, already you know, the expression here what we have shown. So, this τ_r so, this need to be calculated. So, let us see, how this can be calculated at that angle?

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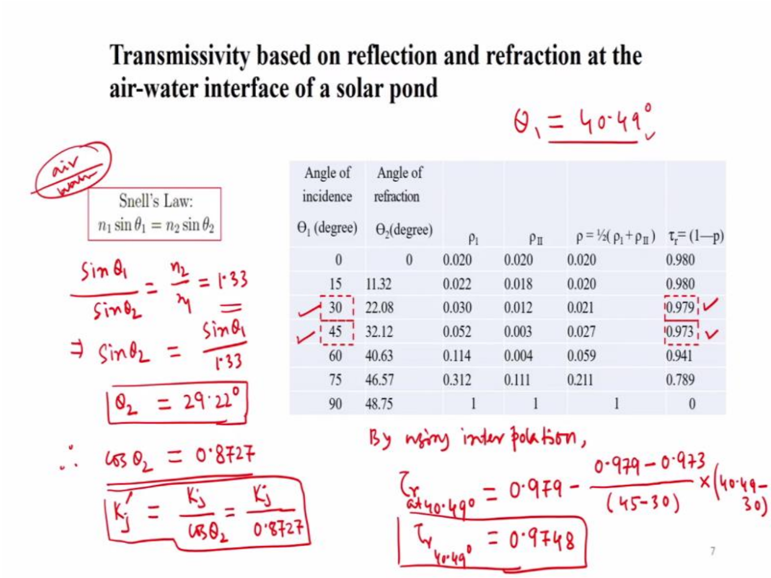

Angle of incidence Θ_1 (degree)	Angle of refraction Θ_2(degree)	ρ_I	ρ_{II}	$\rho = ½(\rho_I+\rho_{II})$	$\tau_r = (1-\rho)$
0	0	0.020	0.020	0.020	0.980
15	11.32	0.022	0.018	0.020	0.980
30	22.08	0.030	0.012	0.021	0.979
45	32.12	0.052	0.003	0.027	0.973
60	40.63	0.114	0.004	0.059	0.941
75	46.57	0.312	0.111	0.211	0.789
90	48.75	1	1	1	0

So, already we know the Snell's law and we know this chart. If we know the angle of incidence, then from that, we can calculate what will be the τ_r. So, from this Snell's law, what we can write, $\frac{\sin\theta_1}{\sin\theta_2}$ will be nothing but the ratios of refractive indices, which will be something like and n_2 or μ_2 okay. So, maybe n_2 I can write here, n_2/n_1 which is nothing but 1.33.

Because this is the surface convective zone and this is the interface between air and water or liquid. So, we know the refractive indices and from that, we can calculate the ratio which is equal to 1.33 and here already we know θ_1 and we can calculate what is θ_2. So, $\sin\theta_2 = \sin\theta_1/1.33$ and from here, we can calculate what is θ_2. So, this $\theta_2 = 29$, because this will be $\sin^{-1}$ of this value.

So, if we calculate it, it will be 29.22°. And also, we can calculate what is $\cos\theta_2$, because this will be requiring in order to calculate K_j. So, this is something like 0.8727 okay and why this is important? Because we need to calculate K_j', which is equal to $K_j/\cos\theta_2$, which is angle of refraction. So, this K_j, K_j will vary from 1 to 4 means K_1, K_2, K_3, K_4. So, everything we need to consider. So, let us prepare for that, 87 then 27. So, these values are also calculated now.

Now, we need to calculate τ_r. So, we need to use this table and as we can see 22.92 is θ_2 and then θ_1 what we already got is, so I will write θ_1 here, θ_1 already we have calculated, it is 40.49°. So, we know the values at 30 and 45. So, we need to calculate at 40.49. So, how to calculate it; by using interpolation.

So, by using interpolation, so τ_r, this is τ_r at 40.49^o which is equal to, first what is data, so this data this two data are required. So, from for 30 to 45, it is decreasing. So, we have to use negative sign, $0.979-\frac{0.979-0.973}{45-30}(40.49-30)$. So, if we do the calculation, then τ_r = 0.9748. So, who is, in between these two okay. So, this τ_r value at 40.49^o is something like this. So, we need this value for calculation.

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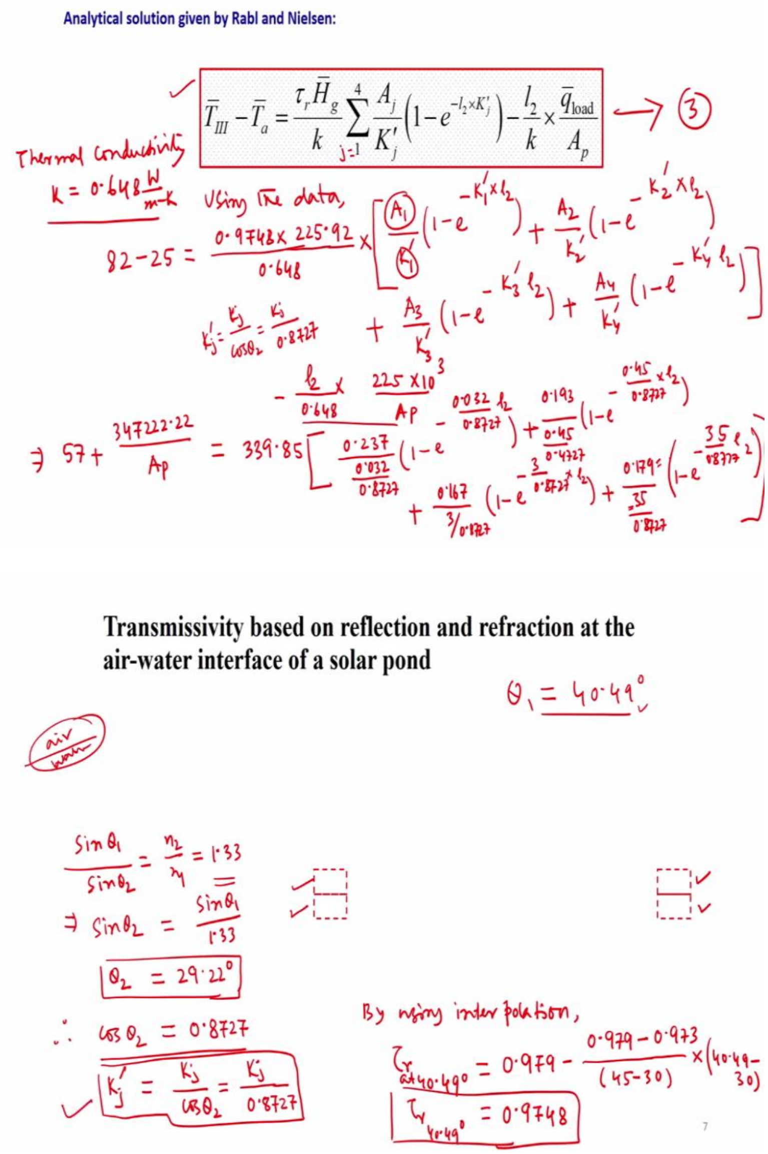

Now, we have been given, so this we need to apply, that is why, I kept it here and what is given thermal conductivity? So, thermal conductivity, k is given which is equal to 0.648 W/m K. Now, we know this expression, analytical solution and straight way, we can use the calculator data and given data. So, using the data, the data, this equation maybe we can write as 3 okay.

So, we know the value of $\overline{T}_{III}$ so, this is $82-25=\frac{0.9748\times 225.92}{0.648}$ and now, we need to use many parameters here.

So, $\left[\frac{A_1}{K_1^{'}}\left(1-e^{-k_1^{'}\times l_2}\right)+\frac{A_2}{K_2^{'}}\left(1-e^{-k_2^{'}\times l_2}\right)+\frac{A_3}{K_3^{'}}\left(1-e^{-k_3^{'}\times l_2}\right)+\frac{A_4}{K_4^{'}}\left(1-e^{-k_4^{'}\times l_2}\right)\right]-\left(\frac{l_2}{0.648}\times\frac{225\times 10^3}{A_p}\right)$.

So, if we simplify it, then what we will have? So, quickly I can write it, so (82 -25)= $57+\frac{347222.22}{A_p}=339.85$.

Now, we will substitute, and these values are known to us, these values are known to us and of course, we know this K_j' is, already we have done. Let us show what is this? $K_j^{'}=\frac{K_j}{\cos\theta_2}$. So, that way we know what is K_j here and these values A_1, A_2, A_3, A_4; all the values are known to us. So, K_j will be we have $\frac{K_j}{\cos\theta_2}$ which is nothing but $\frac{K_j}{0.8727}$.

So, these values are already given, so we can use those values. So, if we use those values, then this will simplifies something like, I will first expression I will show, then later on we will straightway use our spreadsheet,

$$\left[\frac{0.237}{\frac{0.032}{0.8727}}\left(1-e^{-\frac{0.032}{0.8727}\times l_2}\right)+\frac{0.193}{\frac{0.45}{0.8727}}\left(1-e^{-\frac{0.45}{0.8727}\times l_2}\right)+\frac{0.167}{\frac{3}{0.8727}}\left(1-e^{-\frac{3}{0.8727}\times l_2}\right)+\frac{0.179}{\frac{35}{0.8727}}\left(1-e^{-\frac{35}{0.8727}\times l_2}\right)\right].$$

So, so, once we do the calculation, then what we will get, let us write the expression.

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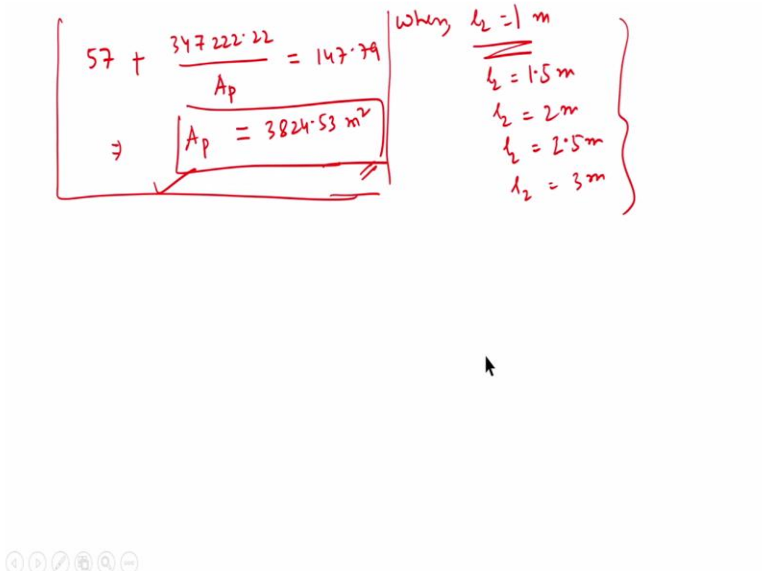

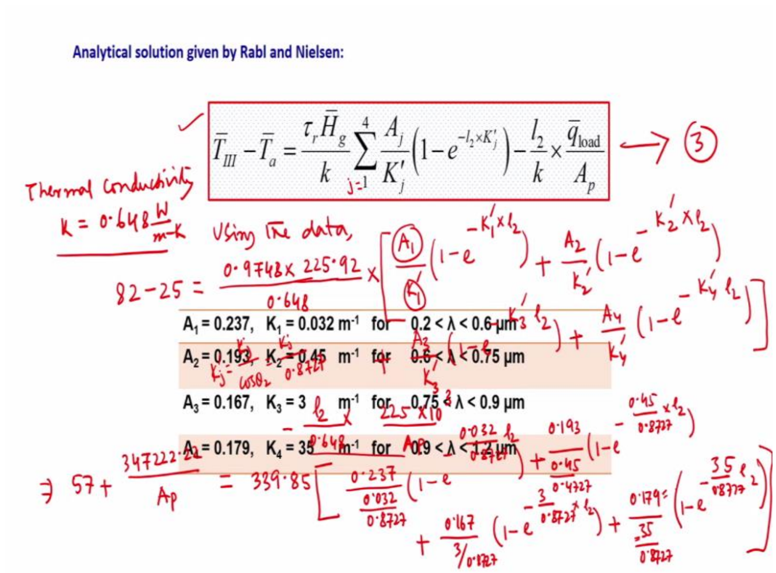

So, it will be something like $57+\dfrac{347222.22}{A_p}=147.79$. This is very long calculation. So, we can also try, so if we now calculate A_p = 3824.53 m^2 okay. So, what we got when l_2 = 1 m, okay. So, in this expression, we got the data and then we have substituted l_2 = 1 m. So, once we have substituted l_2 = 1 m, then what we got, A_p = 3824.53 m^2.

So, we need to do the calculation for l_2 = 1.5 m, l_2 = 2 m, l_2 = 2.5 m then l_2 = 3 m. Then, we can find out, at what depth we get the minimum area. So, that means, at that minimum area, we will get the 18 kW of power from this solar pond power plant. So now, let us use spreadsheet here, so that you can get the idea, how this can be calculated and we need to plot as well.

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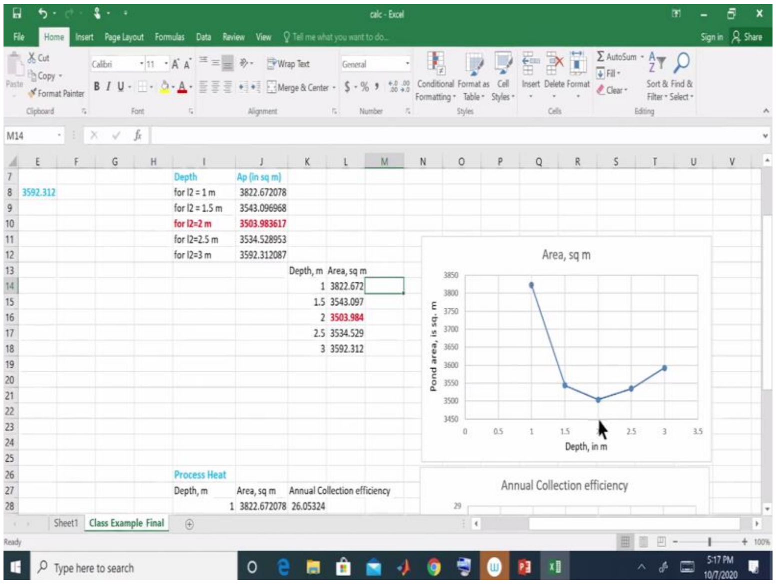

So, I have done this calculation in this spreadsheet and these values A_1, A_2, A_3, A_4, these are fixed; K_1, K_2, K_3, K_4 are fixed. Then we use A_1/K_1, A_2/K_2, A_3/K_3, A_4/K_4 then we use that expression what we have just now made it. These are the expressions and we have multiplied with it then we got the data. Now, this calculation if we substitute 1 here, l_2 = 1 then what happens, see 2822 but in our calculation, what we got is 3824.

So, this may be some kind of error we made during the calculations and there might be some round off error and all. And, if we substitute say 1.5, so, maybe 1.5 see what happens so, it is 3543.097, this is 3543.09 approximately it is 7. Then we will change the value to 2 and see what happens, we get a value of 3503.984. So, which is something like 3503.983617 to be precise, and again we can change to 2.5.

Let us see that, what happens? 2.5 and it comes to be something like 3534.529. And again we can change the values of l_2, which is equal to 3. Let us take 3 here and see what happens. So, we got a value of 35921.31 or so, okay. So, if we take the values now and try to draw it, then see what happens here okay. So, vertical axis shows the pond area and this horizontal axis shows the depth in m. So, with increase in depth, so this l_2 means; what?

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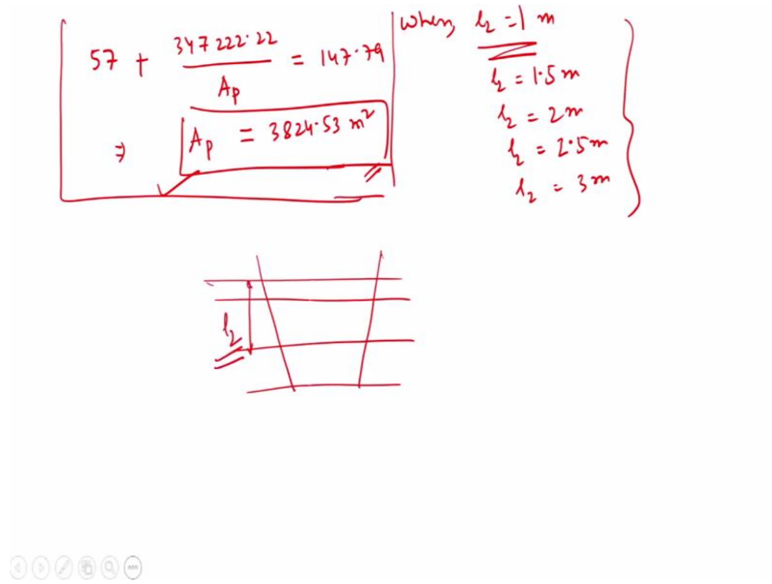

So, here so, this is the pond. So, this is the surface convective zone, then this is non-convective zone and this is the lower convective zone. So, maybe I will surface convective zone. So, this l_2 is nothing but, this is l_2, okay.

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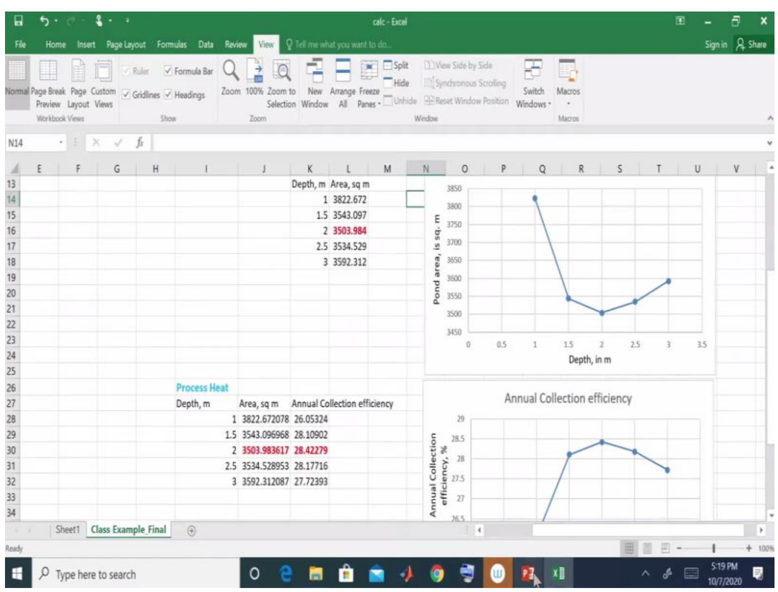

Here what happens, minimum is found to be at l = 2 meter. So, it is decreasing and then minimum, we found that too and then again it is increasing. And also sometimes, if we are interested about process heat application, then we can calculate the collection efficiency, which is annual collection efficiency. So, depth we have and then area we know and then we can calculate, annual collection efficiency.

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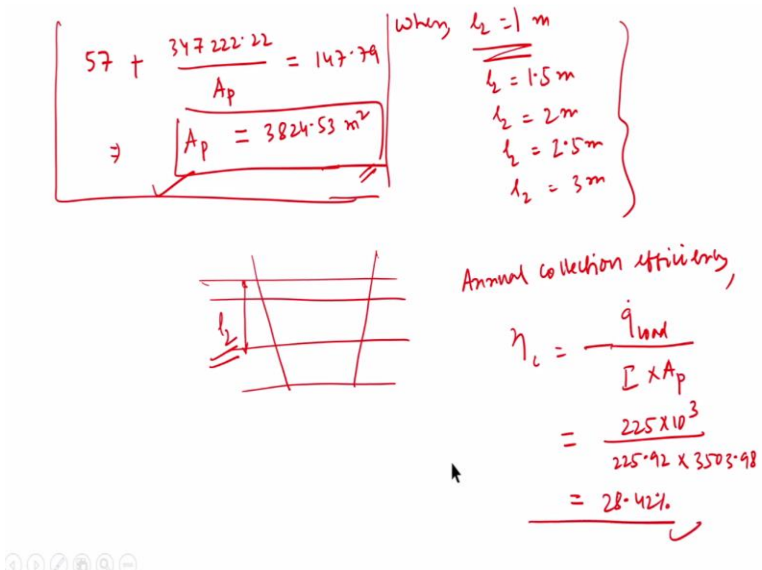

So, I can write it here, how this annual collection efficiency can be expressed, annual collection efficiency, collection efficiency. So, which can be expressed as $\eta_c = \frac{\dot{q}_{load}}{I \times A_p}$. Since, we know the optimum values, maybe any values we can take, maybe for l is equal to 1 or 2 or maybe 3, then we can see what will be the value of annual collection efficiency.

So, $\frac{225 \times 10^3}{225.92 \times 3503.98} = 28.42\%$. So that way, we can calculate the collection efficiency.

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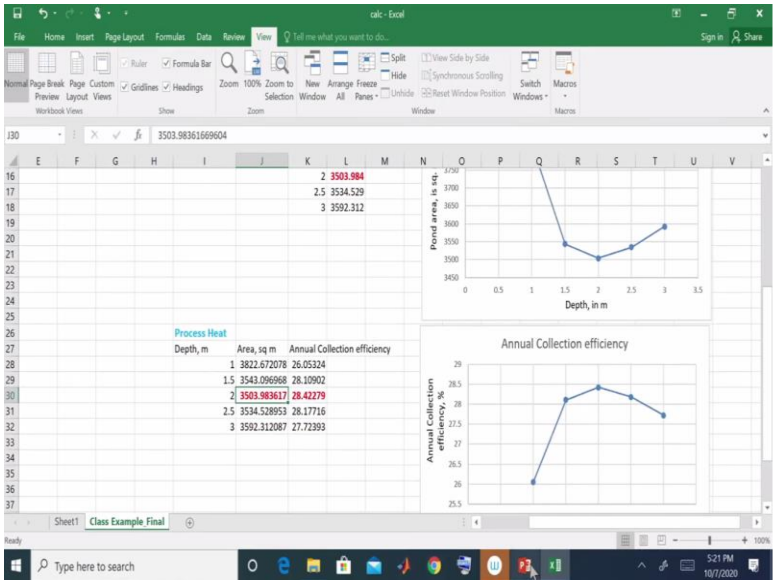

Now, let us go back again to the spreadsheet and develop the chart which shows the variation of annual collection efficiency with respect to depth. So, at l = 1 m, we get 26.05 %, 1.5 m, we get 28.1 % and at depth 2 m, we get about 28.42 %, what we have shown in the presentation and if we increase depth to 2.5 then its efficiency decreases. See at 3, it is 27.72 so, we have to go for this value.

So, l_2 = 2 m is the optimum value for maximization of annual collection efficiency as well as the performance of the solar plant. So, that is how, it is shown here. So, it is starting from 1 and it is increasing and then it reaches a maximum at 2 and then decreases. So, this depth is optimum, and this surface area is the optimum surface area for getting the maximum performance.

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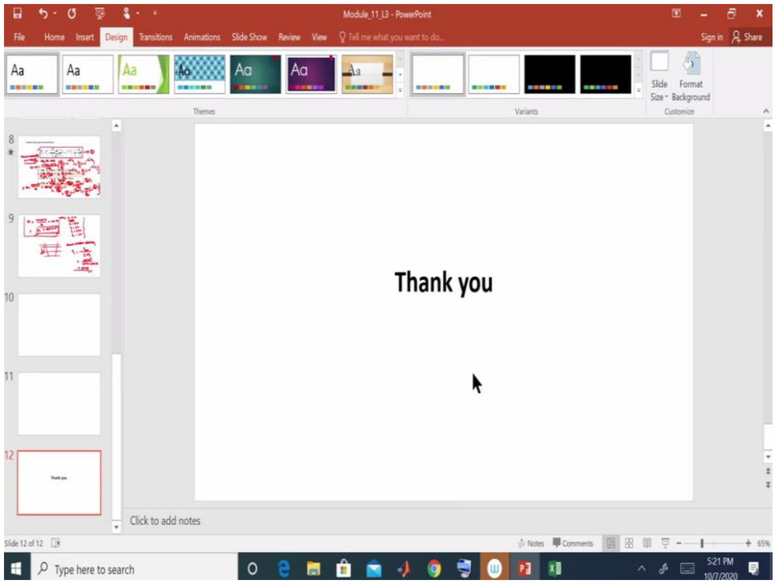

So, thank you very much for your attention. Hope you have learnt, how to design a solar pond power plant and this kind of problems are very, very practical. So, thank you very much for your attention.