Solar Energy Engineering and Technology
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Lecture 34
Module – 12: Solar Energy Applications: Tutorial

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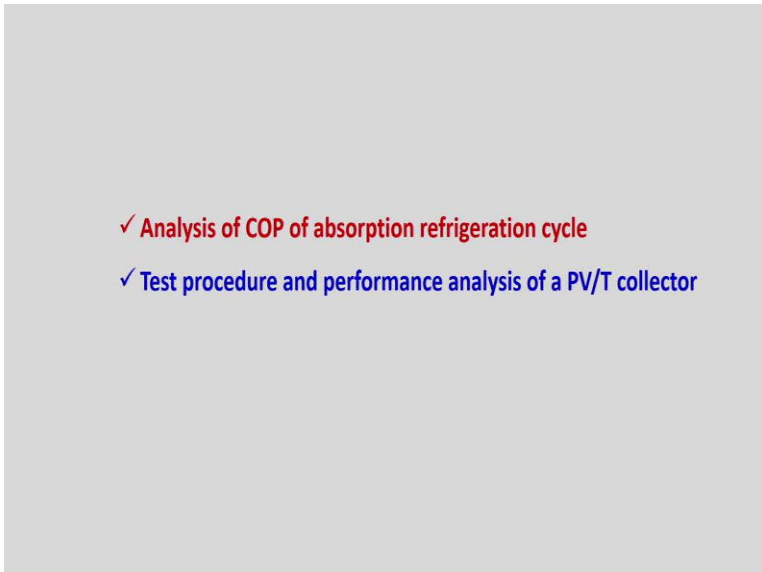

Dear students, today we will discuss a tutorial on analysis of COP of absorption refrigeration cycle and test procedure and performance analysis of a PV/T collector.

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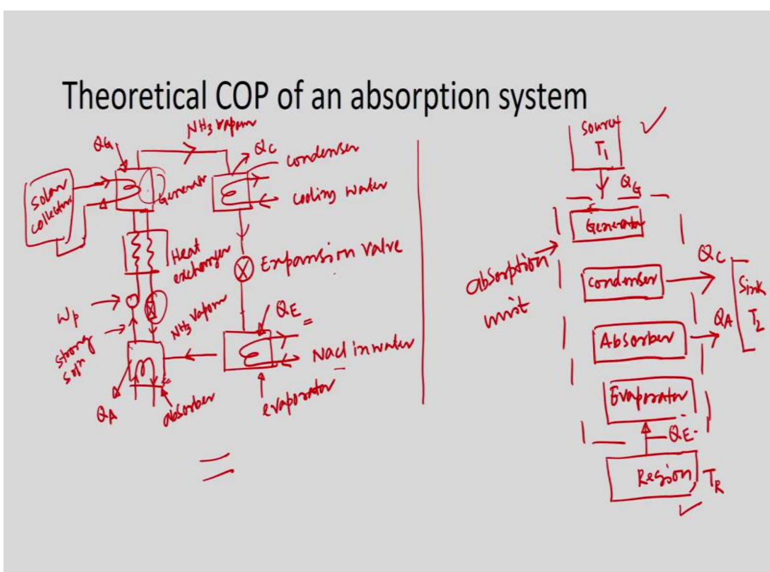

Let us consider the theoretical COP of an absorption cycle first. Let me draw the flow diagram of a vapour absorption refrigeration plant. So, we will draw this plant first, then it will be generator. So, solar collector will generate heat and it will go here; again, it will come back to the solar collectors, there are many collectors.

And then we will have a condenser here. So, we have to supply some kind of fluid to cool the refrigerant. So, we have to remove the heat maybe Q_c and we have to add heat from the solar collector, which is nothing but Q_G, because this is generator. And we will have expansion valve and then we will have evaporator. Then from evaporator, it will go to, what is called absorber. So, this is absorber and we have to circulate fluid to extract the heat of the solution. So, this Q_A has to be removed and here this Q_E, that much of energy which is nothing but absorption of heat from the atmosphere.

And then we will have heat exchanger here and maybe we will have pump here. So, strong solution will have to move up and we have a valve here and it will go down. So, I will write what are the components? This is W_p is the pump work and this is also known as aqua pump and we will have strong solution here, strong solution and we will consider aqua ammonia solution. So, ammonia vapour will be here which is at higher pressure and this is condenser, already known to us. This is condenser and here cooling water will be circulated, cooling water to condense the vapour.

And then this is expansion valve, expansion valve, where pressure will be reduced from certain atmosphere to very low pressure. So, here it is Q_E and this is evaporator and here, brine solution or sodium chloride is introduced. So, maybe sodium chloride in water, this is evaporator, heat exchanger, this is ammonia vapour, it is a low pressure. So, we have already discussed the working of vapour absorption refrigeration cycle in the earlier classes, where we have learn that the absorption refrigeration system is a heat operated unit which uses a refrigerant, that is alternatively absorbed and liberated from the absorbent.

So, here in this case, refrigerant is ammonia, when you talk about aqua ammonia refrigeration system and water is absorbent. So, we will start with this generator, so this is generator, so what happens, heat of this solar collector, which takes the heat and then this ammonia will be vaporised at high pressure and that has to be condensed in a condenser by circulating cooling water and then this liquid refrigerant pass through this expansion valve where pressure is reduced significantly. And then we have this evaporator where space need to be cool. Here, sodium chloride in water, that solution is used and heat is taking from the atmosphere.

And then, this low concentration of ammonia which introduced in the absorber where water actually comes down and mixes with this ammonia vapour and then here what happens is, heat of the solution has to be carried away; because this has to be maintained at constant temperature. Then what happens? It will become very strong solution, so ammonia concentration will be more and that has to be pumped through this heat exchanger to this generator.

So, it works in a loop. So, as you know, this boiling point of ammonia is less than that of the water, the ammonia vapour is given off from the aqua ammonia solution at high pressure here. And this weak solution returns to the absorber through this pressure reducing valve. So, this is important. So, now what we will do, we will do the analysis for calculation of theoretical COP of an absorption system.

So, let us draw the figure first. So, if we consider a source here, source which is at temperature T_1. Already we know the source is giving heat to the generator, so we also know what term represents amount of heat which is given to the generator, which is Q_G. So, it goes to generator, so I will write this is generator, generator and then it goes to condenser, condenser, then we have absorber I will write, absorber and we have evaporator.

And here, we need to maintain this region, this region need to be cooled. And from condenser and absorber, we take out heat Q_c and then we have Q_A. So, if we make this is a sink, sink at T_2 and this is the region we can take; T_R is the temperature need to be maintained for the refrigeration purpose. So, here this dotted portion is nothing but absorption unit, so this is absorption unit, absorption unit.

So here, what we can see, Q_G is the amount of heat we have given to this generator and Q_C is the amount of heat, which is carried away and Q_E is the amount of heat we have taken from the atmosphere and then Q_A is the amount of heat which is given off, that is heat of the solution; because we need to maintain a constant temperature, this absorber.

So, source is T_1 and then region temperature is T_R and sink is $Q_C + Q_A$. We are considering something like this. Now, let us develop the expression by taking the help of first law of thermodynamics and second law of thermodynamics; what will be the maximum coefficient of performance of an vapour absorption refrigeration cycle?

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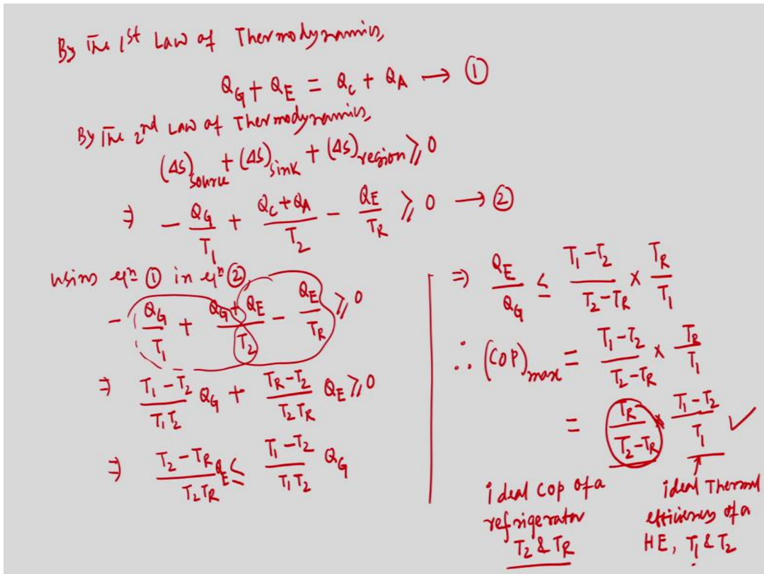

By the first law of thermodynamics, we know, it is a energy balance. Q_G, + Q_E = Q_C + Q_A. So, let this equation be 1. And by second law, second law of thermodynamics, we have, $(\Delta S)_{source}$ + $(\Delta S)_{sink}$ + $(\Delta S)_{region} \geq 0$.

So, entropy has to be ≥ 0. So, locally entropy may decrease or increase, but resultant entropy should always increase. That is the second law of thermodynamics in terms of entropy. Now, when we are taking heat from a source then what happens, then entropy will decrease, because randomness of the molecule will decrease. Something like, we can give an analogy, if we consider a silent library and the busy street, so when we sneeze in a silent library, what will happen? Then there will be lot of destruction, there will be lot of molecular disorderliness, because of that there will be rise in entropy.

If we sneeze or same level of sneeze, if we make in a very busy Street, then the rise of entropy will be not much. Again when we take heat from a high temperature source, then entropy will be negative, entropy will reduce. So, that is how, source is at high temperature, so the amount of heat we are taking is $\left(-\frac{Q_G}{T_1}\right)$ plus sink is getting the heat. So, there will be rise in entropy because when you are dumping heat, then what will happen; there will be lot of chaotic motion, like we are sneezing in a silent library.

So, under that condition, we can see $\left(\frac{Q_C+Q_A}{T_2}\right)$. So, sink temperature is maybe at T_2 and then here, again we are taking heat from the atmosphere, then this will be negative, $\left(-\frac{Q_E}{T_R}\right)$. So, this will be something like this. So, we can name this equation as 2. Now, using equation 1 in equation 2, we have, $-\frac{Q_G}{T_1}+\frac{Q_G+Q_E}{T_2}-\frac{Q_E}{T_R}\geq 0$.

So, if we simplify it, then it will be something like $\frac{T_1-T_2}{T_1 T_2}\times Q_G+\frac{T_R-T_2}{T_R T_2}\times Q_E\geq 0$. So, again if we simplify it, $\frac{T_2-T_R}{T_2 T_R}\times Q_E\leq\frac{T_1-T_2}{T_1 T_2}\times Q_G$.

So, again we can simplify, so what will happen, it will be Q_E, so I missed one here, it will be Q_E. So, this $\frac{Q_E}{Q_G}\leq\frac{T_1-T_2}{T_2-T_R}\times\frac{T_R}{T_1}$. So, if we are interested about COP, coefficient of performance, that is maximum or maximum coefficient of performance, $(COP)_{\max}=\frac{T_1-T_2}{T_2-T_R}\times\frac{T_R}{T_1}$.

So, again we can simplify, something like $(COP)_{\max}=\frac{T_R}{T_2-T_R}\times\frac{T_1-T_2}{T_1}$. So, what is this now. These two parameters, so what does this indicate? This is something like, ideal ideal coefficient of performance of a refrigerator refrigerator. So, that is working between T_2 and T_R. And what is this? This is the ideal thermal efficiency. This ideal thermal efficiency of a heat engine. I will write HE which indicate heat engine working between T_1 and T_2.

So, what we have evaluated, so when we are interested about COP of a vapour absorption refrigeration system which is nothing but multiplication of COP of a refrigerator working between T_2 and T_R and ideal thermal efficiency of an heat engine working between T_1 and T_2. So, that gives the maximum theoretical efficiency. So, now what we will do, we will take one example and try to see what will be the maximum COP of a vapour absorption refrigeration cycle.

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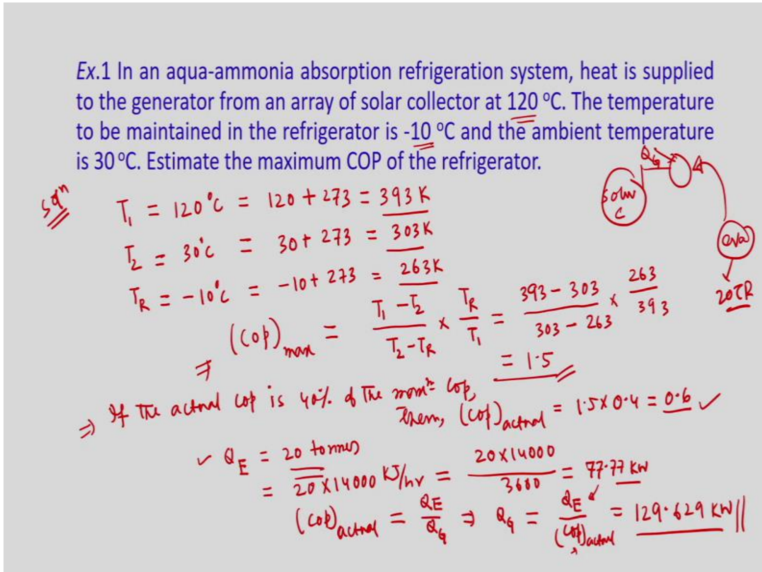

So, our problem goes something like an aqua ammonia absorption refrigeration system, heat is supplied to the generator from an array of solar collector at 120 ^{o}C, the temperature to be maintained in the refrigerator is -10 ^{o}C and the ambient temperature is 30 ^{o}C. Estimate the maximum COP of the refrigerator. So, we need to solve this problem now. So, here what is T_1? T_1 is nothing but source temperature, which is 120 ^{o}C, then we have to convert to K. So, (120 + 273) = 393 K.

So, what is T_2 here? T_2 = 30 ^{o}C, 30 ^{o}C which is the sink temperature. So, (30 + 273), which is nothing but 303 K. And then T_R is given, so we need to maintain the region temperature at -10 ^{o}C. So, (-10 + 273) = 263 K. So, if we know these three temperatures, then we can calculate the maximum COP.

So, we know the expression for maximum COP, $(COP)_{\max} = \frac{T_1 - T_2}{T_2 - T_R} \times \frac{T_R}{T_1}$. So, if we substitute this temperature values, so $(COP)_{\max} = \frac{393-303}{303-263} \times \frac{263}{393} = 1.5$. So, maximum COP of a vapour absorption refrigeration system is found to be 1.5, which is very less if we compare with vapour compression refrigeration system.

Now, if we are interested about actual COP, this is the maximum what we have calculated now. So, if we say the actual COP is 40 % of the maximum COP. So, if the actual COP is 40 % of the maximum COP, then what will happen? COP if we had actual then it will be (1.5 × 0.4), which will be about 0.6. So, actual COP will be about 0.6. Again, if we consider, say refrigeration load is say about 20 tonnes, so if we say Q_E is something like 20 tonnes, then how much heat is required?

So, solar collector is here, solar collector I will write C, then we have to transfer some kind of heat drive which is Q_G, so if evaporator a load is about 20 TR, ton of refrigeration, then how much heat is required? If we need to calculate, then how we will proceed? So, if you consider Q_E = 20 tons, so that means 1 TR is, how much in kJ/hr? It will be (20 ×14000) kJ/hr.

So, we can convert it to kW, if we divide the expression by 3600. So, (20 ×14000)/3600, then what we will get. the value of Q_E = 77.77 kW. So, that way we can calculate what is Q_E and then if we need to calculate Q_G, how to calculate? We know actual COP is nothing but Q_E/Q_G, so this Q_G will be something like $Q_E/(COP)_{actual}$. So, if we substitute this value, Q_E = 77.77 kW and COP = 0.6; then what we will get, it is about 129.629 kW. So, that much of energy is required to provide refrigeration effect of 20 TR. So, that is how we can do the calculation about the heat required to run the refrigeration system.

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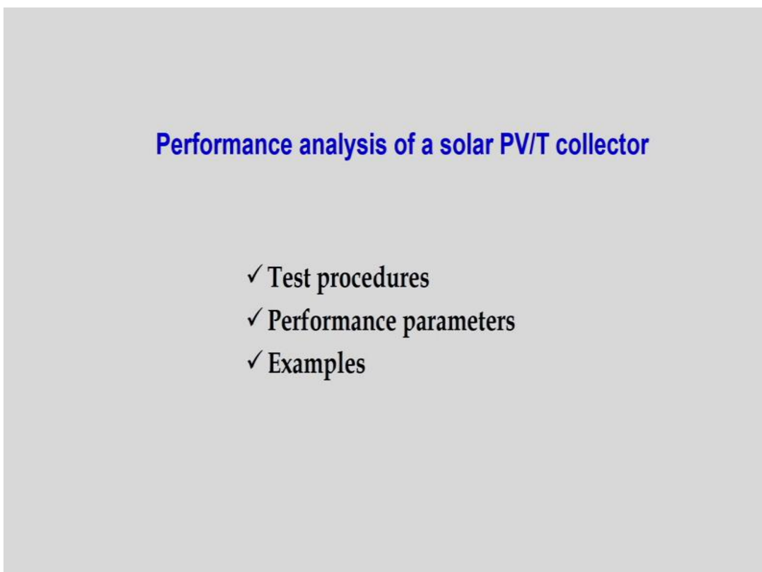

Now, let us discuss the performance analysis of a solar PV/T collector. It includes test procedure, performance parameters and then example.

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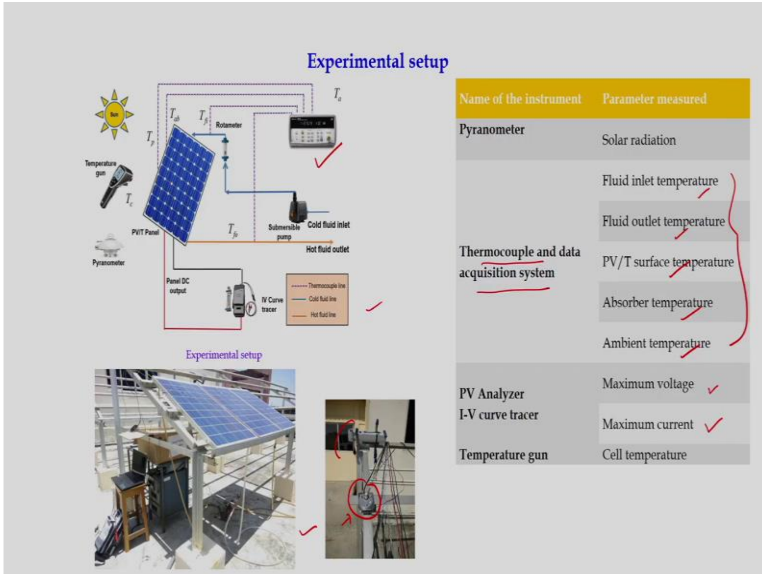

So, here what we have seen, one experimental setup schematic and one photograph. So, here this is the PV/T collector need to be tested. So, we have a test plate, so we can fix the unit at a particular tilt, and we make all the arrangements of measurement. So, you can see the actual picture how we have a mounting structure and all the measurement facilities. So, what are the instruments required for measurement of solar radiation, we need a pyranometer. So, this is the pyranometer.

So, pyranometer is here, so pyranometer will give us the global radiation and also we need to measure fluid inlet temperature, fluid outlet temperature, PV/T surface temperature, then absorber temperature, then ambient temperature. So, for measurement of this temperatures, we have a data acquisition system, which is a very sophisticated data acquisition system. So, we need the sensors and that has to be connected. So, this is something like this, so we can get the data in every second, what is the variation.

And of course, we need a PV analyzer which actually tells about the IV characteristics at particular time. So, from that, we can calculate what is the maximum voltage, what is the maximum current. Also we have used 1 temperature gun, to know the cell temperature. So, here solar radiation is falling here and then this is the collector we need to be tested and we have to circulate known quantities of fluid, the mass flow rate is constant and then fluid inlet temperature is constant and then outlet temperature can be measured and we need minimum solar insulation of 700 W/m^2 for these parameters, we followed standards.

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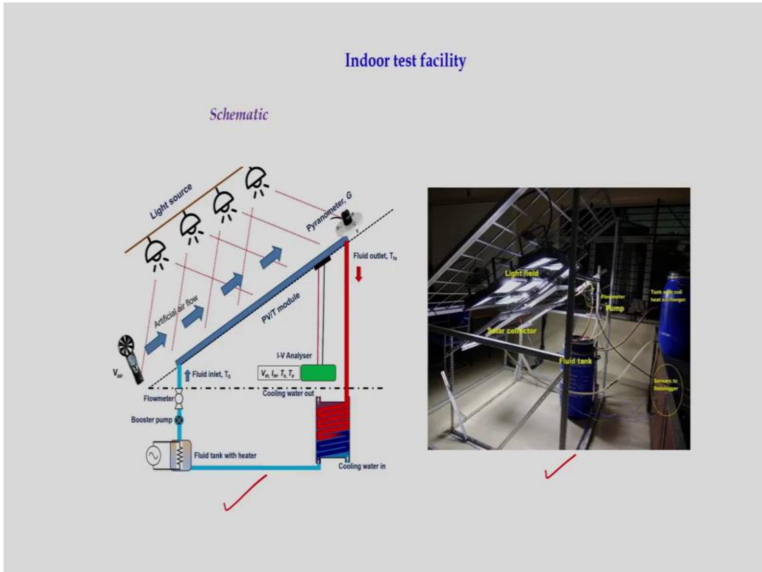

So, let us see how we can move to what is called indoor experiments. The one what I have shown that is a real-time experiments and what I am showing here is the test facility which is developed inside the laboratory. So, this figure shows the schematic and this figure shows the photograph. So, here we will have anemometer to see the wind velocities, because wind velocity also need to be controlled while performing the experiments and we have light source. We have given the sufficient light like simulation of our sun and we will have pyranometer to see the radiation intensity and we have this fluid tank with heater. So, we need to regulate the inlet fluid temperature; that is why we need this regulation tank and then mass flow rate is fixed.

So, under that condition, we have measured all the variables, like what is the V_m, what is I_m, what is surface temperature of the cell, what is ambient temperature, what is fluid inlet temperature, what is fluid outlet temperature. So, photograph can also be seen here. So, this is an indoor test facility.

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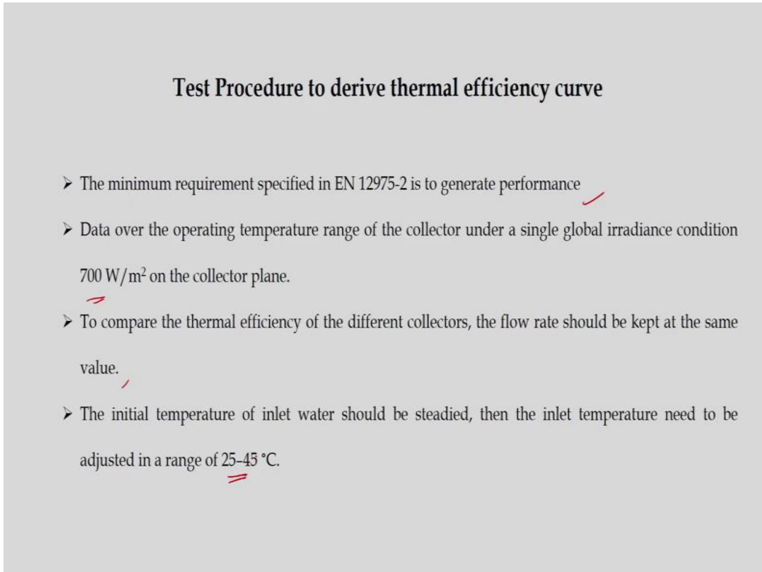

So, we have followed the following test procedure to derive thermal efficiency curve, like minimum requirements specified in EN 12975-2 is to generate performance and we have performed the experiments when solar radiation is more than 700 W/m^2. And to compare the thermal efficiency of different collectors, the flow rate should be kept at the same value and initial temperature we control, in the range of 25 to 45 ^{o}C.

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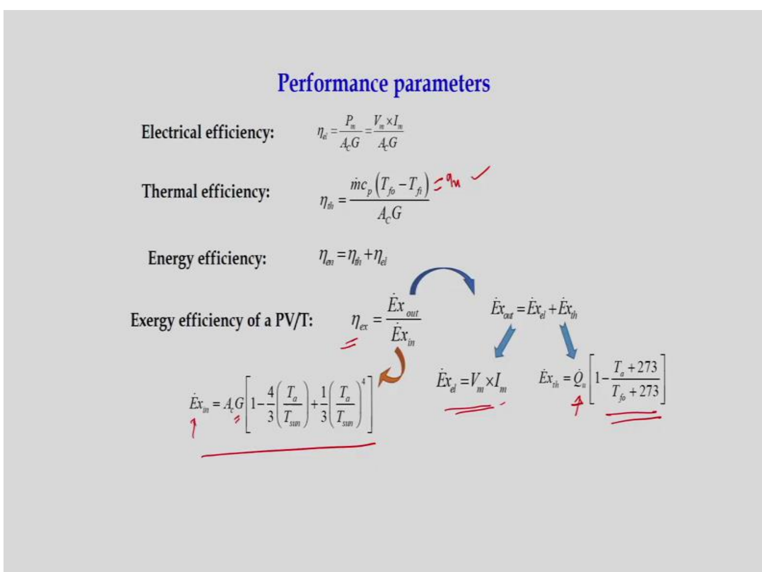

So, we have performance parameters which need to be calculated like electrical efficiency. So, how do we calculate electrical efficiency? Once we know V_m, I_m, for a particular set of experiments and we know the collector area and then amount of solar radiation which is falling on the collector then from that, we can calculate the electrical efficiency. And for thermal efficiency, we need to calculate the useful heat gain and then amount of solar radiation received by the collector.

So, this $\dot{m}C_p\,dT$, $dT=\left(T_{f_o}-T_{f_i}\right)$, so this is nothing but useful heat gain and this is the amount of radiation received by the collector. Then from that, we can calculate what is the thermal efficiency. So, once we know both electrical and thermal efficiency, then we just edit, which will give you energy efficiency and fourthly, what we are interested about exergy efficiency of a PV/T collector.

So, which can be expressed by exergy output to the exergy input. So, if we need to find out the exergy input, then we need to follow this expression. So, which is a function of this ambient temperature, sun temperature, then we will have amount of solar radiation received and then collector area. So, once we know these parameters, then from that, we can calculate what is exergy input and when we talk about exergy output, there are two components, that is electrical component and thermal component.

For electrical component, we can calculate this exergy output = $V_m \times I_m$ and for thermal exergy output, we can get from this expression. So, Q_E is the useful heat gain which is already known to us, in this calculation and T_a is known and T_{fo} is known; then from that we can calculate what is exergy output for thermal. So, we will combine this and then we divide the expression with exergy input then what we will get is the exergy efficiency of a PV/T collector.

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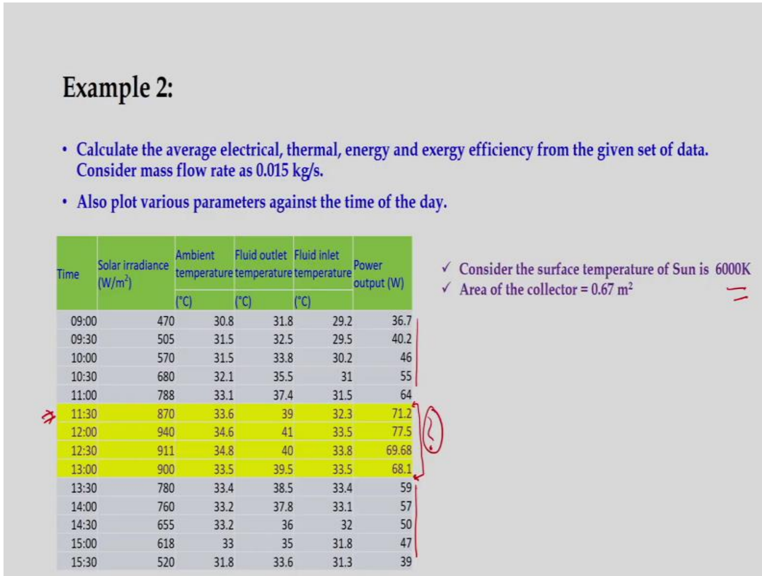

Example 2:

- Calculate the average electrical, thermal, energy and exergy efficiency from the given set of data. Consider mass flow rate as 0.015 kg/s.
- Also plot various parameters against the time of the day.

Time	Solar irradiance (W/m^2)	Ambient temperature (°C)	Fluid outlet temperature (°C)	Fluid inlet temperature (°C)	Power output (W)
09:00	470	30.8	31.8	29.2	36.7
09:30	505	31.5	32.5	29.5	40.2
10:00	570	31.5	33.8	30.2	46
10:30	680	32.1	35.5	31	55
11:00	788	33.1	37.4	31.5	64
11:30	870	33.6	39	32.3	71.2
12:00	940	34.6	41	33.5	77.5
12:30	911	34.8	40	33.8	69.68
13:00	900	33.5	39.5	33.5	68.1
13:30	780	33.4	38.5	33.4	59
14:00	760	33.2	37.8	33.1	57
14:30	655	33.2	36	32	50
15:00	618	33	35	31.8	47
15:30	520	31.8	33.6	31.3	39

- ✓ Consider the surface temperature of Sun is 6000K
- ✓ Area of the collector = 0.67 m^2

So, let us take one example like calculate the average electrical, thermal, energy and exergy efficiency from the given set of data. Consider mass flow rate as 0.015 kg/s and also plot various parameters against the time of the day. So, this is data what we have generated in our experiments. So, this is the timing and solar radiation is given here, so this is global radiation and we have used pyranometer and then ambient temperature is recorded and fluid outlet temperature is also recorded and fluid inlet temperature is here and then output power is known from the IV tracer.

So, normally what we do, when we test a solar collector, we normally perform the experiments during these hours 11:30 to 13 hours or 1 pm. Because during that time, we will get maximum exposure to the sun. So, our primary data will be this for performance analysis, but also we can see, what happens, if we perform the experiments from 9 to about 3:30 pm. And we need to consider the surface temperature of the sun is 6000 K and area of the collector is about 0.67 m^2. So, what I will do first, I will do one calculation and I will show you, then we will use one spreadsheet to calculate all the parameters for a single day, starting from 9 am to 15:30 hours.

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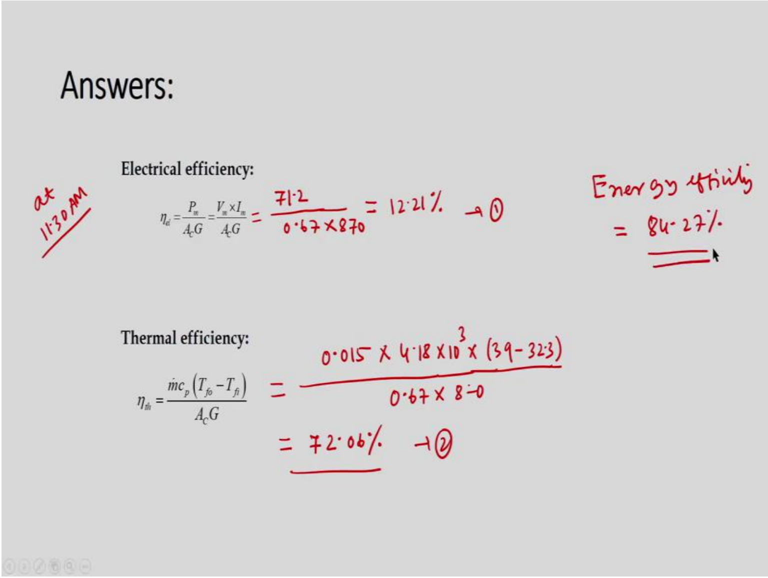

So, first let us calculate what is electrical efficiency for 11:30 am. So, here if we take the value of P_m, which is $V_m \times I_m$, so these are the maximum voltage and maximum current. So, here it is 71.2 and $A_c = 0.67$ and G value which is solar radiation is about 870. So, if we calculate it, it is found to be about 12.21 %. So, the next case, what we will do, we will calculate the thermal efficiency.

So, this is at 11:30 am, $\eta_{th} = \frac{0.015 \times 4.18 \times 10^3 \times (39 - 32.3)}{0.67 \times 870} = 72.06\%$.

So, I am just showing one calculation, then we can use the spreadsheet as there is no point of doing all the calculations here. So, when we talk about energy efficiency, energy efficiency which is nothing but 1 plus 2. So, here we are adding but sometimes you cannot add it, because quality of both the form of energy is different. So, it will be something like 84.27 %. And the next what we will calculate, is about exergy efficiency of a PV/T collector.

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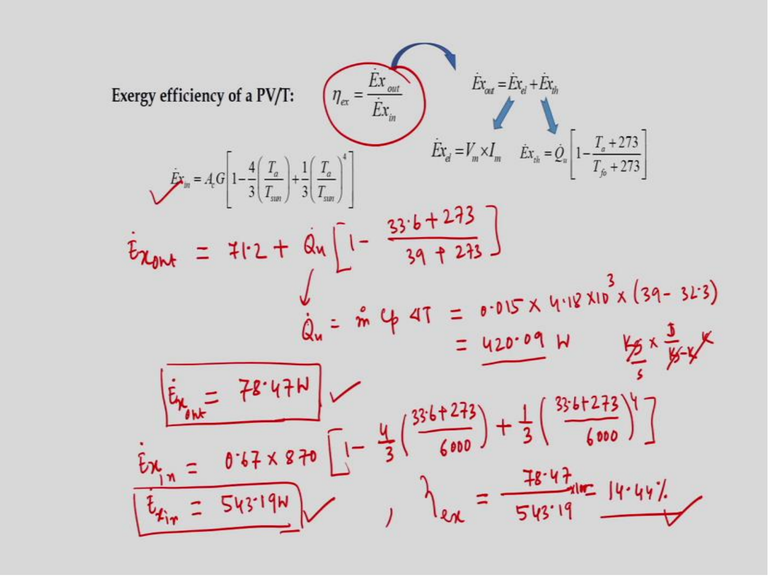

So, now we will calculate one by one. So, let us first calculate exergy output, so which is nothing but $V_m \times I_m$. So, this value is a P_m, P_m is already given which is nothing but 71.2 plus we will have Q_u, so we will write, $\dot{E}_{x_{out}} = 71.2 + \dot{Q}_u\left[1 - \frac{33.6+273}{39+273}\right]$. So, here we will add Q_u, $\dot{Q}_u = \dot{m}C_p\Delta T = 0.015 \times 4.18 \times 10^3 \times (39 - 32.3) = 420.09$.

So, here you can see the unit, so your m is in kg, so here J/kgK, this is K. So, this is coming right and this is mass flow rate, so J/s is W. So, this will be in watt. So, here if we substitute the values, then it is found to be about $\dot{E}_{x_{out}} = 78.47$ W. So, exergy output. So, this is known now.

So, now what we need to calculate is exergy in. So, we can use this expression, so straight away we can substitute the values here, so $\dot{E}_{x_{in}} = 0.67 \times 870 \times \left[1 - \frac{4}{3}\left(\frac{33.6+273}{6000}\right) + \frac{1}{3}\left(\frac{33.6+273}{6000}\right)\right]$.

So, if we do the calculation then exergy input is found to be about 543.19 W. So, this is exergy input. So, now what we will do, we will substitute this value and this value in this equation, so exergy efficiency will be $\eta_{ex} = \frac{78.47}{543.19} = 14.44\%$. So, we need to multiply 100 to get in percentage, so this is the exergy efficiency. So, once we know these values of temperatures and then solar insulation and then maximum power, then from that we can calculate all those efficiencies. Now, what we will do, we will go to the spreadsheet and see how we can generate the plot and do the calculation.

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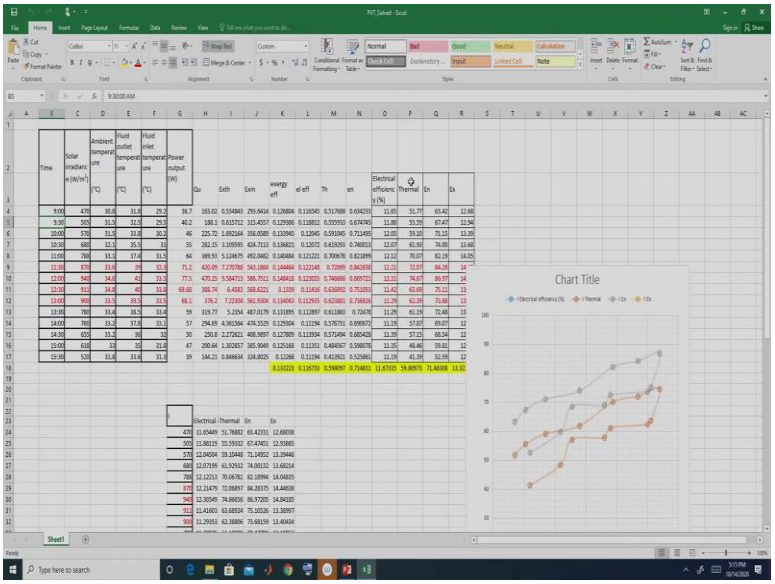

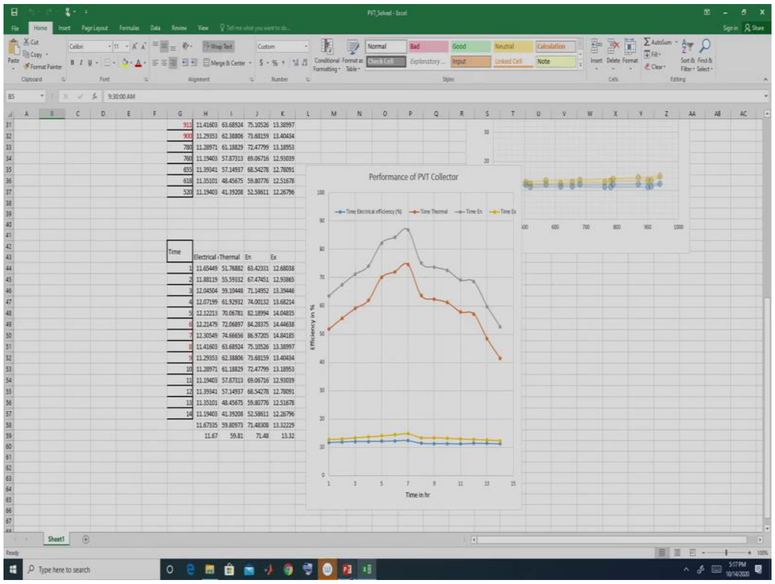

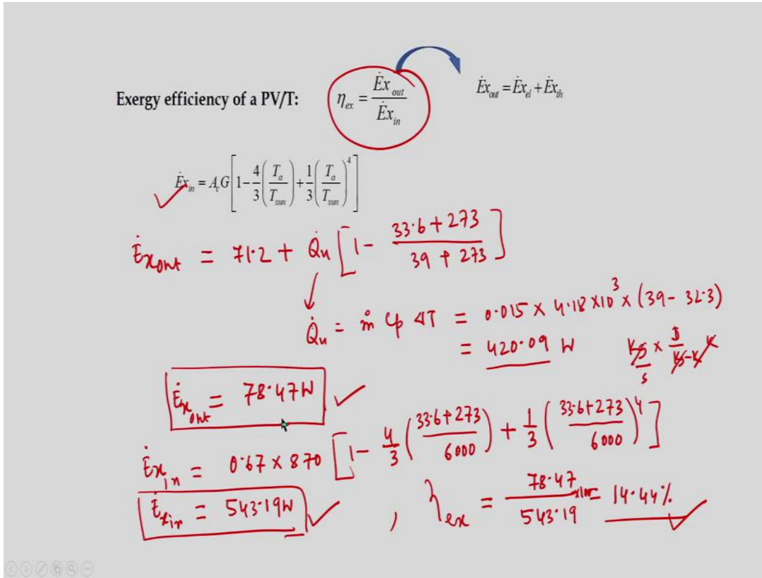

So, all the values are calculated here for 9 am, 9:30, 10, 10:30 till 15:30 and we can see the efficiency, electrical efficiency, thermal efficiency, energy efficiency, and exergy efficiency. So, if we take out these values from here and we can make a separate table and we can generate this kind of plot. So, maybe we can see the variation of efficiency with respect to the solar radiation then what happens and then again we can see, the variation of all the efficiencies at different times.

So, with increase in time what happens, there is increase in efficiency till mid of the day then it is decreasing. All the plots showing the similar pattern, but electrical efficiency is lower compared to thermal efficiency. So, by utilizing this PV/T technology, we can harvest both the energy, electrical energy as well as thermal energy.

So, that is why, it is shown. So, otherwise this energy heat energy would have been wastage, so we could not tap this energy. So, by attaching something at the beneath of the PV collector and then circulating fluid, so of course, there are some configurations such as beneath of the PV. So, water is circulated in those tubes, normally we have used some kind of tubes and from that actually, we can harvest this thermal energy. And this thermal energy can be applied for many of the applications. So, once we generate this plot, then we can take from here and we can use it here, because this problem is asking about the plot.

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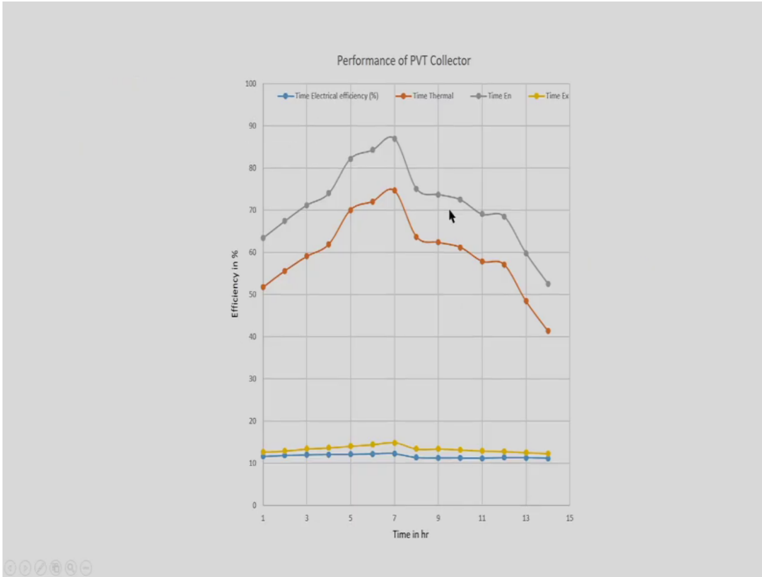
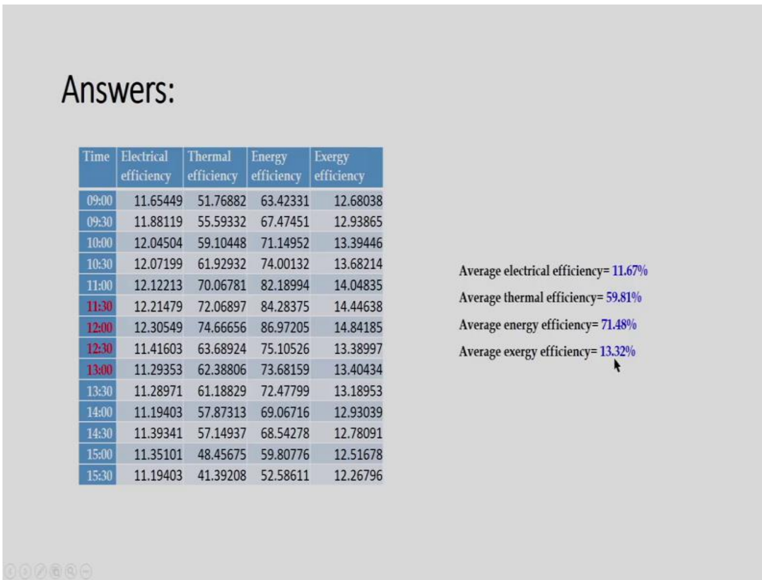




Answers:

Time	Electrical efficiency	Thermal efficiency	Energy efficiency	Exergy efficiency
09:00	11.65449	51.76882	63.42331	12.68038
09:30	11.88119	55.59332	67.47451	12.93865
10:00	12.04504	59.10448	71.14952	13.39446
10:30	12.07199	61.92932	74.00132	13.68214
11:00	12.12213	70.06781	82.18994	14.04835
11:30	12.21479	72.06897	84.28375	14.44638
12:00	12.30549	74.66656	86.97205	14.84185
12:30	11.41603	63.68924	75.10526	13.38997
13:00	11.29353	62.38806	73.68159	13.40434
13:30	11.28971	61.18829	72.47799	13.18953
14:00	11.19403	57.87313	69.06716	12.93039
14:30	11.39341	57.14937	68.54278	12.78091
15:00	11.35101	48.45675	59.80776	12.51678
15:30	11.19403	41.39208	52.58611	12.26796

Average electrical efficiency= 11.67%

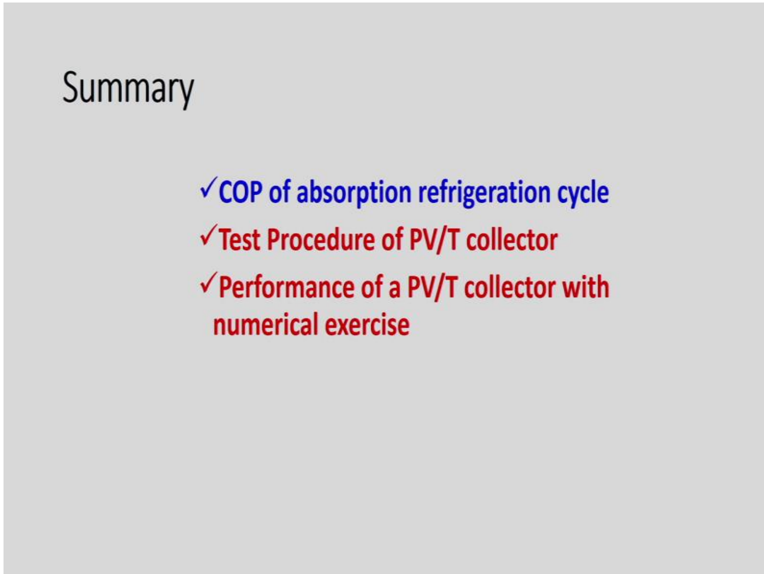
Average thermal efficiency= 59.81%

Average energy efficiency= 71.48%

Average exergy efficiency= 13.32%

So, we can have this kind of plots finally. And these are the results what we got from the analysis and this electrical average efficiency is 11.67 throughout the day, average thermal efficiency is about 60 %, average energy efficiency about 71 % and average exergy efficiency is about 13.32 %. So, this way we can do the analysis and investigate the performance of a PV/T collector.

(Refer Slide Time: 47:30)



So, in summary what we have done, we have investigated the COP of absorption refrigeration cycle and theoretical COP also we have calculated and we have discussed the test procedure of a PV/T collector and also we have studied the performance of a PV/T collector with an example. So, I hope you have enjoyed this video. Thank you very much.