**Elements of Solar Energy Conversion**
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**Lecture - 20**

Hello and welcome back. Today, we are at lecture number 20; in this series of lectures on Elements of Solar Energy Conversion.

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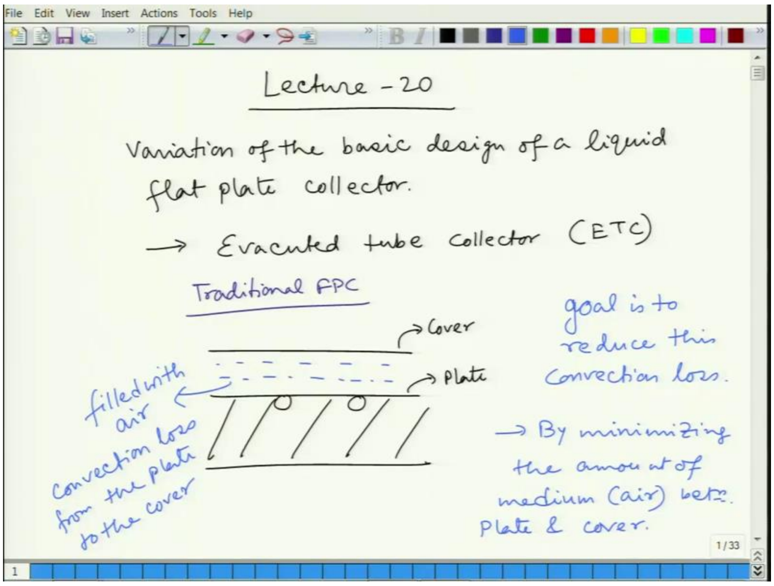


So, we have crossed the halfway mark in this course and what we have completed so far was the basic background that we require to look at anything related to solar.

So, we have built that background first, and then the most basic solar energy conversion device that we have started with is the flat plate collector, or rather liquid flat plate collector, where we have done all kinds of thermal analysis. And we have derived a few key parameters or few key factors, such as collector efficiency factor, collector heat removal factor, collector flow factor.

So, all these factors we have looked at to understand the operation of the liquid flat plate collector. Today, we are going to look at a little variation of that flat plate collector from the basic design; if we have some variation, what kind of variation we are going to see. So, that is the first thing we will talk about today, and then we will see what difference will the design of a flat plate collector have in case of if we use not liquid, but gaseous mostly air heater. So, that part we will start today.

So, first thing, we are going to look at the variation of the basic design of a liquid flat plate collector. Many of you have seen a flat plate collector; I have shown you a picture of that in the last class. And many of you have seen that on top of your rooftop, roof, where these flat plate collectors are installed, but they're sometimes you will see that you see a collection of tubes.

So, those are actually called evacuated tube collectors, or in short, we abbreviate it as ETC or Evacuated Tube Collector. So, why do you use those evacuated tubes? First of all, let me just remind you the basic design.

So, usually, this is the cover; you have a plate that gets heated. This cover is transparent, of course, and below that, you have insulation and some tubes to carry the heat from the plate right; this is the basic design of a flat plate collector. And we have seen that in this region, in this region, we have a convection loss.

So, this is filled with air; so, this is let me just say that this is the traditional flat plate collector, not the evacuated tube. So, here what happens? This region is filled with air, and that is why we have convection loss from the plate to the cover.

And convection loss, if we actually find out what are the different major modes of losses. We will see that this convection loss is one of the most important losses that happens from the plate; that is why our goal is to reduce this convection loss. So, how to do that? We can do that by minimizing the amount of medium, which is air here, that is present in the space between the cover and the plate.

So, by minimizing the amount of medium, which is air ok between plate and cover, if we do that, the convection loss will come down. So, how to do that? The process to do that is to maintain a vacuum in between this gap.

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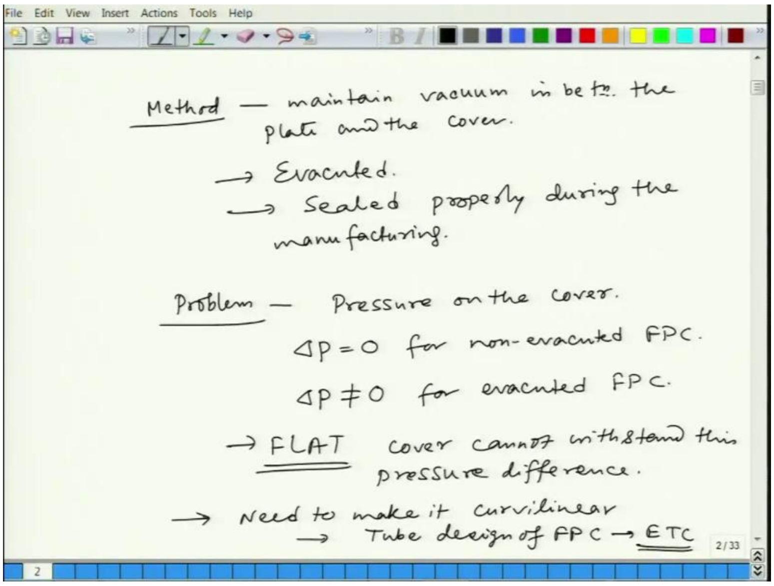


So, the method is to maintain a vacuum in between the plate and the cover, and that is why we called it evacuated. So, you can imagine that if you evacuate it, then it is not going to, we are going not going to fit a vacuum pump along with the flat plate collector right. So, you have to seal it properly so that once during the manufacture, when you evacuate, that vacuum is maintained throughout the lifetime of that flat plate collector.

So, it is needed to be sealed properly during the manufacturing. And often, if this particular vacuum is not being maintained due to some leakage, then we have to do repair and ensure that vacuum is back again at its desired level. Then, only will we get the desired performance from that flat plate collector, but the problem here is for a traditional design of a flat plate collector, we have a flat cover, and below we have a flat plate.

And if we maintain a vacuum in between these two, then there will be, I mean, there will be a pressure on the cover. So, the problem is pressure on the cover; why do we have pressure on the cover because the outside is still maintained at the atmospheric pressure and earlier the inside also had atmospheric pressure.

So, the difference in p was 0 earlier. So, Δp is 0 for non evacuated flat plate collector, but when you maintain a vacuum, that means the inside gap is now at reduced pressure, much-reduced pressure, so that means the Δ p is now significantly high on the cover.

So, Δp is not equal to 0 for evacuated flat plate collector, and the problem with the flat plate is that it cannot withstand a large amount of pressure; the stress develops in such a way that it cannot withstand a large pressure, large force. So, a flat plate which is the basic name of the collector, you have to modify it. So, flat plates or flat cover cannot withstand this pressure difference.

It is anyway made of brittle material because usually it is made of glass which is transparent the most ubiquitous material as the cover; so, that cannot withstand high pressure. So, what we need to do? We need to make it curvy linear. So, if you have a circular thing, a circular cover, then it can withstand a much larger amount of pressure difference.

And that is how we come into the tube design, tube design of flat plate collector which is called this evacuated tube collector ETC. That is the reason why we need to make it in the form of a tube. Now, let me show you this particular thing in an actual schematic diagram. Now, let us look at this particular design in little more detail.

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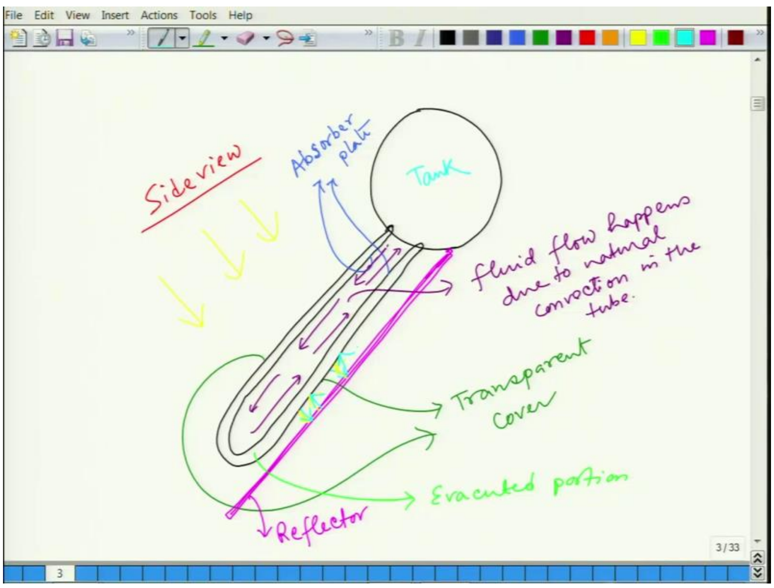

So, let us say that we have a hot water tank here, we are taking a side view ok, and from here, we have multiple tubes that are coming out. So, what can we have? These are sealed tubes and this portion, the inside part this, as well as this portion, is our absorber plate, and the outside one like this these portions are our transparent cover ok and what happens? In between, we have the fluid flow. So, you can say that fluid will come due to natural convection, like this get heated and again go back by natural convection to the tank.

So, this is the tank, and this fluid flow happens due to natural convection in the tube. And this part you can see that this part, this inside part between the plate and the cover we have evacuated portion ok, and the whole thing is a tube. So, basically, there are two concentric tubes at one end; it is merged together and the other end, it is open to the tank, and this whole thing is completely sealed ok; that is why that vacuum is maintained ok. So, this is typical, so and I should tell this that this is the side view.

So, and what happens? Of course, the radiation will come from this direction, and what we do, we often use a reflector at the back; we often use a reflector. So, this is the reflector which what it does?

This radiation that in-between tubes which are which pass through the tubes, it comes back and then gets reflected these and then gets reflected to the tubes again. So, that reduces the amount of loss that happens. So, now let me show you a picture of where this evacuated tube is used in such a geometry.

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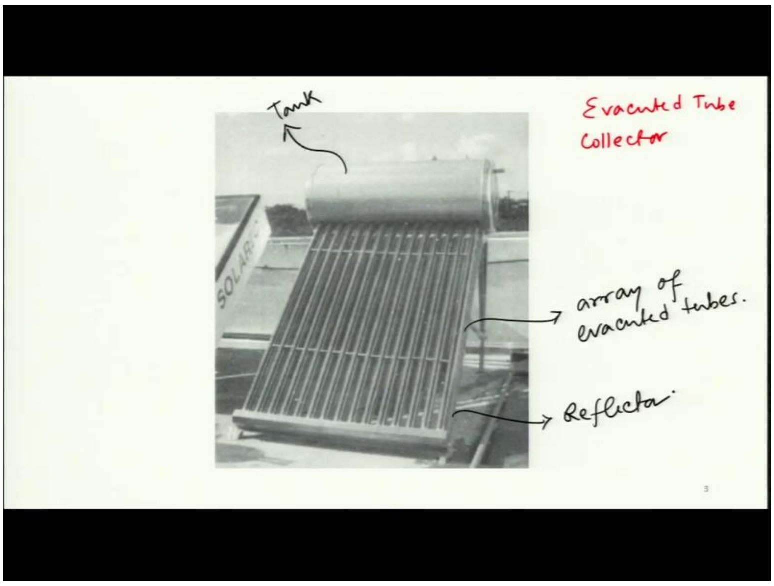


So, here we see an evacuated tube collector, so, this is an evacuated tube collector, which is more often than not, you will see these kinds of configuration in the rooftop solar heaters. So, here what is the different portions? So, you can see this is the tank, and this is the array of evacuated tubes. So, each tube will look like the one that I just showed, and at the back, you have some reflector. So, this is a typical evacuated tube collector.

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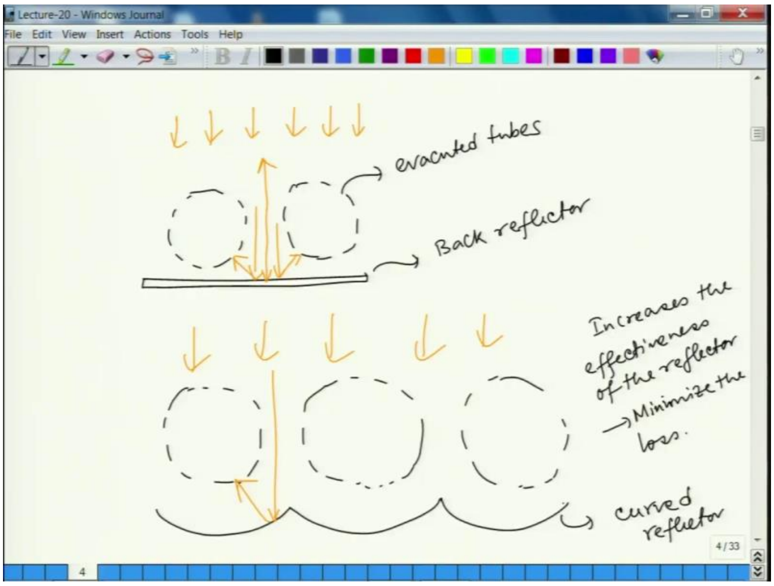


Coming back to the reflector, if we look at it a little more closely, what we can have like you can have one configuration where you have this reflector at the back, and you have these different tubes. So, these are evacuated tubes, and this is the back reflector.

So, what is the purpose here? The radiation is coming like this, and a few of them will not cut the evacuated tube, so that is why the reflector is here. So, a portion of that will be reflected back to the evacuated tubes, and that is how to minimize the loss. And often, you can see that a portion that comes directly here will go directly back again.

So, it is not being affected by the reflector. So, what can we do? The other common geometry of reflector we have, if we have this kind of evacuated tubes, we have reflectors like this. So, here we have a curved reflector to increase; here again, the rays will be like this, and the one that is coming here will definitely go back to one of the evacuated tubes.

So, this increases the effectiveness of the reflector, and that is how it minimizes the loss, so that is evacuated, tube collector. One more variation we have for evacuated tube collectors is in terms of a heat pipe.

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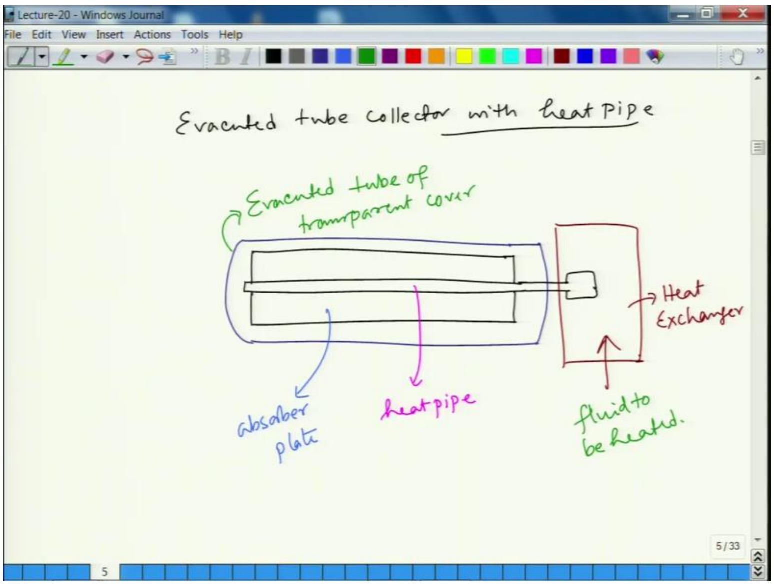


So, evacuated tube collector with heat pipe, I assume that heat pipe how it works you are familiar with the concept. The heat pipe is nothing but a pipe where natural convection is used, and the phase transition is also accomplished.

So, when you have solid wax, so, often it is used as the heat pipe material, solid wax if you have then one part if you heat it in a pipe; one part if you heat it that will get liquefied and by natural convection due to low lower specific gravity. It will move the other direction, while from the other direction, the solid heat by solid wax will be replaced slowly; that is how the heat will be carried from one end of the pipe to the other.

So, here also, a similar concept can be used. So, how does it look like? So, suppose you have a heat pipe ok, which carries some particular material, and you have a portion of absorber plate attached, just below it, and then the whole thing is encapsulated in an evacuated tube, and that has to be sealed, and in between this heat pipe comes out, and now, it is connected to a heat exchanger.

So, suppose some particular fluid is flowing through this area. So, here is a heat exchanger; it takes that heat from the heat pipe. So, this is the heat pipe, this is the absorber plate, and this outside one is the evacuated tube of the transparent cover.

So, this is just a design variation of the same concept of evacuated tube collector, where the fluid itself is not moving to the plate area, but it is taking the heat from a heat pipe through a heat exchanger; this is the fluid to be heated, so, just a variation of that. So, now we are going to look a little bit at the testing procedure of the performance of a flat-plate collector.

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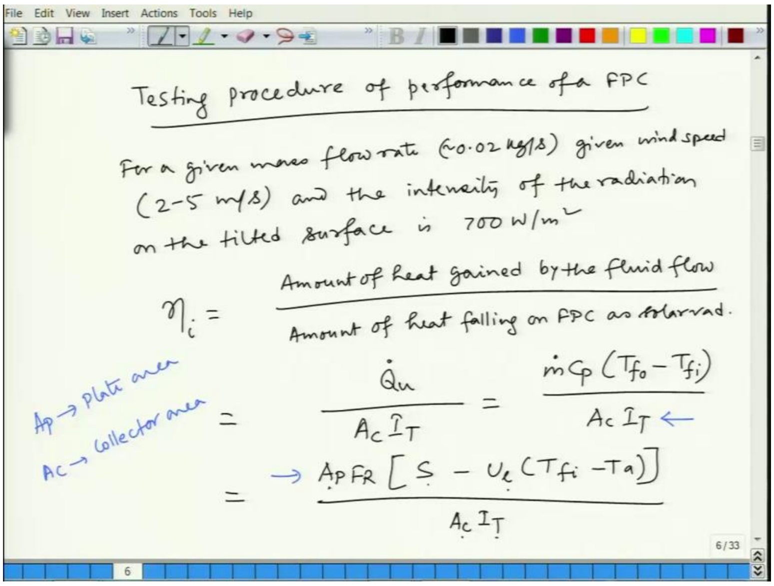


So, the testing procedure of performance of a flat plate collector, so, as I have told you earlier that all these different factors, this heat removal, flat factor flow field collector, flow factor all these things they are supplied to you by the manufacturer and the manufacturer what does it do? It does all kinds of performance testing before launching that product into the market.

And that particular flat plate collector design; how much you heat you can expect, how much efficiency you can expect? These are the goal of a testing procedure. So, what is a typical method or typical setup to do this testing? Let us look at that first.

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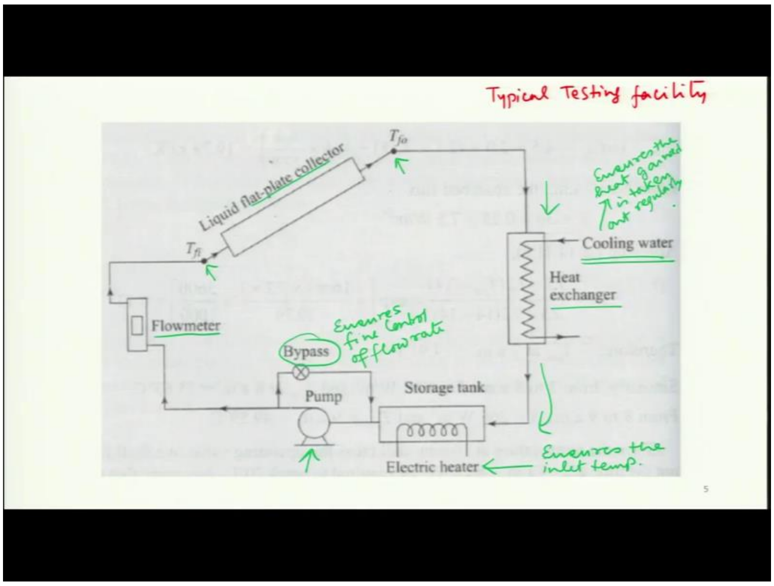


So, this is a typical testing facility. So, what do we have here? We have this the liquid flat plate collector, and here we have some measurement of temperature at the inlet and some measurement of the temperature at the outlet ok. And for the inlet, we also have a flow meter that measures the amount of or the rate of flow through the flat plate collector.

And here we have a pump which pumps the fluid through the flat plate collector and this bypass; what it does? It helps us maintain the fine-tuning of the rate of flow; that is how why the bypass is used. And we have an electric heater here and associated with a storage tank which ensures what will be the inlet temperature of your fluid. Otherwise, it is difficult to get the ambient is always varying right.

So, ambient temperature, you cannot just rely on all the time. So, you need to maintain it for a testing facility, the auxiliary heater to get it, and then after it comes back, when you reuse the same fluid, you have to take that heat out.

Otherwise, the inlet will never be consistent, and that heat is brought out by cooling water which is used through the heat exchanger. So, this is a typical setup for your testing of a flat plate collector, where our major goal is to ensure that the flow rate, as well as the inlet temperature these are accurately controlled.

Now, so let me just write it here. So, bypass what it does? It does ensure fine control of flow rate ok. This storage tank and heater ensure the inlet temperature, and this cooling water flow ensures the heat gained is taken out regularly. Now, suppose for a given mass flow rate, suppose it is 0.02 kg per second and given wind speed because that tells us what would be the loss coefficient, effective loss coefficient wind speed, let us say 2 to 5 meter per second.

And the intensity of solar radiation of radiation on the tilted surface is 700 W/$m^2$. So, few external factors you have to control; otherwise, the testing will not be uniform. So, these conditions if you control, then what you can write the efficiency which is the most important factor for a flat plate collector.

How much heat of solar radiation you can convert to the heat of the fluid. So, that efficiency is nothing but the amount of heat gained by the fluid flow, divided by the amount of heat falling on the flat plate collector as solar radiation. So, how much radiation is falling, and how much you are able to convert it.

So, this is nothing but the rate of useful heat gain right $\dot{Q}_u$ which we were analyzing up to the last class. And the bottom one, you can write the collector area multiplied by the intensity on the tilted surface $I_T$. Now, this $Q_u$, you can write $\dot{m}C_p$ specific heat and difference in outlet and inlet temperature of the fluid right. So, this is the definition of efficiency.

Now, you can further write it in terms of this particular numerator; now, you have several expressions for that. So, what we want in terms of $T_{fi}$ and $T_A$; if we write that,

$$\eta_i = \frac{A_p F_R(S - U_l(T_{fi} - T_a))}{A_C I_T}$$

So, here you note that we have used two different areas $A_p$ and $A_c$. A p is the plate area, and $A_c$ is the collector area.

So, far we have not distinguished between these two areas. Plate area and collector area we have kept same as if the edge effect end effects, these are negligible, which are majorly true. But, when you are testing it, you want an accurate result, and that is why we are distinguishing between $A_p$, which is the plate area, and $A_c$ which is the collector area. So, solar radiation is available in the whole collector area. So, the denominator will, of course, have the collector area, but the numerator here, you can see only the plate area which is effectively absorbing that radiation, and that is why we are using A p.

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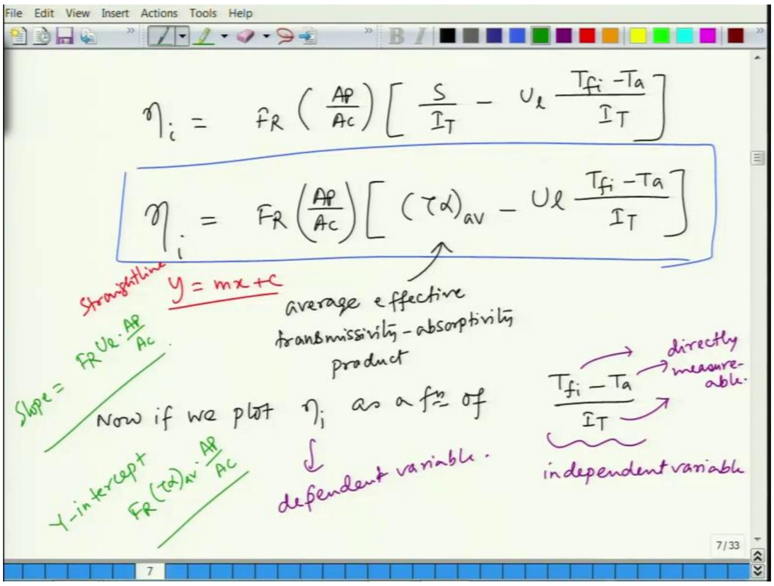


So, now, further, we can write

$$\eta_i = F_R(\frac{A_p}{A_C})(\frac{S}{I_T} - U_l\frac{T_{fi} - T_a}{I_T})$$

So, nothing new whatever we have obtained in the last expression; we have just have taken this $A_c$ with $A_p$ and this $I_T$, we put at the bottom of these two terms ok. Now, further, we can write $F_R(\frac{A_p}{A_C})$ and this $\frac{S}{I_T}$; what is that? S is the absorbed radiation right, and $I_T$ is the available radiation.

So, this $\frac{S}{I_T}$ is nothing but the average effective transmissivity absorptivity product. So, this is nothing but average effective transmissivity absorptivity. What it means we have discussed at length in earlier classes, and this part stays the same $U_l\frac{T_{fi}-T_a}{I_T}$. So, now, from this equation, let me just highlight it because that is the equation we are going to use.

Now, in this equation, you can see that now, if we plot this $\eta_i$ as a function of this quantity $\frac{T_{fi}-T_a}{I_T}$. So, you can see the independent variable, which should be directly measurable. So, everything here is directly measurable. If that is exactly measurable, so, this whole thing gives us the independent variable, and this is our dependent variable.

So, if we do that, then the and if usually, it is, it comes as a straight line because you can see that the form of the equation is of a straight line y equal to so, y equal to $mx + c$ in this form, straight line. So, in this case, what will we get? That the slope of this plot slope will be $F_R U_l(\frac{A_p}{A_C})$that will be the slope, and the y-intercept will be $F_R\tau\alpha$ average multiplied by $(\frac{A_p}{A_C})$.

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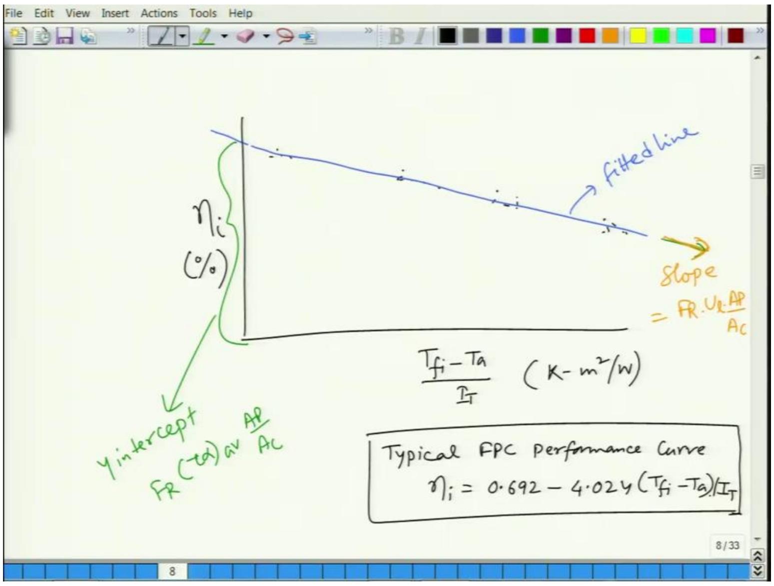


So, if we have a plot like this, efficiency, and this is $\frac{T_{fi}-T_a}{I_T}$. And let me write the unit, the typical unit is Kelvin-$m^2/W$ and here it is in percent. Now, suppose you have few different data points and through which you can fit a straight line; this is the fitted line. So, here for this, if you extend it, this y-intercept, this y-intercept will be your $F_R\tau\alpha$ average multiplied by $(\frac{A_p}{A_C})$. And the slope of this slope will be equal to $F_R U_l (\frac{A_p}{A_C})$.

So, from these two quantities, you can find out what would be the collector heat removal factor $F_R$, as well as what will be $U_l$, because you have two quantities and the effective absorb transmissivity absorptivity product is usually known, or you can measure it separately. So, that is how under different flow rates, you can find what would be the $F_R$ and what would be the $U_l$; that is how the testing of a flat plate collector is done.

And a typical flat plate collector, so, I should write a typical FPC performance curve is under this particular set of the unit that we have used, $\eta_i$ is

$$\eta_i = 0.692 - 4.024(T_{fi} - T_a)$$

So, this is a typical performance curve you can give for your flat plate collector, and the consumer can actually measure this $T_{fi}$, $T_a$, and $I_T$, and it can know what would be what the efficiency to be expected of the collector.

So, so far in this class, what we have seen is the variation of the flat plate character that is evacuated tube collector, and also we have seen how the typically the testing of the performance of this flat plate collectors are done. The typical performance curve is a straight line that we have seen. Now, what we are going to do is another variation of flat plate collectors, which are air heaters, and what are the major differences and how to analyze such air heater? That is what we are going to look at now.

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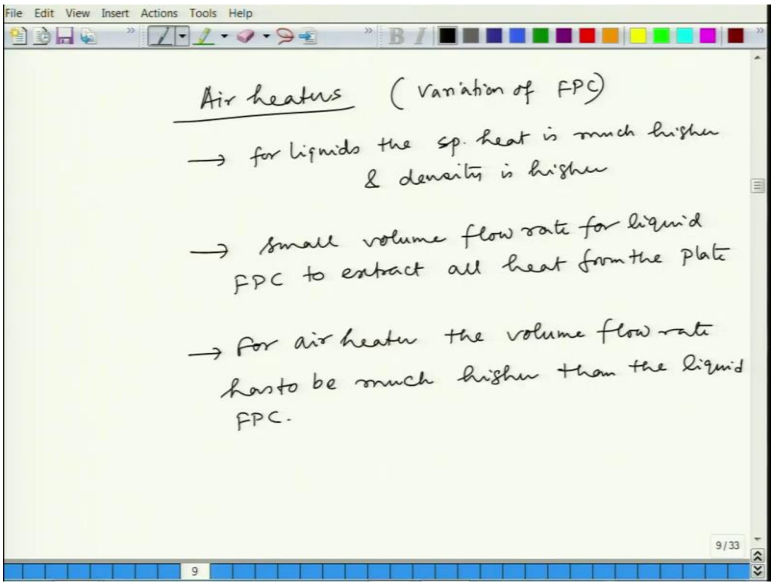


This is also what I should mention; this is a variation of the flat plate character itself. It is a variation, but what is the major difference? The major difference is for liquids, the specific heat is much higher, and density is higher ok.

In the case of water, the specific heat is 4.2 Joule per kg right, kg degree centigrade, and for air, it is 1.5; 1.005 right 1. So, specific heat is higher as well as density is much higher. So, you can have a small amount of volume flow rate, and you can have all the heat extracted from the plate in the case of a liquid flat plate collector.

So, this leads to a small volume flow rate for liquid flat plate collectors to extract all heat from the plate. But in the case of air, the density is low, so volume will be automatically high, and the specific heat is also low, so the amount of heat it carries is low. So, what you need to do?

You have to increase the area to make sure all the heat is taken away by the flow. So, for an air heater, the volume flow rate has to be much higher than the liquid flat plate collector. So, now, we cannot simply use the typical design of a flat plate collector, which is few tubes are running or attached at the bottom of the plate; that way, it will not work. So, what are the geometric variation we have to make; to make an air heater work?

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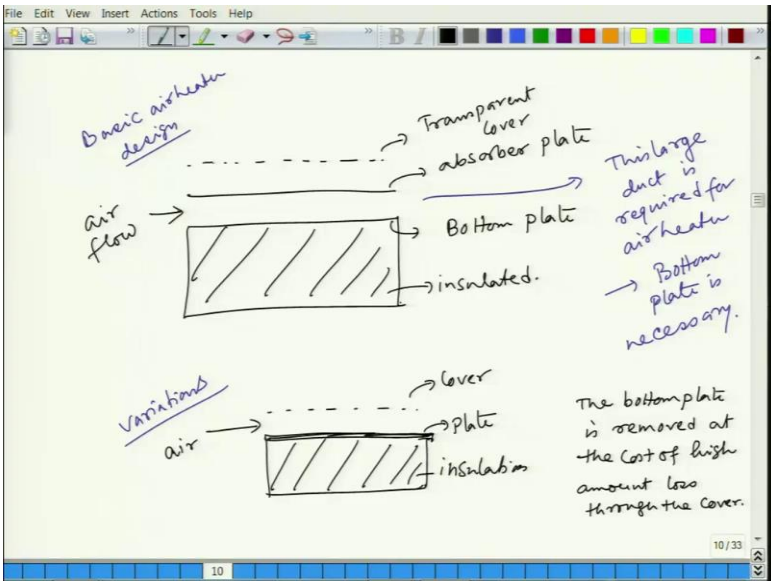


So, typically what we do have, we use two plates: one is the absorber plate, and another is the bottom plate. So, suppose we have this is the absorber plate and typically what we have? The cover, transparent cover here. Now, as the volume flow rate is high, we need a bigger channel or bigger duct through which the air is flowing.

So, we need to have a bottom plate to ensure this duct is large enough, and then the rest is the same; this part is insulated, so this is the difference. So, here you know, so, this is the airflow rate. So, note that this large duct is required for an air heater, and that is why a bottom plate is necessary, which was not there in the case of a liquid flat plate collector.

And you can have so, this is the basic design, again this is the basic air heater design, and you can have variations of that too, such as one can be without a bottom plate. But what you need to do? So, this is your absorber plate, this is cover, and this is insulation, and you allow air to pass in between the cover and the plate. So, that is also possible if you want to avoid the bottom plate itself. However, you can see that we have done the evacuation of the region between the cover and the plate to reduce the convection loss.

And here, we are providing the airflow there; so, you can see the amount of loss that we will incur will be large here. So, the bottom plate is removed at the cost of a high amount of loss through the cover.

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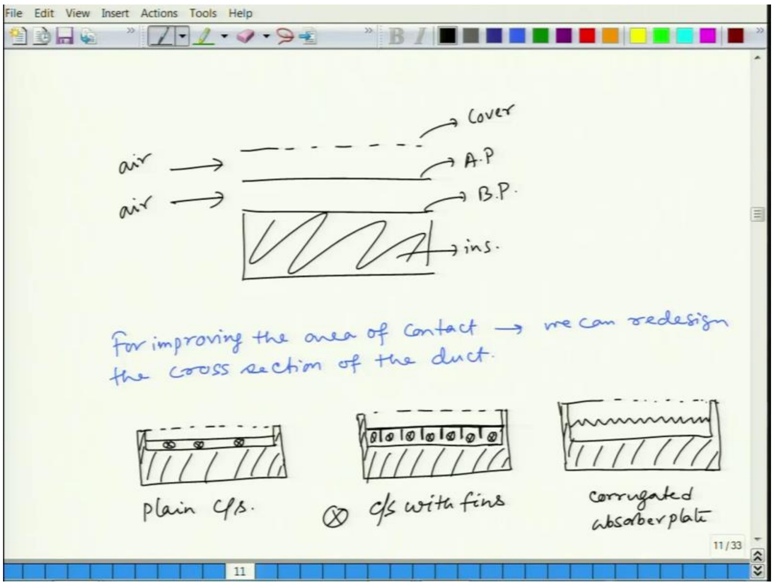


So, that is one variation you can have, and you can also have the cover. Now, you have the plate, bottom plate, and cover everything you have. This is insulation, this is the bottom plate, this is absorber plate, and this is cover, and you can also have the airflow through both these portions.

So, that is also one possibility that you can have. Anyway, and what other variation can you have? In terms of improving the amount of, so, for improving the area of contact, we can redesign the cross-section of the duct. So, you can have a plane cross-section such as. So, this is the cover; this is the absorber plate. So, here the flow is happening here, perpendicular to the plane of the board.

So, that is a plane cross-section, or you can have a cross-section with fins. So, on a similar and this part is insulation. Now, you have a plate here, which is the absorber plate, and you can have fins coming down to the bottom plate, and flow is again happening through these channels.

By this sign, what I mean is flow is happening perpendicular to the board. So, you can have fins cross-section with fins, and often this kind of thing is also done when you do not want to put fins ok, but still, you want to increase the surface area.

So, we make the absorber plate corrugated. So, these kinds of variations can happen for air heaters. Now, with the change in geometry, you can understand the analysis; the thermal analysis will also be completely changed for the air heater; so, we are going to look at that now.

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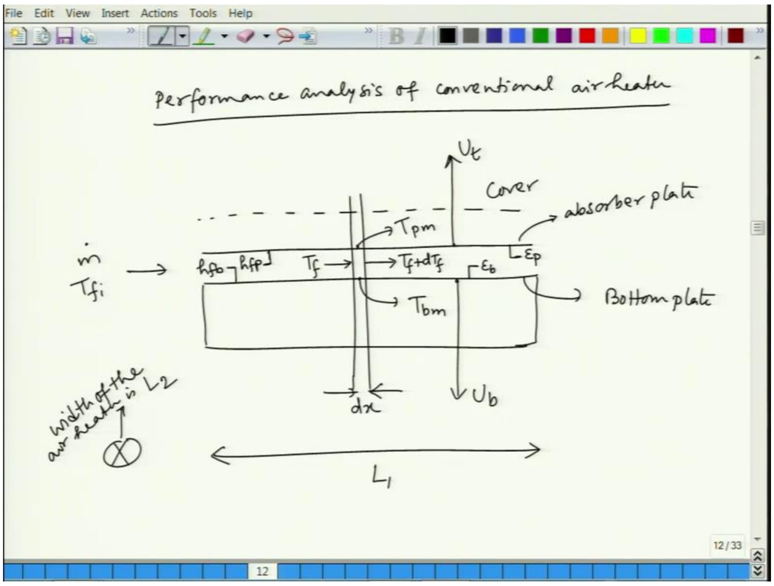


You can see that we have ducts now, and those are large cross-sections, completely covering the whole of the bottom of the plate. So, that is how it will not be relevant to consider those fin efficiency, those temperature distribution, everything will be different, and that is why we have to redo the thermal analysis for an air heater. So, for the most basic design that a bottom plate and an absorber plate, that is what we are going to look at now.

So, if we have a block bottom plate like this with the insulation at the bottom and we have an absorber plate, and we have a cover. And we have the mass flow rate of air coming from this side, and we have a certain inlet temperature $T_{fi}$, and this is the bottom plate. And for this particular case, we will have the heat transfer coefficient from the bottom plate; we will designate it as $h_{fb}$, b stands for the bottom, and $h_f$ stands for the heat transfer coefficient of the fluid.

And similarly, the absorber plate will designate it with $h_{fp}$ and will also need to have the emissivity of the bottom plate and emissivity of the plate, p stands for plate; that means, absorber plate and the bottom plate is just mentioned with b. And suppose, we take a cross-section of this flow channel with length dx and there, we can have the temperature of the bottom plate to be $T_{bm}$, which is the temperature of the bottom plate; the mean temperature and for the absorber plate it is $T_{pm}$.

And here the fluid is coming at $T_f$ and leaving the cross-section at $T_f + dT_f$, with certain added heat, it is with more temperature it is leaving the cross-section. Now, from the plate, we have a certain loss coefficient $U_t$, top plot loss coefficient, and from the bottom plate similarly, we have some bottom loss coefficient $U_b$.

Now, let us say the length of the whole channel is $L_1$ and perpendicular to this direction; the length is or rather a width of the collector or air heater is $L_2$. So, this is the most typical basic air heater geometry, and this is the dimensions.

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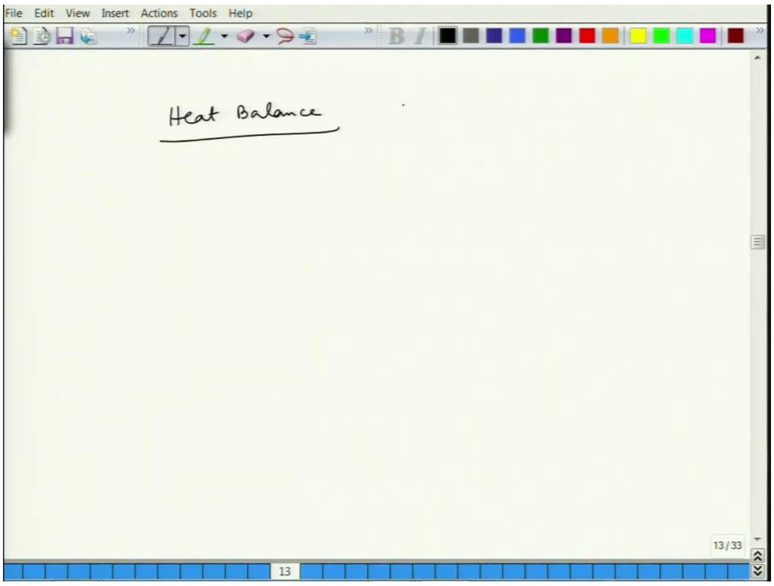


So, in this case, what we can write, the heat balance for each of these absorber plates, the bottom plate, and the fluid, we can do the heat balance. And that is how we will get the total picture, and that will do in the next class.

Thank you very much for your attention.