Solar Energy Engineering and Technology
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Lecture 26
Fundamentals of concentrating collectors

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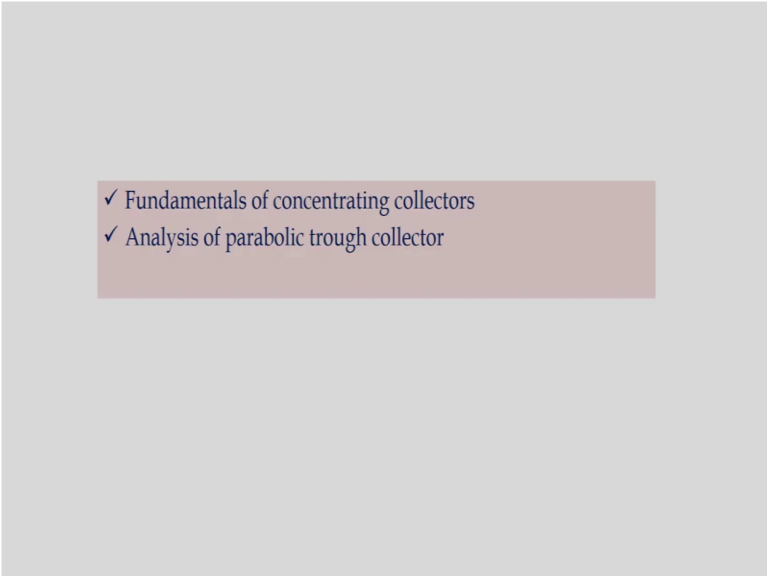

Dear students, today we will be discussing about fundamentals of solar concentrating collectors and analysis of parabolic trough collector.

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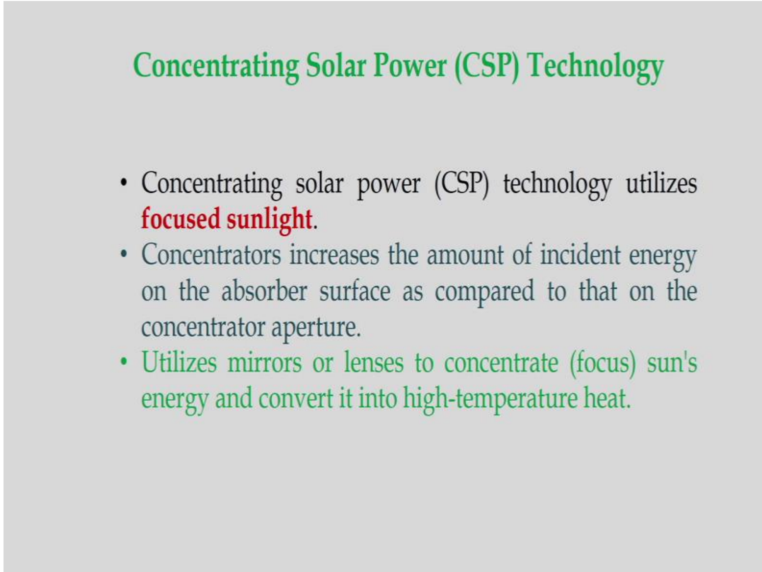

Now, what is concentrating solar power technology? This concentrating solar power technology utilizes focused sunlight. The concentrators increases the amount of incident energy on the absorber surface as compared to that on the concentrator aperture. And this CSP technology utilizes mirrors or lenses to concentrate Sun's energy and convert it into high temperature heat.

So, the kind of collectors we were discussing in the last classes, those collectors could be employed for generation of fluid temperature of about 100 or slightly more than 100 ^{o}C. But if we have to generate high temperature, or we have to think of application of high temperature application more than say 200, 300 or may be 400, so we need to go for concentrating solar collectors.

So, how it will work? That is what, we have explained here; and with the help of other slides, we will understand what is the importance of this technology as far as high temperature application generation is concerned.

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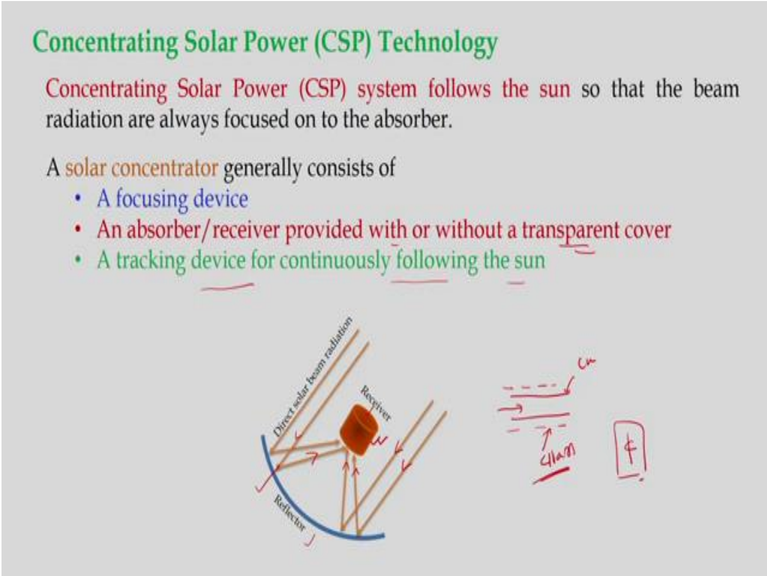

So, this concentrating solar power technology follows sun so that the beam radiation are always focused on the absorber. So, as you can see here, a solar concentrator generally consists of a reflector, there is a reflector or concentrator, we can say and this is a receiver. So, solar radiation comes and strike on this reflector and it reflects to this absorber. That is how it works and heat transfer fluid flow through this receiver and then that can be collected in a collection unit and that can be applied or used as per the applications.

So, we need a focusing device, this is nothing but a focusing device, an absorber or receiver. So, this is an absorber or receiver, so that may be with or without transparent cover. Sometimes, so if we draw this tube through which heat transfer fluid flows, so this may be steel or maybe copper, so material of construction is copper and just above it, will have a glass transparent cover. This is glass, so this is glass, so that is why it is said, with or without transparent cover.

And of course, we need a tracking device for continuously following the sun. So, in case of flat plate collector, that kind of systems are not required. So, that is installed in a location based on the phi value or latitude value and that is fixed throughout the year. But in case of concentrating collector, we need to rotate the device based on the solar radiation or to capture solar radiation throughout the day.

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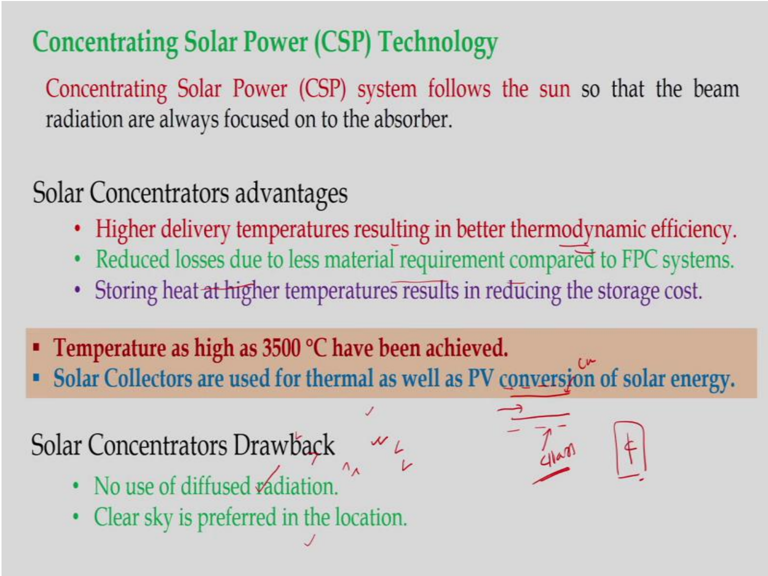

So, there are some advantages of this kind of technologies. So, first is, it is a better thermodynamic efficiency; because its operating temperature is higher or range of temperature is higher. And less material requirement compared to flat plate collector and reduced storage cost. So, these are the primary advantages of these solar concentrating collectors.

And as we can say, or as we have said, temperature as high as 3500 ^{o}C have been achieved by using this kind of collectors. So, these are high temperature collectors. These solar collectors are used for thermal as well as PV conversion of solar energy. So, there are some drawbacks, like we cannot employ diffused radiation for energy conversion, only beam radiations are applied in case of CSP. And that is why, we need a clear sky or cloudless sky for installation of this kind of devices.

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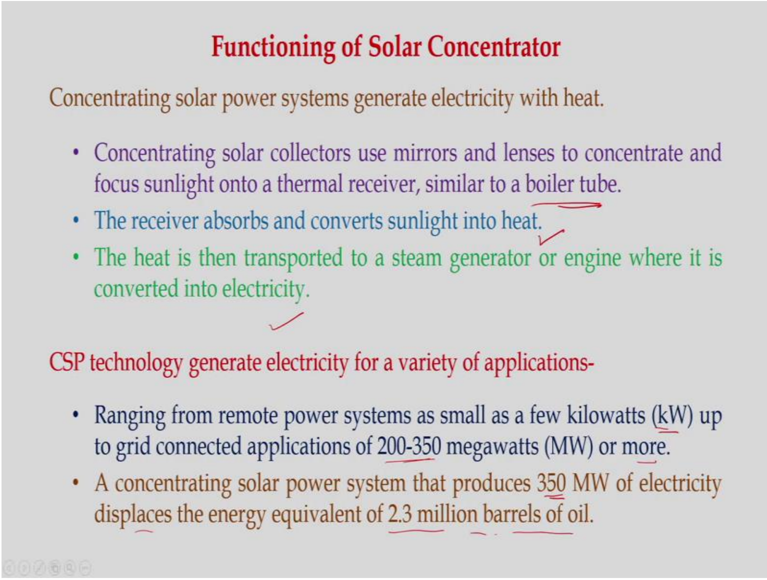

So, how this solar concentrator works if we have to see, this concentrating solar power system generate electricity with heat, that we must know. This concentrating solar collectors use mirrors and lenses to concentrate and focus sunlight onto a thermal receiver similar to a boiler tube like conventional power plant.

The receiver absorbs and convert sunlight into heat. The heat is then transported to steam generator or engine, where it is converted to electricity. So, when we talk about solar PV system, so it converts sunlight to electricity directly. But in case of solar concentrating collectors, we are utilizing thermal energy to generate electricity. So, first we have to convert this solar energy to heat, then heat has to be converted to electricity by using this generator.

So, CSP technology generate electricity for a variety of applications, like ranging from remote power systems as small as few kW upto grid connected applications of 200 to 350 MW or more. A concentrating solar power system that produces 350 MW of electricity displaces the energy equivalent of 2.3 million barrels of oil, so which is very-very advantageous.

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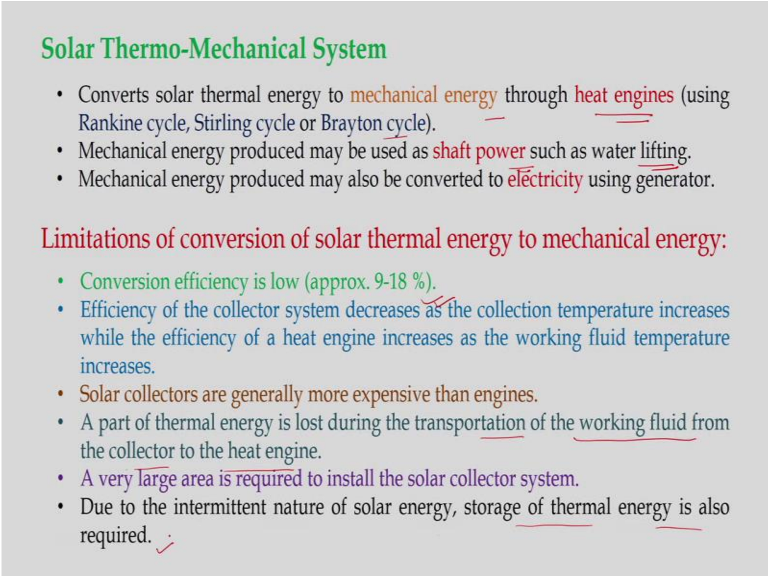

And now let us pay more attention on this thermo-mechanical system. How this heat energy is converted to electricity? So, as we say thermo-mechanical system, which convert solar thermal energy to mechanical energy through heat engine using Rankine cycle may be, maybe Stirling cycle, maybe Brayton cycle. So, this mechanical energy produced may be used as shaft power such as water lifting. And this mechanical energy produced may also be converted to electricity using generator.

So, what are the limitations of this conversion? This conversion efficiency is low. It is about 9-18 %. The efficiency of the collector system decreases as the collection temperature increases, which is reverse in case of heat engine. The efficiency of the heat engine increases as the working fluid temperature increases.

The solar collectors are generally more expensive than engine, and a part of thermal energy is lost during the transportation of the working fluid from the collector to the heat engine. That has to be considered. A very large area is required to install the solar collector system. And due to intermittent nature of solar energy, storage of thermal energy is also important.

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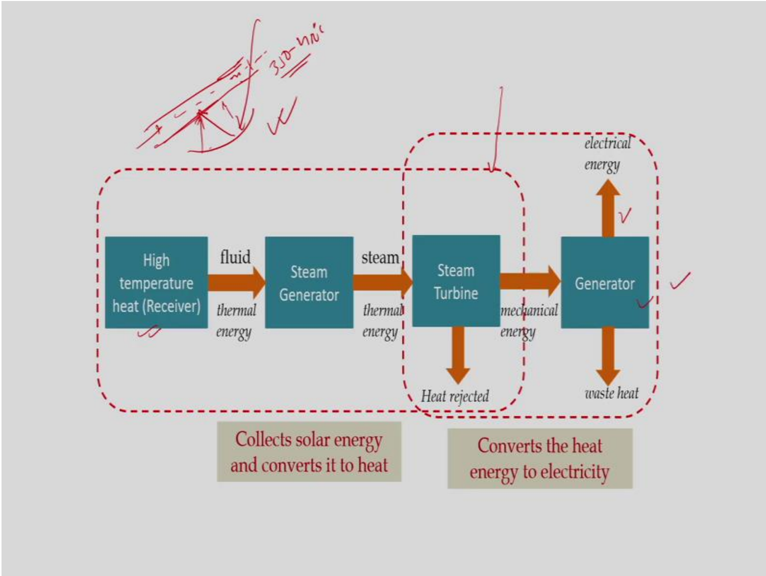

Now, let us see this picture how this high temperature heat which is generated in the receiver system. So, as we can see thermic fluids are used in the tube through which heat exchange takes place. Solar radiation, so may be this is the collector, so radiation falls here, beam radiation falls here and strikes in the receiver system; so heat transfer fluid flows.

So, here this heat will be very-very high, if we talk about parabolic trough, may be 350-400 ^{o}C. It is a very high temperature, so the thermic fluid will be heated up. And then that will move to thermal generator or maybe heat exchanger, so that heat will be utilized, and then that heat will be used for heating the secondary fluid. And then it will pass through the steam turbine. Because once that fluid what is used in this Rankine cycle will be expanded in the turbine, and that mechanical energy can be converted to electrical energy by using this generator.

So, of course, heat rejection will be there from the turbine. So, this will work in a closed loop. So, this heat transfer fluid or say the fluid what is used in this cycle may be different from the fluid what is used in this concentrator cycle. So, this is how from thermal collectors to the electricity generation takes place.

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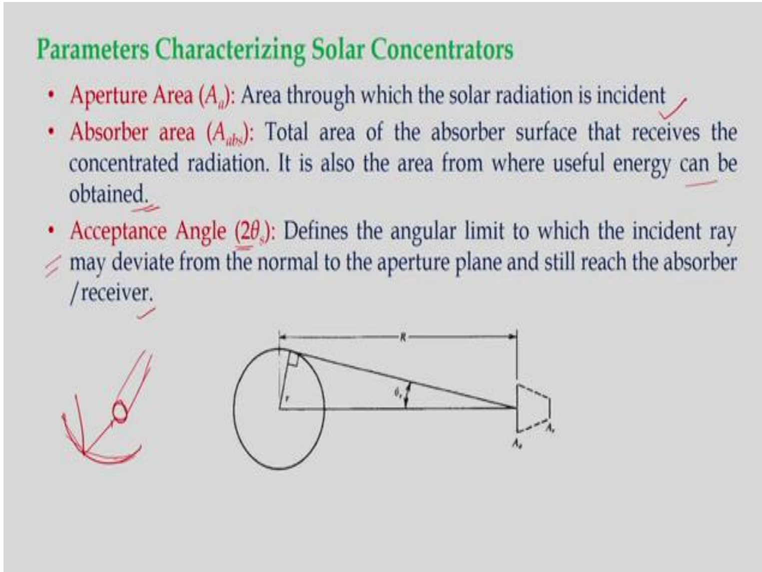

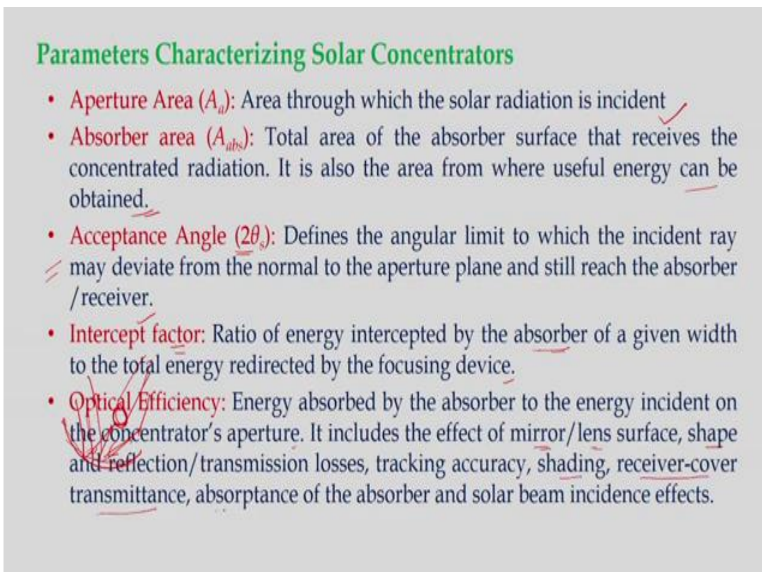

Now, let us learn some of the parameters which characterizes solar concentrators, like aperture area. So, if we talk about this tube and this is the reflector part, so this area is nothing but aperture area. The area through which solar radiation is incident, is nothing but aperture area. And this absorber area is something like that, it is a very long tube if we talk about parabolic trough.

The total area of the absorber surface that receives the concentrated radiation, it is also the area from where useful energy can be obtained. And then acceptance angle, which is represented by $2\theta_s$, which defines the angular limit to which the incident ray may deviate from the normal to the aperture plane and still reach the absorber or receiver. So, this is the aperture angle, what you can see here. So, this is sun and this is the receiver, earth surface.

And also, we need to know what is intercept factor, which is defined as the ratio of energy intercepted by the absorber of a given width to the total energy redirected by the focusing device. So, the amount of radiation which is striking onto this absorber. So, some of the radiations may not be striking here, so it may goes off or maybe it is coming in that way and then it might not be striking this absorber. So, that is why, this factor need to be considered. Of course, we are looking for unity, but always you will not get this unity.

And also, we need to know what is optical efficiency. So, this optical efficiency defines the energy absorbed by the absorber to the energy incident on the concentrators aperture. It includes the effect of mirror or lens surface, shape and reflection transmission losses, tracking accuracy, shading, receiver cover transmittance, absorptance of the absorber and solar beam incident or solar beam incidence effects.

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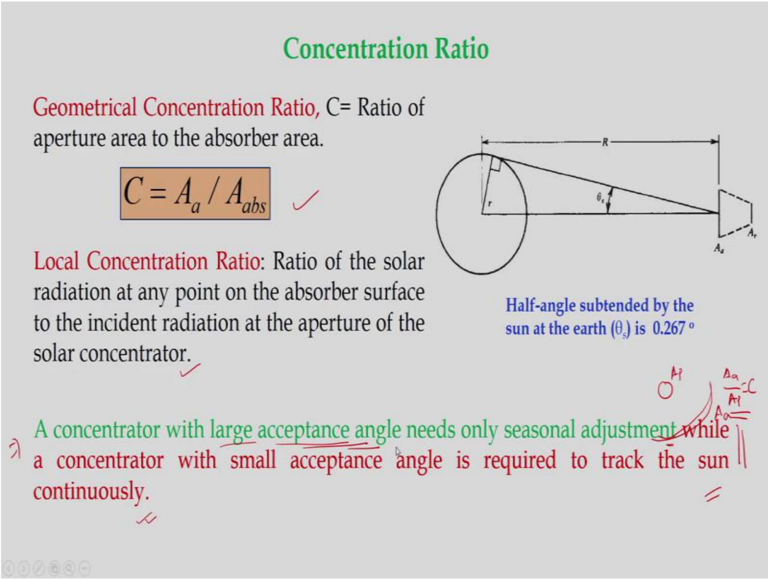

So, let us define concentration ratio. So, how we can define concentration ratio? Concentration ratio is the ratio of aperture area to the absorber area. So, as I am writing this again and again, so this is an aperture area, so maybe A_a I can write and this is the absorber area, so this $\frac{A_a}{A_p} = C$, which is concentration ratio. The local concentration ratio can also be defined which is the ratio of solar radiation at any point on the absorber surface to the incident radiation at the aperture of the solar concentrator.

So, we can see the definition of C here. And this is very important point like a concentrator with large acceptance angle, needs only seasonal adjustment; while a concentrator with small acceptance angle is required to track the sun continuously. So, this is very very important, so sometimes we need to design the concentrator in such a way that it has to operate continuously and sometimes intermittent adjustment is also fine. So, this defines acceptance angle is important for deciding this adjustment.

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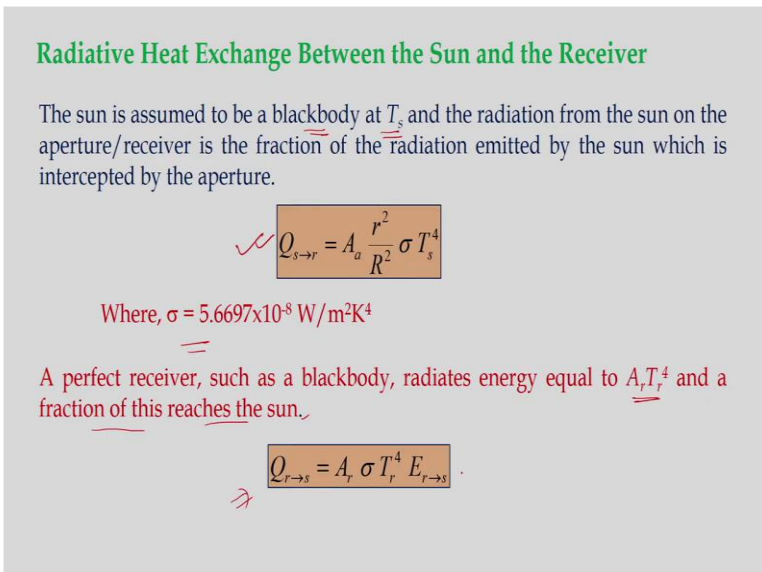

Now, let us see the radiative exchange between the sun and the receiver. So, if we consider a black body, sun is always considered as a black body having temperature T_s and the radiation from the sun on the aperture or receiver is the fraction of the radiation emitted by the sun which is intercepted by the aperture, which can be represented by this expression, $Q_{s\to r} = A_a \frac{r^2}{R^2}\sigma T_s^4$.

So, sigma is known to us, it is Stefan's Boltzmann's constant and a perfect receiver such as black body radiates energy equal to $A_r T_r^4$. This is the receiver temperature and the function of this reaches the sun, and the fraction of this reaches the sun. So, this can be expressed by using this expression.

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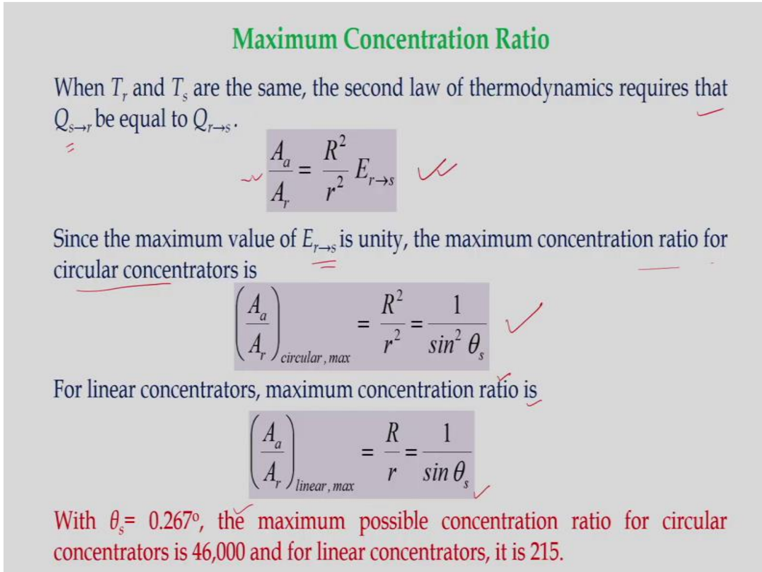

Now, if I am interested for estimation of maximum concentration ratio, then we need to do something. Like when T_r and T_s are the same or fixed values of this T_r and T_s, the second law of thermodynamics requires that heat transfer from source to the receiver or sun to the receiver should be equal to receiver to the sun. So, if we use this expression, then what we will get, this kind of expression.

Now, since the maximum value of $E_{r\to s}=1$, the maximum concentration ratio for circular concentrator is found to be $\frac{1}{\sin^2\theta_s}$, this is for circular concentrator. So, geometry of the concentrator may be different, so this is for circular concentrator. And for linear concentrators, the maximum concentration ratio is found to be $\frac{1}{\sin\theta_s}$.

So, if we know this $\theta_s = 0.257^o$, the maximum possible concentration ratio for circular concentrator is calculated to be about 46000 and for linear concentrator, it is found to be about 215.

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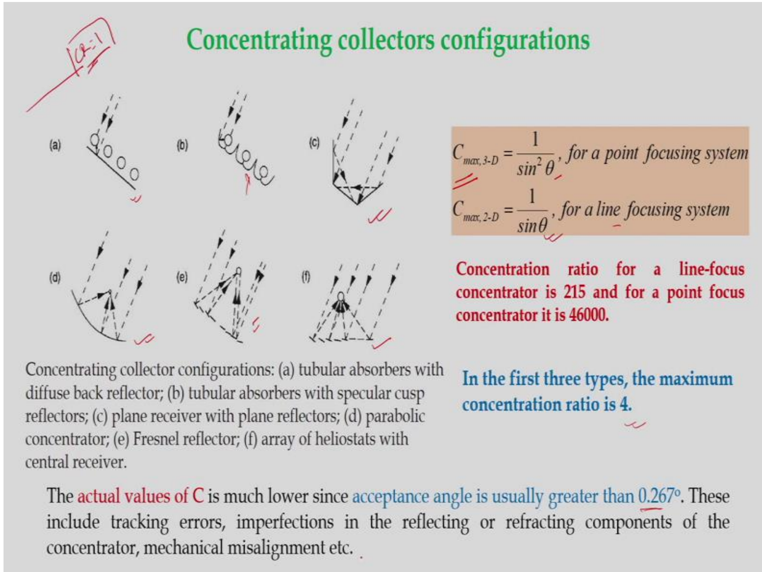

Now, let us pay attention about the different configurations of concentrating collectors. As you can see, these are tubes and one reflector is placed at the bottom of the tubes. And this is one more configurations, which is nothing but tubular absorber with specular cups reflectors. So, this kind of configurations are there to increase the concentration ratio.

So, normally what happen in case of flat plate collector will have concentration ratio is equal to 1. So, if we can increase the concentration ratio, so we can increase the operating temperature of the collector. So, these are different attempts. And this is a compound configuration, so where we can have more radiation exposure and then we can get slightly higher concentration ratio.

And this configuration is, for say, parabolic trough. So, receiver is here, this is a reflector, so these rays are focused on this axis, because this is a long tube not a point. And this configuration is for Fresnel reflectors and this configuration is for arrays of heliostats with central receiver system. So, we will learn details with time.

So, as we understand for point focus system, this concentration ratio can be defined as $\frac{1}{\sin^2\theta}$ and for line focus system, this is $\frac{1}{\sin\theta}$. So, if we know this θ value, then we can straight away calculate what will be the maximum concentration ratio for a point focus system and for a line focus system.

And as I said, so these are the attempts to increase the concentration ratios, though this first three, the maximum concentration ratio can be achieved is 4. And the other configurations, of course, concentration ratios are quite high. The actual value of this concentration ratio, C is much lower since the acceptance angle is usually greater than 0.267°. This includes tracking errors, imperfections in the reflecting or refracting components of the concentrator, mechanical misalignments, et cetera. So, these are the causes of reduction of this actual concentration ratio.

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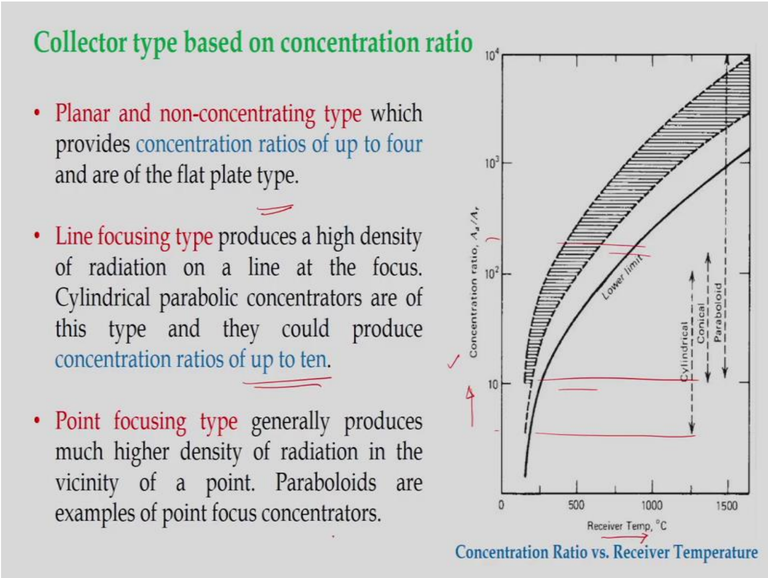

And this slide shows the collector type based on concentration ratio. So, as we can see this planar and non-concentrating type, which provides concentration ratios of upto 4 and are of flat plate type. So, if you see this figure, this vertical axis shows concentration ratio and horizontal axis shows receiver temperature. So, these are the lower limits and this is the band. Normally, this is the band at which the concentration ratio falls, when temperature increases.

And the ranges of operation, or ranges of concentration ratios are shown. So, this is for paraboloid, you can see the range of operation, of course that can be adjusted by using different means. And for conical configurations, we can see this is the range and for cylindrical, this is the range. So, for line focus system, we can have concentration ratio up to 10 and for point focus system, it is very-very high.

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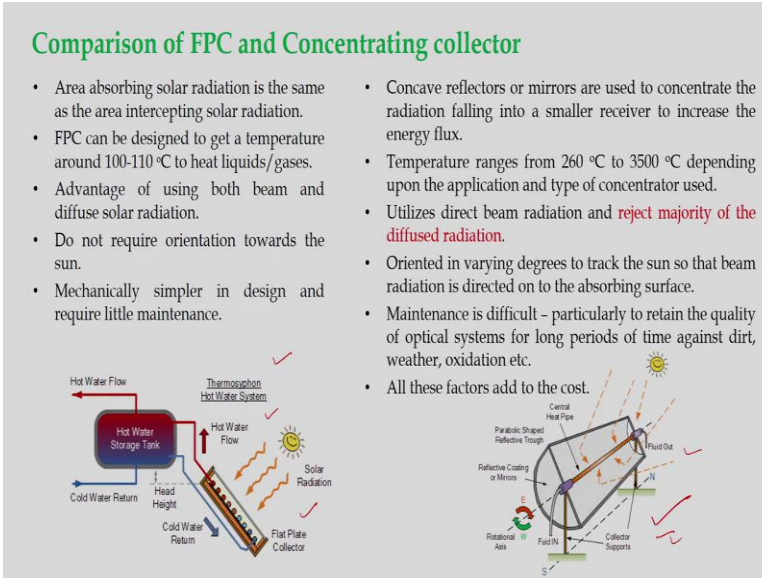

So, this slide shows about the comparison of flat plate collector and concentrating collector. As already we are aware that, this flat plate collectors are normally used for low temperature applications. So, maximum may be 100, 110 ^{o}C. For this kind of configurations, for concentrator, it may go up to 3500 ^{o}C, starting from 260 ^{o}C.

And here, in case of flat plate collectors, what primary advantage is, we can employ both normal and diffuse radiation, but in case of concentrator, only normal radiations are applied for energy conversion. So, diffuse radiation cannot be employed. Or even though diffused radiation falls on these devices, contribution of these radiations are very-very less.

And here no tracking is required but in case of concentrating collectors, tracking is must. And because of this, mechanically, it is unstable and then it requires maintenance, but in case of flat plate collector, maintenance is very-very less.

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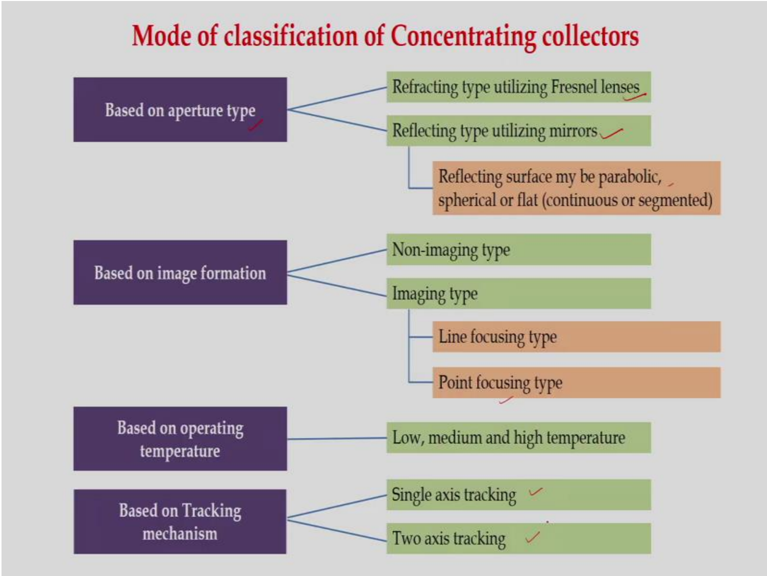

So, let us classify the concentrating collectors, there are different modes of classification. So, based on the aperture type, it’s a reflecting type utilizing Fresnel lens or refracting type utilizing mirrors. So, if we have to use mirrors, then refracting surface may be parabolic, spherical or flat; that may be continuous or segmented.

And classification based on image formation, may be non-imaging system or non-imaging type or maybe imaging type. So, under imaging type, again we have two classes; like line focusing type or point focusing type. And based on operating temperatures, may be low temperature, medium temperature and high temperature.

And then fourth category of classification is based on tracking system. So, single tracking system or two axis or double tracking system. Sometimes we need double tracking system to track the sun in order to capture more beam radiation.

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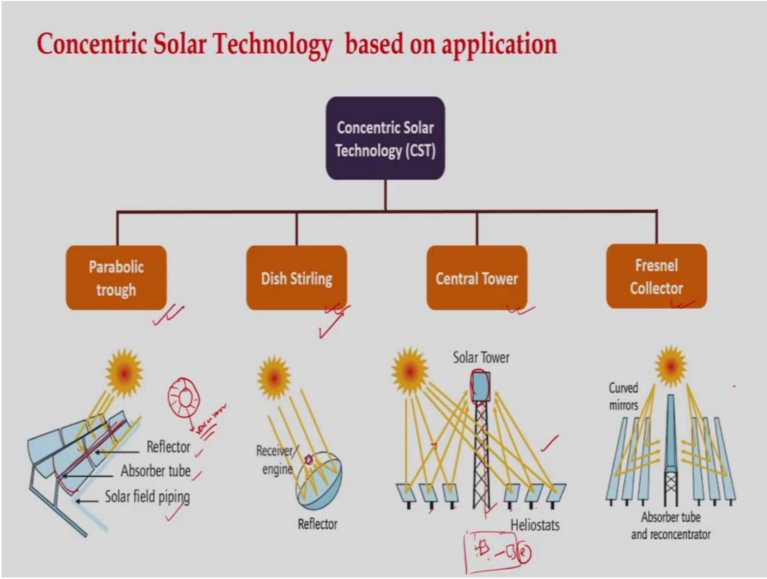

Now, let us see different CSP technologies what is available. So, first technology is parabolic trough, then dish stirling, central power receiver system, then Fresnel collector. So, what we can see here, so this is a concentrator, this part is concentrator and this is receiver system. So, solar radiations falls here and is reflected to this focal axis. So, reflector, then absorber tube, then this is solar field piping.

So, here as we can see, this is an absorber tube, then over it, this is a glass cover. So, this is maintained vacuum, so this is vacuum, in order to reduce the heat losses. So, in case of dish stirling system, so reflector is something like this and it will focus on this system. So, engine is placed, normally stirling engines are attached here. It is a external combustion engine, so heat is supplied here and then expansion of fluid will be there and from that, electricity can be generated directly.

And this is central power receiver system. So, here lot of heliostats are there, so these are heliostats, mirrors. Solar radiation falls and it is reflected to this receiver system. So, normally molten salt and oils are used so that may be collected and later on, will have powerhouse here. So, this heat exchange will be there to the secondary fluid of this Rankine cycle and then from that if we have generator, we can generate electricity. This is solar tower and Fresnel collectors are something like, these are segmented pieces of mirrors, solar radiation falls here and strike on this absorber tube and then heated fluid can be taken out for applications.

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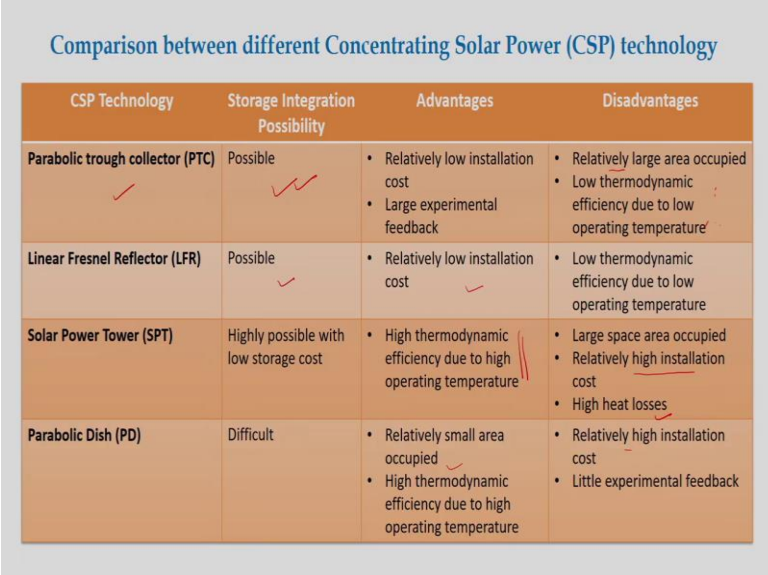

Comparison between different Concentrating Solar Power (CSP) technology

CSP Technology	Storage Integration Possibility	Advantages	Disadvantages
Parabolic trough collector (PTC)	Possible	• Relatively low installation cost • Large experimental feedback	• Relatively large area occupied • Low thermodynamic efficiency due to low operating temperature
Linear Fresnel Reflector (LFR)	Possible	• Relatively low installation cost	• Low thermodynamic efficiency due to low operating temperature
Solar Power Tower (SPT)	Highly possible with low storage cost	• High thermodynamic efficiency due to high operating temperature	• Large space area occupied • Relatively high installation cost • High heat losses
Parabolic Dish (PD)	Difficult	• Relatively small area occupied • High thermodynamic efficiency due to high operating temperature	• Relatively high installation cost • Little experimental feedback

And we can compare those technologies with different aspects like for parabolic trough collectors whether possibility of storage systems are there or not, or what are the other advantages, we can list it out. So, if we talk about possibility of integration of storage system, it is yes, it is possible and advantages includes relatively low installation cost and large experimental feedback is there in case of parabolic trough collector.

And disadvantages are relatively large area occupied, low thermodynamic efficiency due to low temperature. So, since this temperature difference is low, because of that, will have lower thermodynamic efficiency. And in case of linear Fresnel reflectors, storage is possible and advantage is relatively low installation cost and disadvantages include low thermodynamic efficiency due to low operating temperature, which is primary.

For solar power tower, it is highly desirable, that kind of storage system because that has to be stored. Huge amount of heat is generated and that has to be stored for night use or maybe when demand is very-very high. And its thermodynamic efficiency is high as the operating temperatures are high, but it requires large space area and relatively high installation cost and high heat losses are taking place for this kind of technologies.

And in case of parabolic dish, it is difficult to install storage system. Advantages are relatively small area occupied and high thermodynamic efficiency, but disadvantages are relatively high installation cost and little experimental feedback. So, this slide shows about the comparison of four different CSP technologies.

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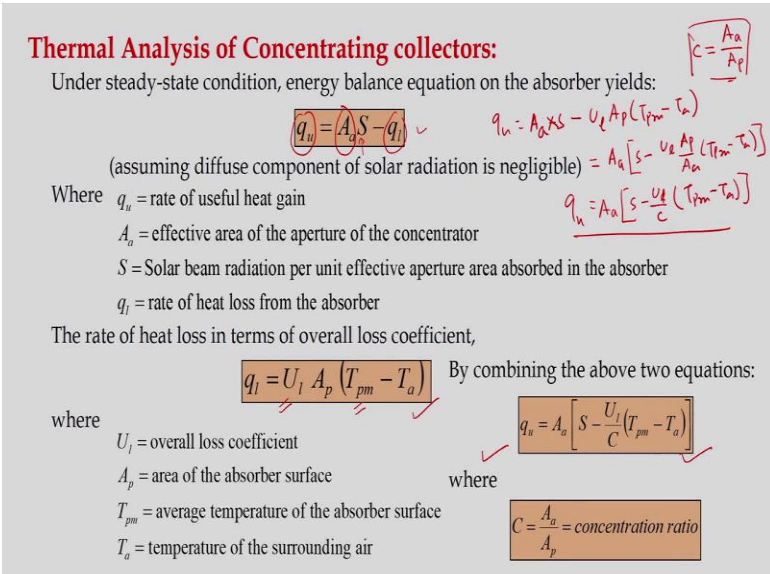

Now, let us pay attention about thermal analysis of concentrating collectors. So, under steady state condition, the energy balance on the absorber plate can be written as something like this. So, this q_u is the useful heat gain and A_a is the effective area of the aperture of the concentrator and S is the solar beam radiation per unit effective aperture area absorbed in the absorber and q_l is the rate of heat loss from the absorber.

So, if we write q_l, that is, rate of heat loss in terms of overall loss coefficient, so we can use this expression. So, $q_l = U_l A_p (T_{pm} - T_a)$. So, T_{pm} is average temperature of the absorber surface and U_l is overall loss coefficient. So, if we use it here, $q_u = A_a S - U_l A_p (T_{pm} - T_a)$. And if we, so this is Aa, so if we take out Aa, $q_u = A_a \left[S - U_l \frac{A_p}{A_a} (T_{pm} - T_a) \right]$.

So, we can define concentration ratio now. Already we know what is concentration ratio, the aperture area to the absorber area. So, this will be 1/C. So, $q_u = A_a \left[S - \frac{U_l}{C} (T_{pm} - T_a) \right]$. So, this is l, so this will be useful heat gain. So, that is how we can write this expression, $q_u = A_a \left[S - \frac{U_l}{C} \left(T_{pm} - T_a \right) \right]$.

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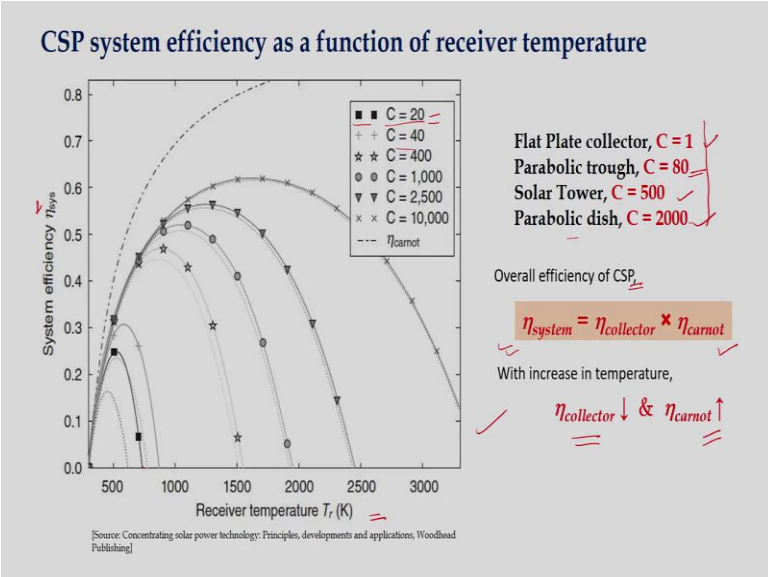

And this slide shows the efficiency vs receiver temperature. So, this is the system efficiency and this is the receiver temperature at different concentration ratios. So, these are different concentration ratios. So, it goes maximum and then it come back to 0. So, it shows the variation of efficiency with respect to receiver temperature at different concentration ratios.

So, for flat plate collector concentration ratio is 1, for parabolic trough it is about 80, for solar tower it is 500, parabolic dish about 2000. So, this overall efficiency of a CSP plant can be expressed something like this, $\eta_{system} = \eta_{collector} \times \eta_{carnot}$. So, if we know the Carnot efficiency and collector efficiency then straight way, we can calculate what will be the system efficiency of the plant.

So, with increasing temperature, this collector efficiencies decreases but Carnot efficiencies increases, so that is how we can get higher system efficiency if Carnot efficiency is significantly higher.

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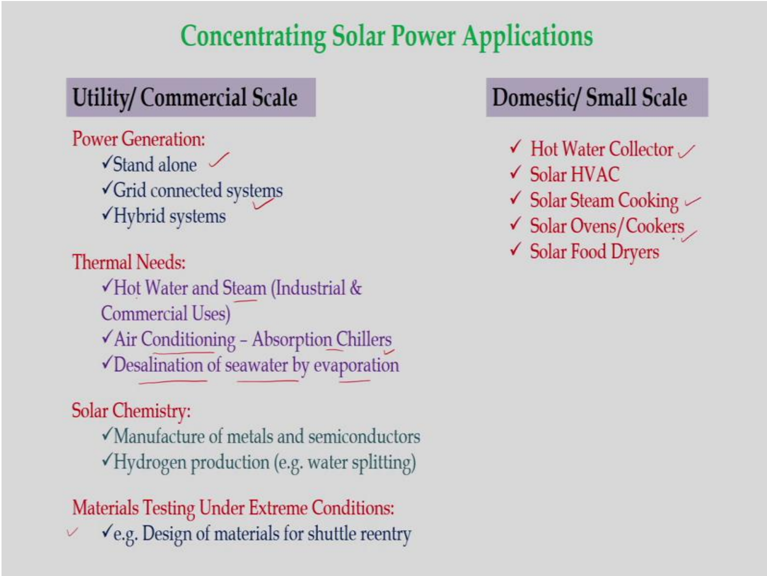

And this slide shows the applications of CSP in commercial scale and domestic level. So, for commercial scale, the CSP can be applied for power generation in stand alone mode or maybe grid connected system or maybe hybrid system or maybe to meet the demand of thermal requirement; hot water and steam generation, air conditioning, absorption chillers, desalination of sea water by evaporation.

Solar chemistry, manufacture of metals and semiconductors, hydrogen production may be water splitting or material testing under extreme conditions like, design of materials for shuttle reentry. Or as far as domestic applications are concerned, it may be applied for hot water generation or maybe HVAC or air conditioning system and solar steam cooking, solar oven or cookers, then solar food drying.

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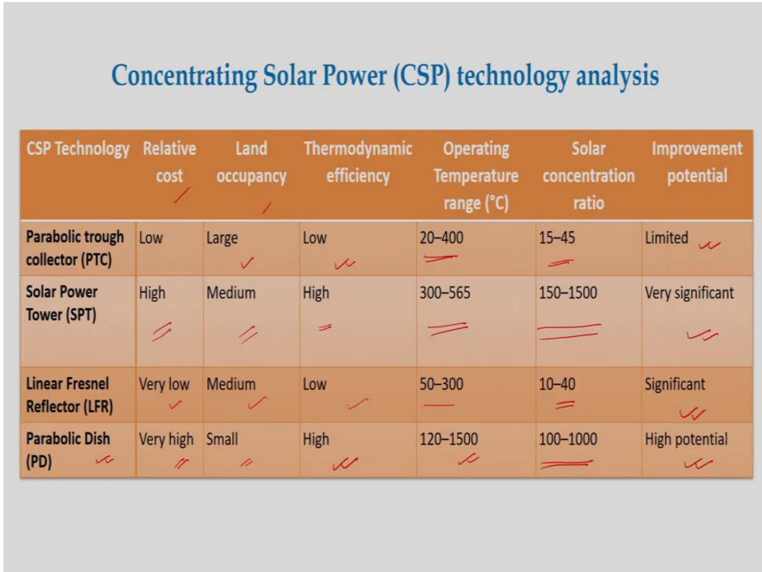

CSP Technology	Relative cost	Land occupancy	Thermodynamic efficiency	Operating Temperature range (°C)	Solar concentration ratio	Improvement potential
Parabolic trough collector (PTC)	Low	Large	Low	20–400	15–45	Limited
Solar Power Tower (SPT)	High	Medium	High	300–565	150–1500	Very significant
Linear Fresnel Reflector (LFR)	Very low	Medium	Low	50–300	10–40	Significant
Parabolic Dish (PD)	Very high	Small	High	120–1500	100–1000	High potential

And also, we can compare these technologies with different parameters. So, like relative cost, then land occupancy, thermodynamic efficiency, operating temperature, solar concentration ratio and then improvement potential. So, as far as parabolic trough is concerned, it is a relatively low cost but large land is required.

But thermodynamic efficiency is lower and operating temperature ranges from 20-400 ^{o}C and concentration ratio varies from 15 to 45 and improvement potential is limited. So, for solar power technology or solar power tower, so it is a very high cost and occupancy is medium, so not much land area is required. Thermodynamic efficiency is higher and operating temperature is also higher, concentration ratio we can see, it varies from 150 to 1500 and improvement potential is very-very significant.

In case of linear Fresnel reflector, it is a relatively low cost and land occupancy is medium, thermodynamic efficiency is low, operating temperature may go up to 300 ^{o}C and concentration ratio varies from 10 to 40 and there are a lot of scope for improvement. And parabolic dish collector, so it is a very high cost, land requirement is small, thermodynamic efficiency is high because operating temperatures are high and you can see the operating temperature 120-1500 ^{o}C and concentration ratio varies up to 1000 and it has got a lot of potential for improvement.

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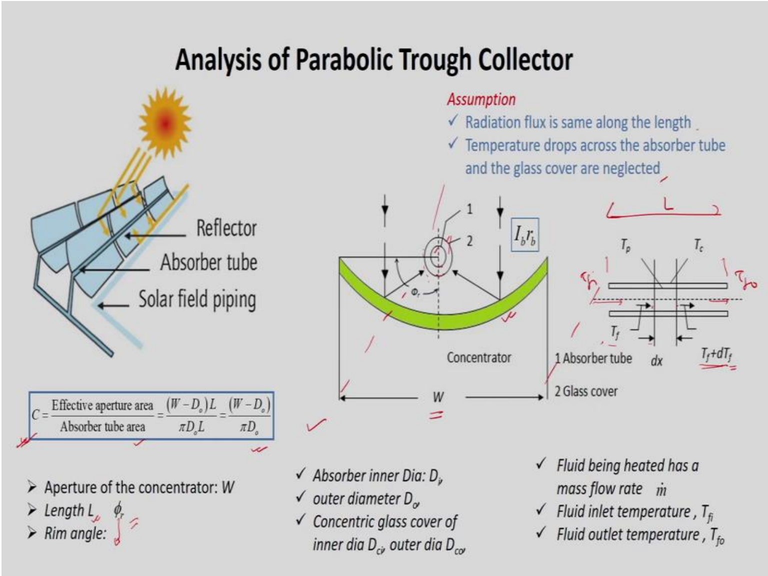

So, now let us pay attention about the analysis of parabolic trough collector. So, let us consider this configuration. So, we will have solar field, then you have absorber tube and then reflector. So, if we take a section, so it appears like this, so this is concentrator and this is the receiver system. So, when we call receiver system, it includes absorber tube plus this glass cover, which is placed concentrically and vacuum is maintained in between this.

So, if we consider a section, so this is the tube through which heat transfer fluid flows and if we take the length of the tube, this is the length of the tube and start from is x = 0, may be x = 0 here and it moves something like this and take a section dx, so fluid is flowing from this tube, so maybe at this point, fluid temperature is T_f and at this point, this fluid temperature is $(T_f + dT_f)$.

So, we will assume some parameters or some of the information like radiation flux is same along the length. So, it is assumed that this radiation flux which is falling in the absorber is same. Of course there will be some differences in actual case but what we will consider is same. And temperature drop across the absorber tube and the glass cover are neglected. So, this is absorber tube, this is a glass cover, so temperature drop is neglected, it will be same.

So, this aperture of the concentrator is W which is represented here and length is L is the length of the tube is L, so this length or we can say this is the length, so this length is L. So, I can write this way also, this length will be L along the length, so length of this tube and rim angle is ϕ_r and it should be here, so rim angle is ϕ_r, so this is the ϕ_r.

And this absorber inner diameter is D_i and outer diameter is D_o and concentric glass cover, inner diameter is D_{ci} so here so thickness will be here. So, it has got some thickness and outer diameter is D_{co}. And the fluid is heated from inlet temperature T_{fi} here, at this point is T_{fi}, T_{fi}, it is T_{fo} so outlet temperature is T_{fo}. And let $\dot{m}$ be the mass flow rate, mass flow rate of the fluid that is flowing through the tube.

And if we are interested about concentration ratio of this configuration, so it will be something like this, $C = \frac{Effective\,aperture\,area}{Absorber\,tube\,area} = \frac{(W - D_o)L}{\pi D_o L}$. So, that way if this L is common in numerator and denominator, this will goes off then, $\frac{(W - D_o)}{\pi D_o} = C$ is the expression for concentration ratio.

So, if we know aperture of the concentrator and then outer diameter of the absorber then we can straightaway calculate what will be the concentration ratio of that configuration. Now, let us draw an energy balance or write an energy balance expression on the absorber plate.

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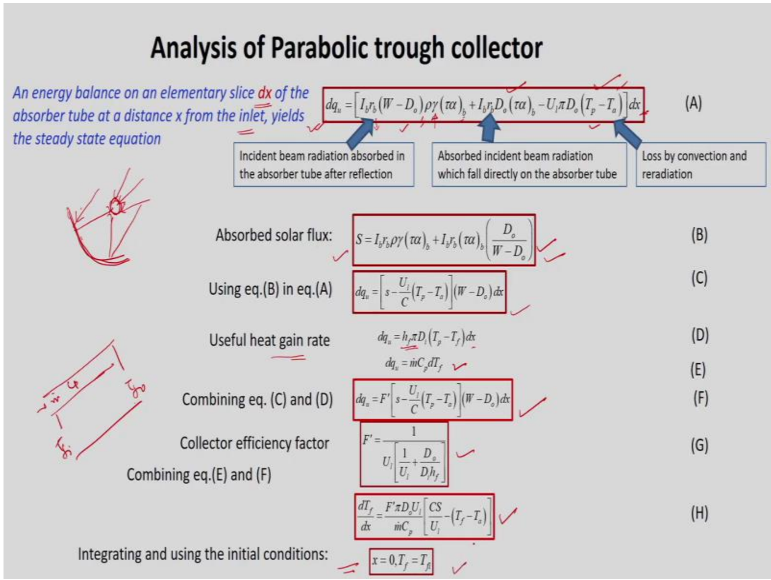

So, this energy balance on an elementary slice of the absorber tube at the distance x from the inlet. So, this gives a relationship of something like this. So, q_u is the useful heat gain which is equal to $I_b \times r_b(W-D_o) \times \rho\gamma \times (\tau\alpha)_b$, because beam radiation is only employed.

So, this part is the direct radiation which is falling on the absorber tube and this part is for losses. So, this component is coming from the reflector, so from here, from this reflector solar radiation is falling here, it will go, this will go. So, first component is contribution from this reflected radiations, second component is, since it is exposed to the sun, so it will directly fall on this absorber. And this is the losses. So, U_l, it take cares of this conduction and convection losses from the absorber tube.

So, this I_b is the beam radiation and tilt this r_b is the, that component which has to be multiplied, because all the radiations are not coming, so some losses will be there. Then this is a reflectivity of the reflector and this is the γ, which has to be multiplied because all the radiations are not coming and striking on the absorber. And these values are already defined and these are the losses. And T_p is the absorber plate temperature or absorber tube temperature, this is the ambient temperature and is the dx or is the slice.

So, absorber solar flux we can write something like this. So, using this equation, in equation A then this equation simplifies to something like this. And also heat gain rate, we know

$dq_u = h_f \, \pi D_i \left(T_p - T_{fi}\right) dx = \dot{m} C_p \, dt$, because mass is flowing. So, ṁ is the mass flow rate, C_p specific heat of the thermic fluid and we know the temperature difference T_{fi} and T_{fo}. From that we can calculate what is the rate of heat transfer is $\dot{m}C_p dt$.

So, now combining this equation C and D what will have, useful heat gain in that particular section will be something like this. So, F′ is the collector efficiency factor, which can be expressed something like this. And if we combine this equation E and F, then we will have this kind of equation. And we need to integrate this using the initial conditions, at x = 0, $T_f = T_{fi}$, which is already shown.

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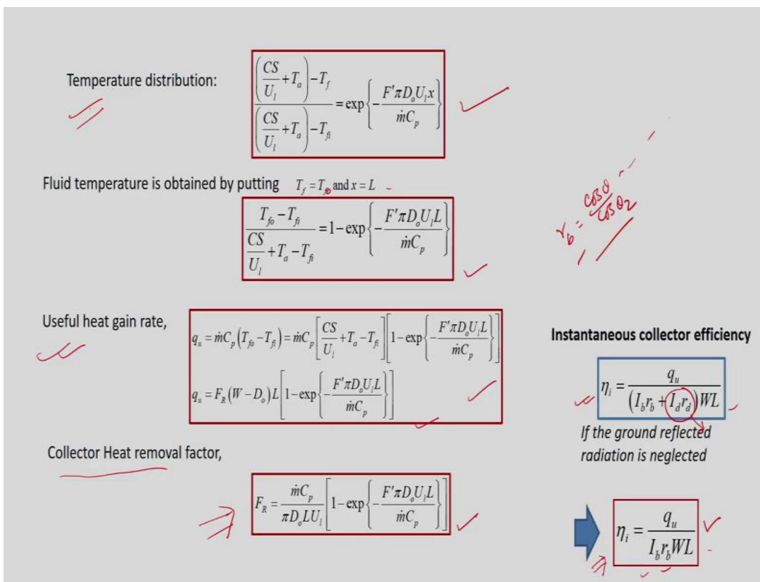

So, once you do it then we will get temperature distribution of something like this. So, fluid temperature is obtained by putting $T_f = T_{fi}$ and $x = x_o$, so this should be T_{fo}. So, if x = L, the $T_f = T_{fo}$. So, if we substitute this, then we can have this kind of configuration.

So, now we can calculate what is the useful heat gain rate. So, this useful heat gain rate can be calculated and it is found to be something like this. And also we can define collector heat removal factor, which is expressed by this expression. So, once you know this, then we can calculate what will be the instantaneous efficiency of the collector. So, this instantaneous efficiency is expressed something like $\eta_i = \frac{q_u}{\left(I_b r_b + I_d r_d\right)WL}$.

So, this is the diffuse radiation component which is coming from the ground. Sometimes this may be neglected. If we neglect this term, then this equation for instantaneous collector efficiency simplifies to this equation. So, if we know $\eta_i = \frac{q_u}{I_b r_b WL}$, then straight away we can calculate what will be the instantaneous collector efficiency. So, r_b already we know for beam radiation, what is the r_b, that is $r_b = \frac{\cos\theta}{\cos\theta_z}$.

So, there is a long expression for all the angles. So, this can be calculated and I_b is known and see here, no diffused components are present. Only beam radiations are included. So, this analysis will be very much important to characterize a parabolic trough. So, we must know the procedure, how this can be characterized.

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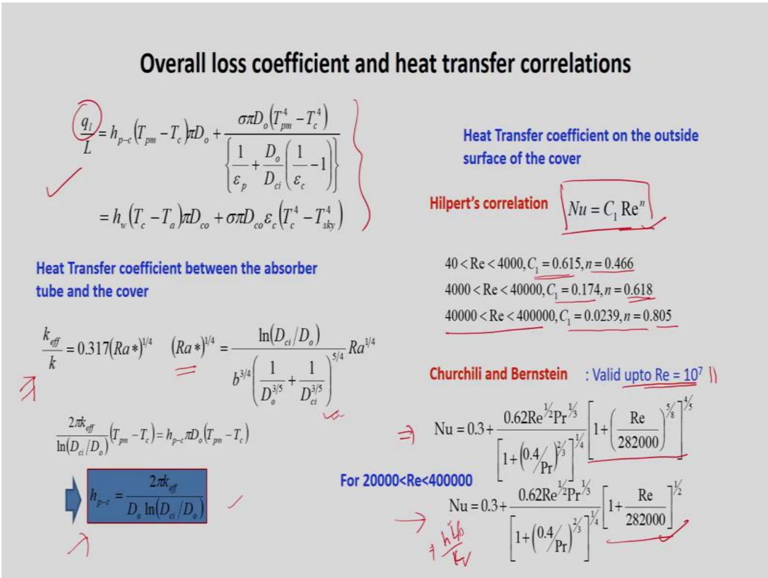

So, now next phase is how to calculate the heat transfer coefficient. So, once we know those values, instantaneous efficiency value, F_r value, F' values and then useful heat gain, then we need to know the heat transfer coefficient. How this heat actions is taking place from the collector to the absorber, then absorber tube to the glass tubes and then fluid? So, all the things we need to calculate.

So, this overall heat transfer coefficient and heat transfer correlations need to be understand. So, this is the q_l heat losses, we can express q_l in terms of U_l as well and also we can use this expression for calculation of heat loss. And then heat transfer coefficient between the absorber tube and the cover can be estimated by using this expression. This Ra^* is the modified Reynolds number, which is defined something like this. Once you know this, then finally what we can calculate, the heat transfer coefficient from the plate to the cover.

And then next phase is to calculate heat transfer coefficient on the outside surface of the cover. So, the correlations proposed by Hilpert's are normally used. So, it is expressed as $Nu = C_1 \mathrm{Re}^n$. So, there are different conditions, for 40 < Re < 4000, this C_1 = 0.615 and n = 0.466.

And for a value of 4000 < Re < 40000, C_1 = 0.174 and n = 0.618. And for this, so if Reynolds number is very-very high, which is more than 40000 < Re < 400000, then we need to use this set of data for calculation of heat transfer coefficient on the outside surface of the cover.

Also we can use some alternate correlations developed by Churchili and Bernstein. So, this correlation is valid up to a Re = 10^7 and if 20000 < Re < 400000, then we can go for this correlation. So, there is slight change in this value, so this is the difference. So, here it will be 1/2 of this section and but here it is 5/8 and then 4/5 whole to the power this bracket section.

So, once you know this Reynolds number and Prandtl number is known at that temperature, and then we can calculate what is heat transfer coefficient. Because $Nu = \frac{hL}{k} \, or \, \frac{hd}{k}$, now it will be L, hd/k or sometimes it is d also. So, hL or hd by k. So, once we notice k, L or d then we can calculate what is h, or heat transfer coefficient.

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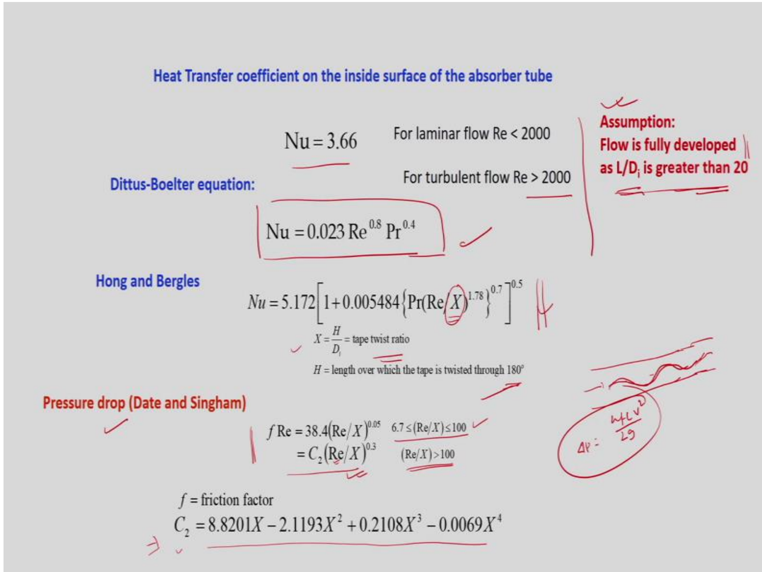

So, this heat transfer coefficient on the inside surface of the absorber tube if I am interested to know, then we need to go for this kind of correlation. Nu = 3.66, for the flow having Re < 2000. So, if the flow is turbulent having Re > 2000, then we need to use the correlations developed by Dittus-Boelter, which is something like this, $Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$.

So, we can calculate the heat transfer coefficient on the inside surface of the absorber tube by using these correlations. But while using this correlation, we must pay attention about this assumption. Just flow is fully developed, that assumption has to be done and it is valid as L/Di is larger than 20. So, under that condition we can use flow is fully developed and we can have this kind of expression.

And Hong and Bergles developed a correlation which is expressed something like this. So, apart from Reynolds number and Prandtl number, one term is there which is X, is X is nothing but tape twist ratio. So, sometimes what happens, heat transfer in a flow can be augmented by using some kind of twisted tapes. So, if this kind of tapes are introduced in that flow tube then heat transfer coefficient enhances.

So, in order to define this twisted tape or this kind of configuration, we need to define this twist ratio. So, $X = \frac{H}{D_i}$, so H is nothing but length over which the tape is twisted through 180^o, so this is something like twisting. So, once it is twisted and it is introduced in that flow tube, then it is investigated that heat transfer is augmented or heat transfer can be enhanced by applying twisted tape in a flow process.

Also once we done with this heat transfer coefficient, researchers are interested to know the pressure drop. How much pressure drop is taking place? So, there are many correlations to investigate this pressure drop. One of the correlations which is applied here in concentrating collectors are proposed by Date and Singham which is expressed something like this, $f\,\mathrm{Re} = 38.4\left(\frac{\mathrm{Re}}{X}\right)^{0.05}$.

So, this value should be in between this range and also this friction factor multiplied by Reynolds number can be expressed something like this, if this value is more than 100. So, this C can be calculated by using this expression. So, X is known to us from here and then if we apply here and we will get C_2, once we know C_2 and Reynolds number is known to us, then we can calculate f which is friction factor. So, once we know friction factor, we can calculate the pressure drop. So, $\Delta P = \frac{4 fLv^2}{2g}$. So, that way we can calculate the pressure drop.

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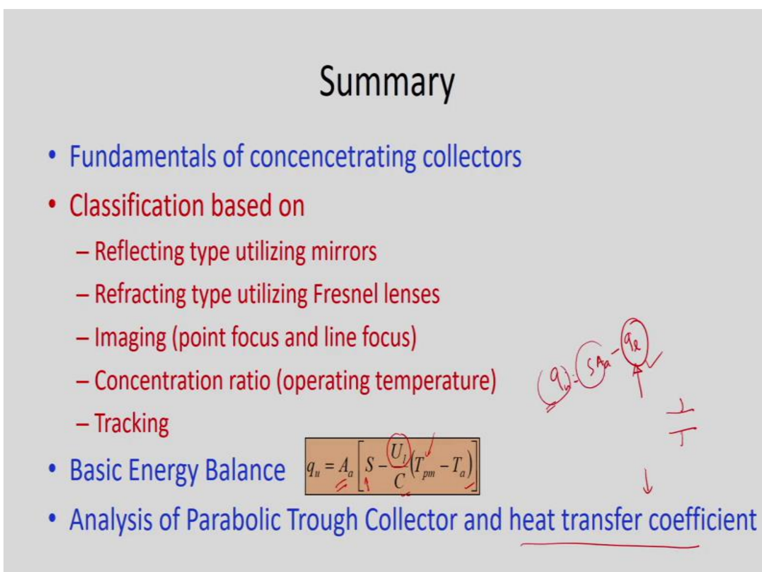

So, let us summarize what we have discussed today. Primarily we have discussed the fundamentals of concentrating collectors and also the classifications, which are made based on reflecting type utilizing mirrors, refracting type utilizing Fresnel lenses, imaging technologies, it may be point focus system or maybe line focus system.

So, if we are talking about point focus system, it is a high concentration ratio and its operating temperature is very-very high. And in case of line focus system, even though concentration ratio is compatibly higher, but it cannot achieve as normally done in case of point focus system. And there is also one basis of classifying its concentration ratio, which is nothing but the operating temperatures as you can see. So, as the operating temperature increases, this concentration ratio also increases.

And tracking also one of the classifications, what kind of tracking normally adopted, maybe single axis tracking, may be double axes is tracking. So, based on the requirement that can be decided. And also we have learned the energy balance on an absorber plate of a concentrating collectors. So, this q_u can be expressed something like $q_u = A_a \left[S - \frac{U_l}{C} \left(T_{pm} - T_a \right) \right]$, where U_l is the overall loss coefficient and A_a is the aperture area, C is the concentration ratio.

So, if we know mean absorber plate temperature or tube temperature, an ambient and solar flux, we can calculate what will be the useful heat gain. Also, we have learned the analysis of parabolic trough collectors and heat transfer coefficient. How this can be calculated heat transfer coefficient can be calculated and how this can be applied for calculation of useful heat gain? Because as you know $q_u = SA_a - q_l$. So, in order to calculate this q_l, we need to learn this heat transfer coefficient.

So, once we know this heat transfer coefficient of different system from where to where the heat transfer is taking place, so once you know this, we can substitute in this equation then we can calculate what will be the useful heat gain. So, I hope you have enjoyed this video. Thank you very much for watching.