Physics of Renewable Energy Systems
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Lecture 09
Solar Heaters

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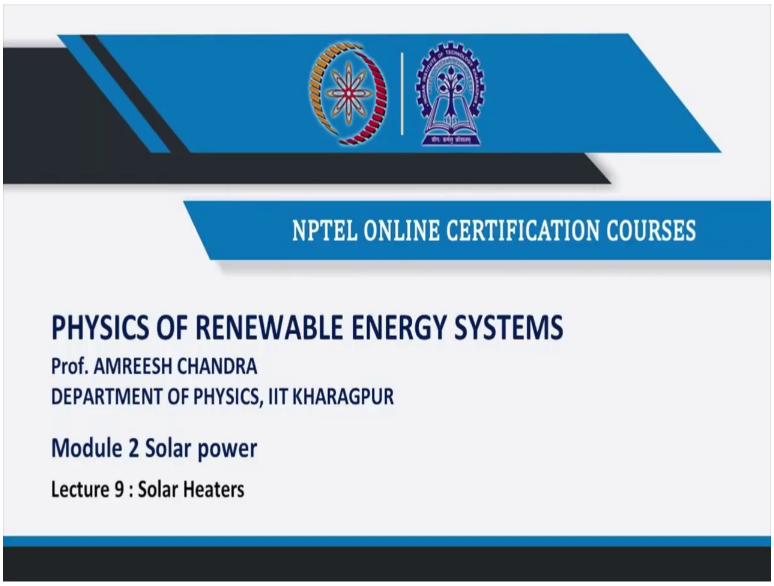

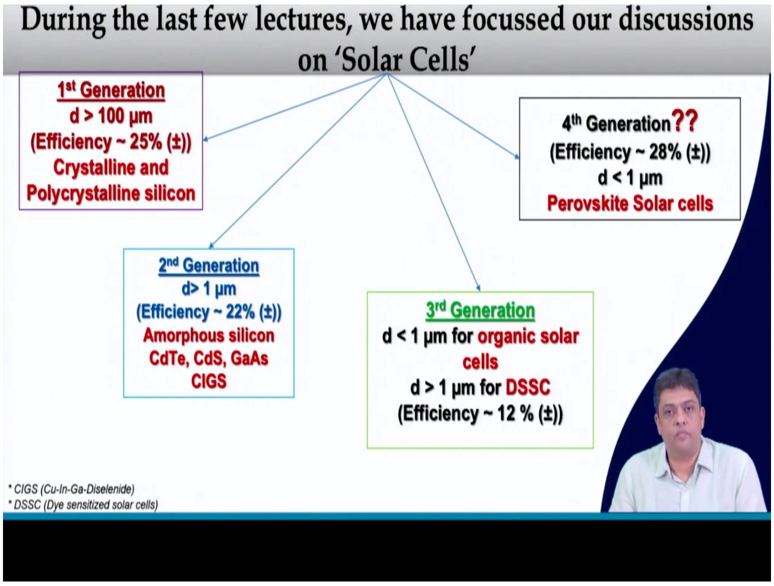

Hello, welcome again to the course on Physics of Renewable Energy Systems. During the last few lectures, we are focused mainly on solar cells based on silicon and also focused some of the discussions on perovskite solar cells, I also gave you an overview on the second-generation solar cells, which were based on amorphous silicon or various other types of p-n junction or semiconductors.

And we had also discussed about the use or the method of mimicking the nature in DSSC that is in dye-sensitized solar cells. So, we have spent significant amount of time in this module on solar cells.

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But, in today's lecture, let us now start looking at few other solar-based devices and the devices which I would be focusing on are the ones which would be very useful for our country and the first device which I would like to talk to you is solar heater.

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And therefore, the concept that would be covered in this lecture what are solar water heaters? How does heat transfer process or processes take place in this solar water heater or various types of solar water heaters? And what are the limiting factors that limits the efficiency of these solar water heaters. And you will see the limiting factors are coming in from processes like thermal conduction and convection which lead to heat losses.

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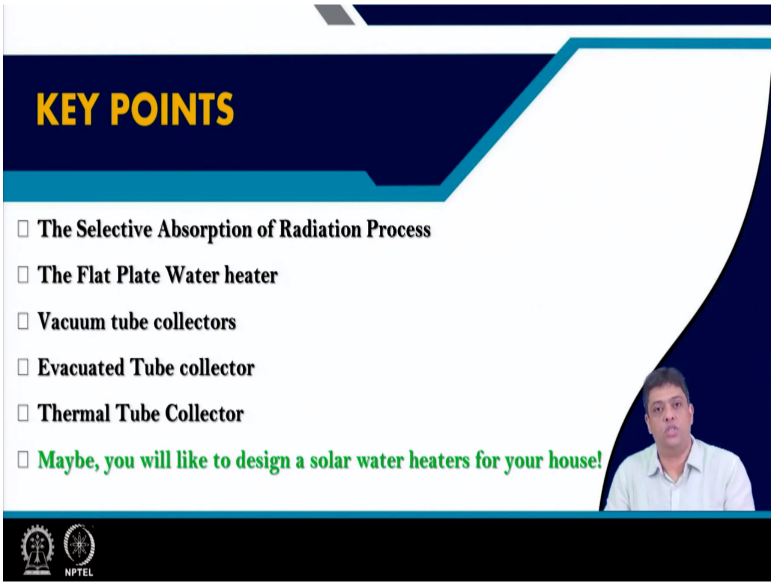

And I hope that by the time I finish this lecture, you will understand the concept of selective absorption of radiation process and the range in which the device or the system I am talking about should operate. What are the flat plate water heaters? If flat plate water heaters have certain limitations, then how do we try to counter them in subsequent water heaters like in vacuum tube collectors, evacuated tube collectors, thermal tube collectors.

And my hope is that maybe you will like to design a solar water heater for your own house and you will see that the designs are quite simple. And if you can perform the engineering carefully, you will be able to design, fabricate, and install a working solar water heater by your own self. So, these are the key points which I hope you will take back after listening to this lecture.

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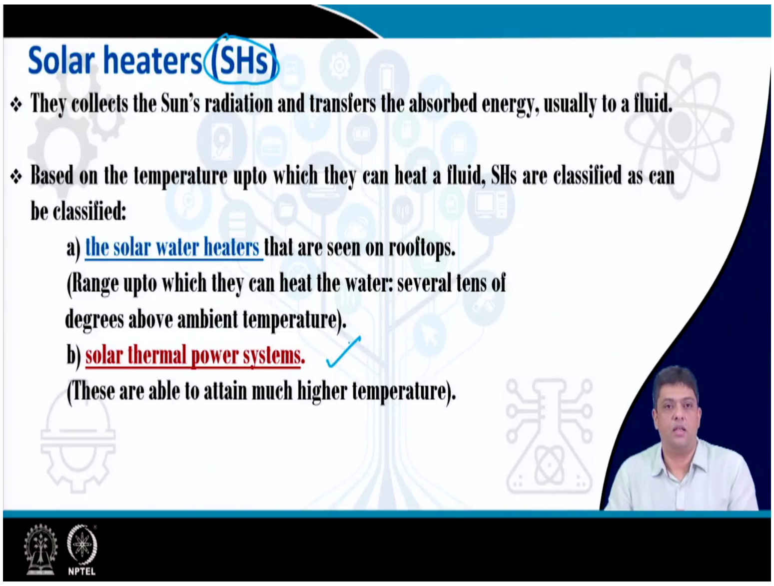

So, let us start by asking a very fundamental question. That is what are solar heaters? I have just used an acronym SHs. So, I am just, I am using an acronym SH for solar heater. Solar heaters are primarily defined as systems, those collect the sun's radiation and transfers the absorbed energy usually to a fluid, these are called as solar heaters.

And based on the temperature up to which they can heat a fluid. These solar heaters are classified as solar water heaters and solar thermal power systems. So, solar water heaters are the ones which can heat typically water to several 10s of degrees above the ambient temperatures. So, we are looking let us say at a temperature of 25 degrees, then using solar water heaters, you can heat the water which is at 25 degrees to let us say 75 degrees or 80 degrees.

So, few 10s of degrees above the ambient temperature. In comparison to solar water heaters, we have solar thermal power systems, these are the ones where you can attain much higher temperatures than just few several 10s of degrees. And we will discuss about solar thermal power stations when we talk about thermal energy storage systems.

So, solar thermal power systems form an intrinsic part in the classification of energy storage systems that is based on thermal. So, we will talk about the solar thermal power stations in energy storage technologies which are classified under this subheading thermal energy storage.

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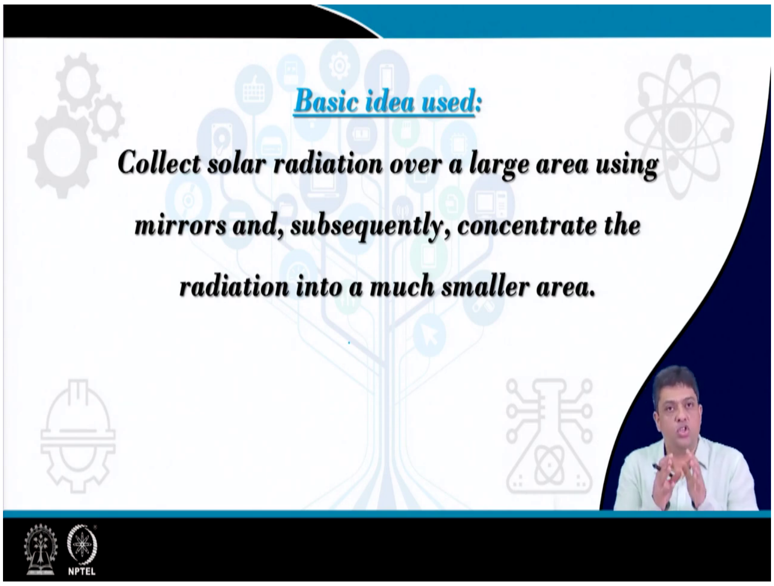

So, the basic idea which is used to fabricate and operate a solar water heater is that you collect the solar radiation over a large area using different types of mirrors. And then what you do you concentrate the radiation into a smaller area and behind this smaller area, you can have a fluid which is flowing and taking this heat which is getting concentrated in a smaller area. So, this is the basic idea that is used to fabricate and operate a solar water heater.

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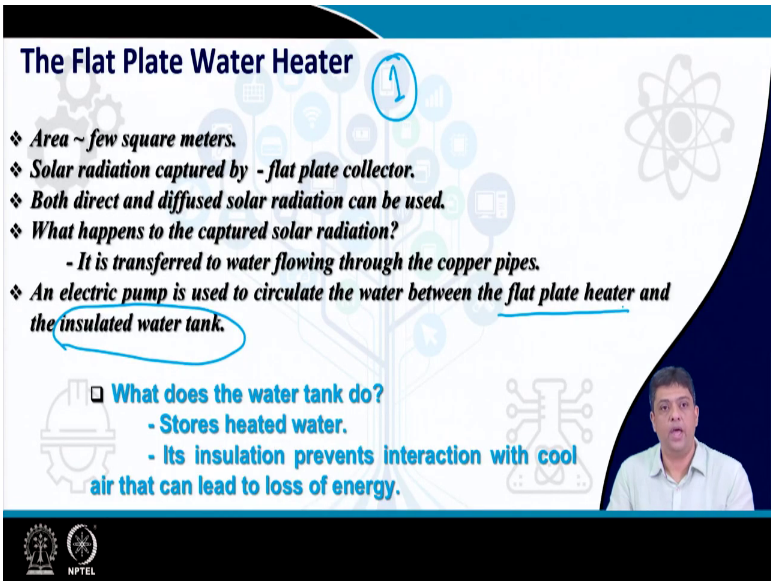

And the first type of solar water heater which we will discuss is the flat plate water heater. And typically, the size of a flat plate water heater is few square meters. So, you can have let us say 2 cross 2 dimensions of length and breadth in meters and the area, therefore, I am talking about is approximately 4-meter square. So, we have such kind of dimensions.

And solar radiation is captured by the flat plate. So, there is a flat plate on which the radiation is falling and this is collecting the radiation. And the radiation which this flat plate is collecting can be both direct or diffuse-type solar radiation. So, any solar radiation which is falling on this flat plate, the flat plate is trying to collect. And what happens to the captured solar radiation?

Once the radiation has been captured by the flat plate what happens to it? This is followed by a transfer of heat to the water flowing through the copper pipes which is lying on top of this flat plate or they are embedded in the flat plate. And an electric pump is used to circulate the water between the flat plate heater and the insulated water tank and suddenly you find that I have introduced an additional term that is insulated water tank.

What is it to do when I am talking just about a flat plate water heater? It is very critical to understand that the water tank does two things, it stores the heated water that is clear. So, you have water getting heated by the flat plate water heater, and then it has to be stored somewhere. But this water tank is also so designed that the insulation prevents the interaction of this heated fluid in this case water with the cool air that can lead to loss of energy.

So, if you have a jar of water and you heat it and then you let it to cooled down by interacting with the surrounding cool air, you will find that after a certain time the water will reach to the temperature of the ambiance, but I want to keep the water at higher temperatures so that it becomes the source of warm water and therefore, I must prevent the interaction of this heated water with the surrounding cool air and this is performed by ensuring proper insulation of the water tank.

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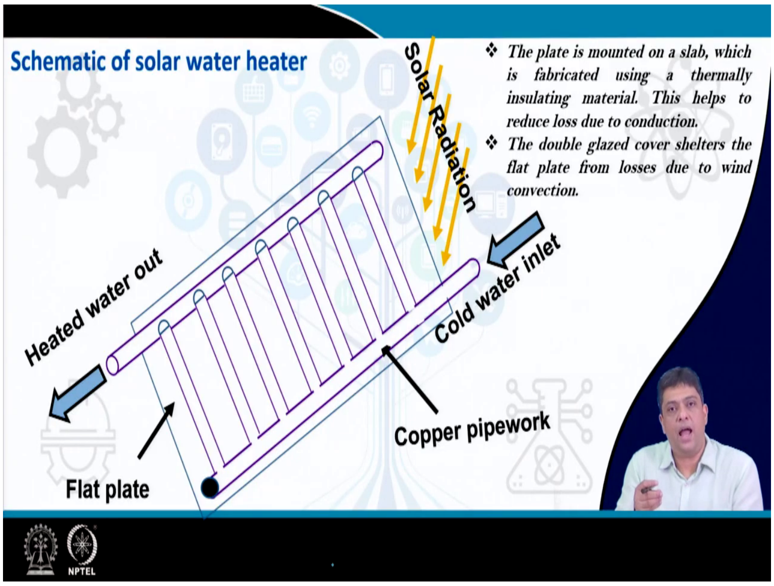

And this is a typical schematic of a solar water heater. It is a very simple design and the operation is also very, very simple if you can understand something. So, what is happening that I have a flat plate and on top of it the rays are falling and this flat plate is absorbing the heat and on top of it I have kept the network of these copper pipes which in the schematic is shown as copper pipe work.

So, the plate is mounted on a slab which is fabricated using a thermally insulated material. So, you mount this plate on top of a substrate, which is thermally insulating, so that I do not start losing heat to this slab on which I am mounting the plate. So, this helps to reduce the loss due to conduction.

And the double-glazed cover shelters the flat plate from losses due to wind convection. So, now you have these glazed covers, which prevents the flowing wind to interact with the copper pipe work and that also prevents the losses due to convection. So, this is a typical schematic of a solar water heater.

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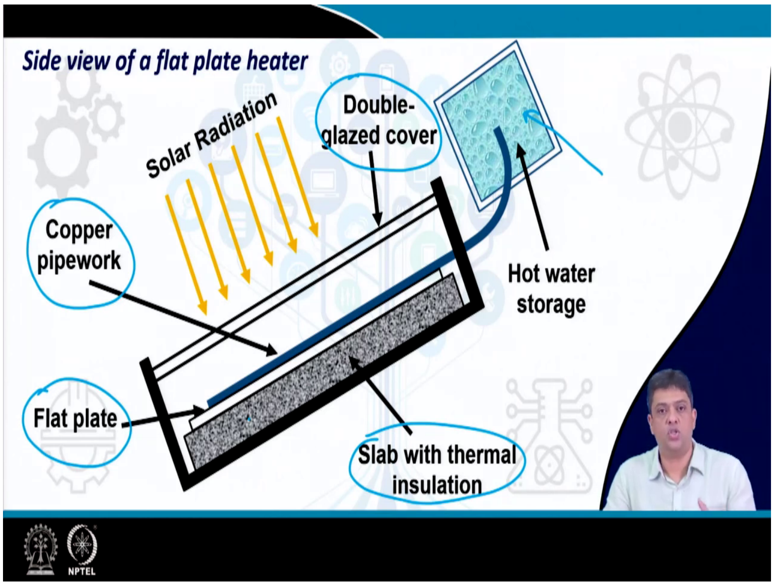

This slide gives you this side view of a flat plate water heater and hopefully, now the things will become very clear to you. What was the first thing which I said in the earlier slide? that you are going to install this flat plate receiver on top of a slab with a thermal insulation. So now you have the slab with thermal insulation, on top of it what do I do I put the flat plate receiver, on this flat plate receiver now the copper pipe work is fabricated.

So, flat plate receives the heat, the pipe network is on top of it, it receives the heat from the flat plate and now the water which enters this copper pipe work gets heated by passing through the various channels and then through the outlet, it can go and get stored in hot water storage. And you have this double-glazed cover which prevents the interaction of cold wind with the copper pipe work and avoid losses due to convections.

And if you want to carry out this process n number of times, so that the temperature of the water which is flowing can increase further, you can use a pump to circulate water back and forth from the storage area. So, when the water goes into storage area, if you want to heat it again you bring the water back, let it get heated up, then you send the water back to the storage and that is the way you can increase the temperature of the water and the system can attain 10s of degrees heating capacity for a fluid in comparison to the ambient temperature.

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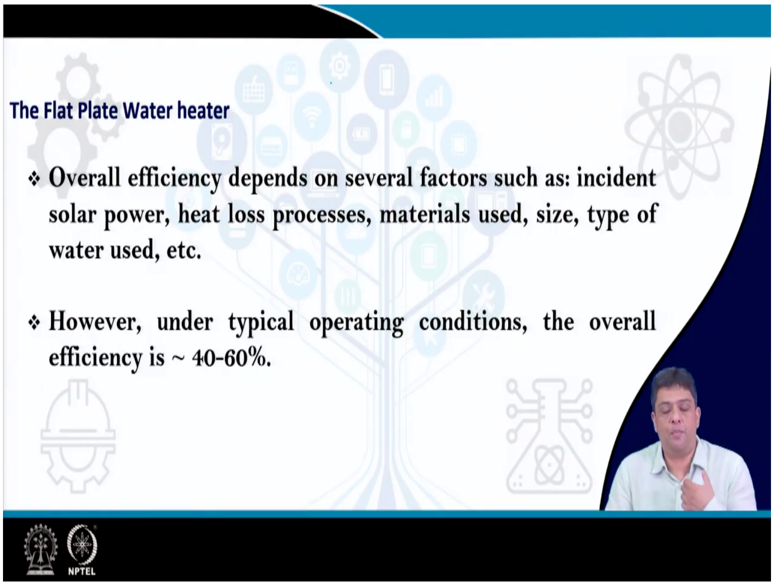

And the overall efficiency of the flat plate water heaters generally depends on various factors. First, incident solar power, different kinds of heat loss processes, what is the material which are used to extract heat first from the flat plate to what type of pipe, and also what type of flat plate am I using.

Suppose, I use a flat plate which over a period of time develops a layer which has a very poor thermal conductivity then the heat transfer process from the plate to the copper pipe work would be very different. So, the materials used to fabricate these flat plate water heaters also become quite critical. What is the size of the flat plate?

Suppose, I use 1-centimeter square or I use 1-meter square, which size do you think will be able to deliver the results which you require and in shorter periods of time? Most probably the answer would be that 1-meter square flat plate water heater will be able to heat 1 liter of water much faster than what a 1-centimeter square area plate will be able do. Also, what is the type of water we are using? Is it pure, is it distilled water or it has a lot of minerals?

So, because then the thermal conductivity properties of the fluid also change. But under typical operating conditions, the overall efficiencies of these water heaters are typically in the range of 40 to 60 percent. So, not bad if you are designing it for your home and you are also maintaining low cost.

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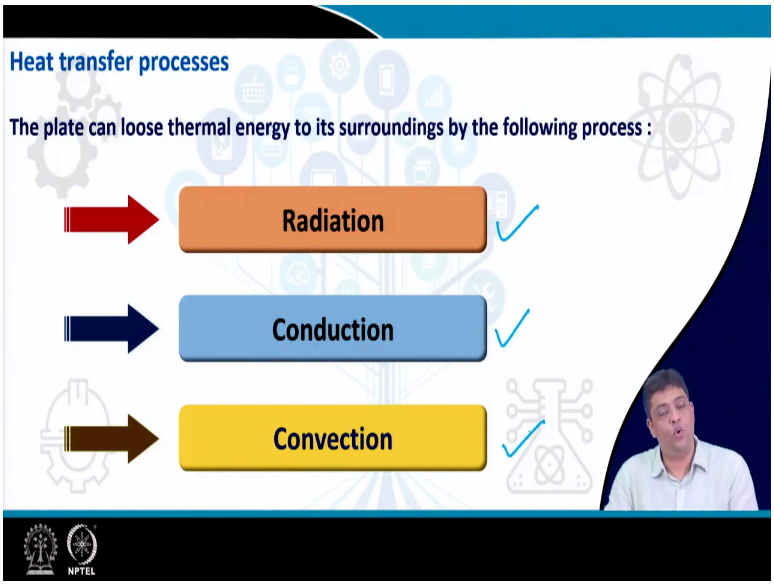

Please remember what have we shown that the plate can loose thermal energy to its surrounding by various processes. It includes all the three processes, which we have been learning from our school days. Such as radiation, conduction, or convection. And if you are able to restrict losses due to these phenomenas the efficiencies will automatically improve.

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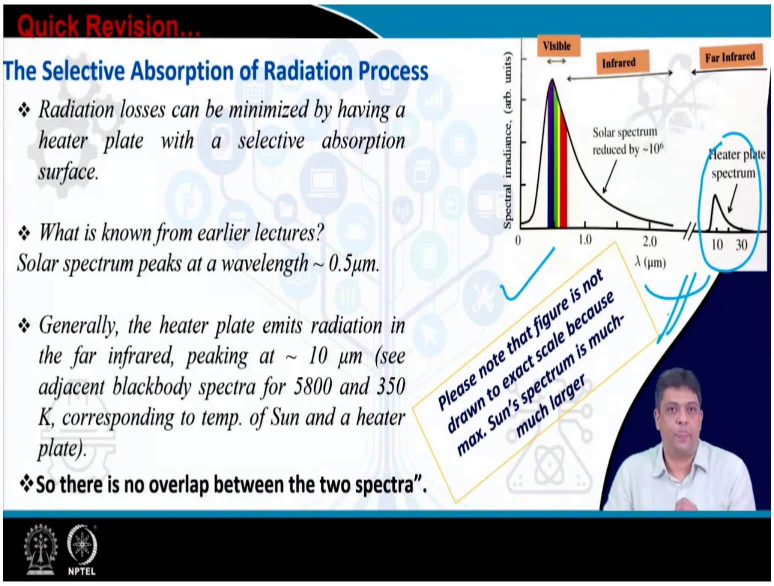

And before I start talking to you, how do we start improving the efficiencies by restricting losses to due to the three phenomena just mentioned. Let us have a very quick revision of the fact what do you mean by selective absorption of radiation process. So, now please remember that solar spectrum peaks at around 0.5 micrometers, the wavelength is approximately 0.5 micrometers and that is where the solar spectrum is peaking.

And if you can have a system by which that the region where I am absorbing and the wavelength region where the emission is taking place, if there are no overlaps, then the losses would be much reduced. And this is what is tried in making an efficient solar water heater based on flat plate design or subsequent designs which we are going to discuss. You should remember that generally the heated plate emits radiation in the far-infrared.

So, this is the region in which the heater plate is emitting radiation, absorption followed by emission. And so, that is approximately around 10 micrometers or so, but there are no overlap in the absorption region and the emission region. So, that is the way you can prevent the losses that you absorb in very different region than the region in which some emissions will be taking place.

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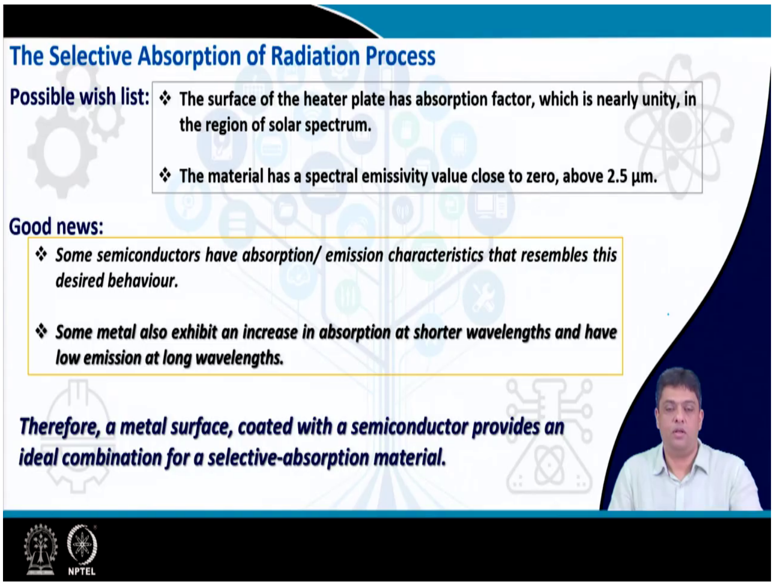

Based on the selective absorption of radiation process concept, I developed the possible wish list. What do I want? The first thing I say that let there be a surface which has an absorption factor that is nearly 1 in the region of the solar spectrum, where the solar spectrum is peaking. And the material has spectral emissivity value close to 0 above let us say 2.5 micrometers.

So, I do not lose any energy or power because of emission from the material. And there comes some of the good news. We have already developed semiconductors that have absorption and emission characteristics that resembles this desired behavior. Along with some semiconductors, that are metals, that also exhibit an increase in the absorption at shorter wavelengths and have quite low emissions at long wavelengths.

So, please remember we have discussed the free electron model, the origin of bandgap, and we have seen that by tuning the lattice parameters, you can tune the band gaps, and depending upon the bandgap you will have the absorptions. So, how will you change the properties of semiconductors, you will make different types of semiconductors with different lattice parameters and that is where your nanotechnology or fabrication technologies come into picture.

Tune the fabrication conditions, and you can tune the absorption and emission characteristics of semiconductor. So, everything we have studied in the earlier lectures also become useful for these kind of water heaters. And based on the understanding, I now have an idea that probably the solution lies in making a metal surface that is coated with a semiconductor, so that I can have proper absorption and I can reduce the emission. And that kind of combination would be used for substrates or coatings or receivers or any other purposes in water heaters of different kinds.

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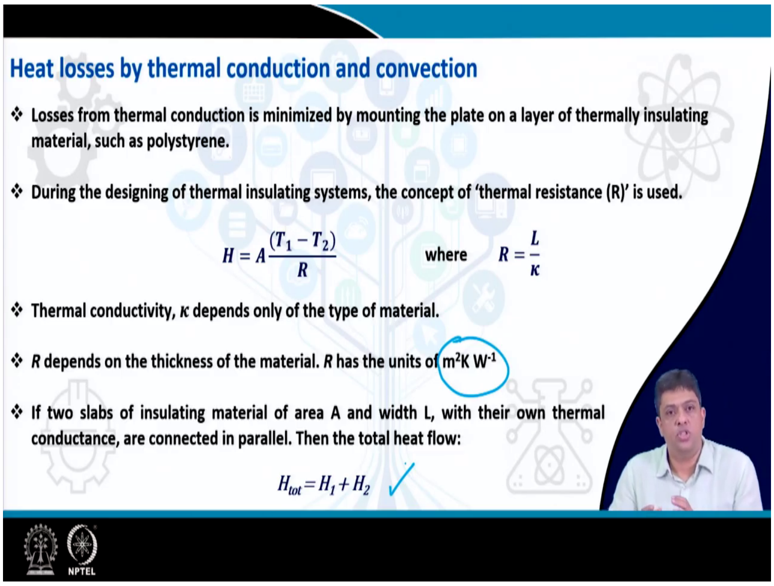

And if you revise your thermal conduction and convection topic, we already know that the losses from thermal conduction can be minimized by mounting the plate on a layer that is thermally insulating. So, the bottom of the layer is on a substrate which is thermally insulating. So, there is no losses between the base and the substrate. So, the insulating layer which is typically used is polystyrene.

And during the designing of thermal insulating systems, the concept of thermal resistance is used where R is equal to L by Kappa and Kappa is thermal conductivity of a material and it changes its value depending upon the material and the size, the shape, and the nature of the elements constituting that particular material. R depends on the thickness of the material and it has a unit such as this.

So, if you have two slabs of insulating materials of area A and width L, they will have their own thermal conductance and if they are connected in parallel the total heat flow would be equal to H1 plus H2. So, by changing the insulating material, the area, or the width, you can also control the total heat flow.

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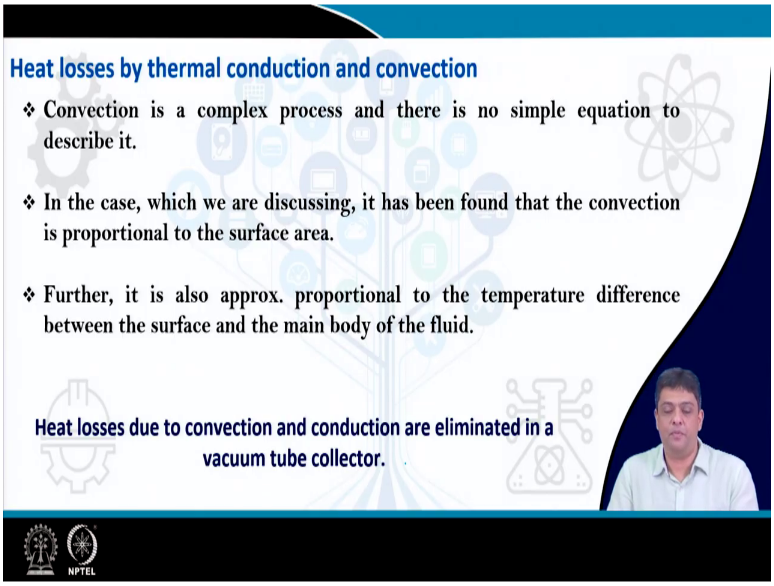

That was more so about the conduction processes and the loss, how to protect the heat losses owing to conduction. Now, in comparison to conduction convection losses are much more complex phenomenon and there are no simple equations to describe it. In the case, which we are discussing, that is the flat plate water heaters, I go back to the example which I took that is 1-centimeter square and 1-meter square which of these two flat plates do you expect, and if they are not covered properly with glazed covers, which of these areas would have higher losses due to convections?

I guess the answer is known and I will ask this more when we have the live sessions. So, you should be ready with the answers when we have the live sessions. And this will be clear that convection losses are proportional to the surface area. Further, if the temperature difference between the surface and the main body of the fluid are very different, then the losses are of different magnitude.

And if the temperature difference between the surface and the main body of the fluid is low, the losses are much lower. And the heat losses due to convection and conduction, which we encounter in flat plate designs are eliminated in vacuum tube collectors, which we will now discuss.

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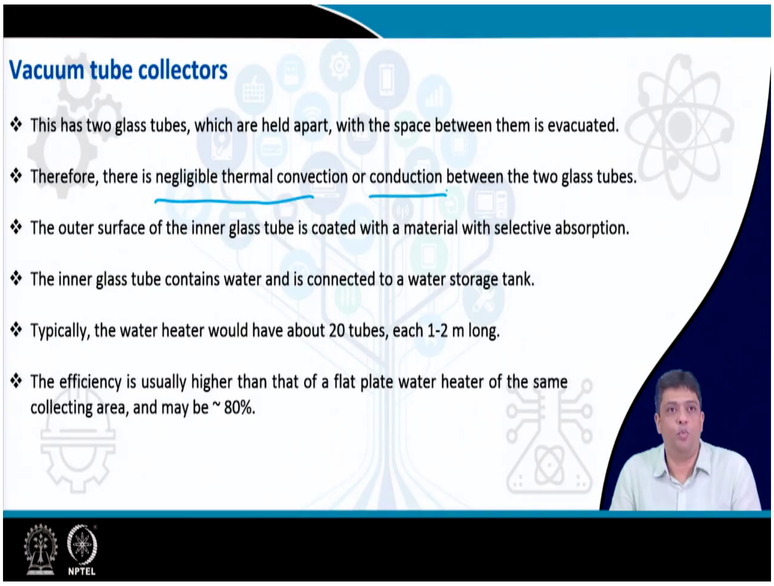

And please remember a thermal flask which you use to store hot water and you now have various types of flasks which can keep a water warm for 12 hours, 24 hours, and what do you know that for in these kinds of flask, you have two layers the inner chamber and the outer chamber and in between this chamber there is vacuum in a typical flask where you are storing hot water.

Based on similar idea, can we start our discussions on vacuum tube collectors and you will find that yes, we can do so. So, let us see what I mean. In vacuum tube collectors, there are two glass tubes which are held apart. So, they are slightly apart and if they are slightly apart there is a space between them. What do you do for the space in between them? You evacuated and remove the air from this space. What happens if there is no air?

There is negligible thermal convection or conduction between the two glass plates. So, I have removed air in between the two glass tubes. So, conduction and convection losses are reduced. Along with that, the outer surface of the inner glass tube is coated with a material with selective absorption.

So, if this is the inner glass tube and this is the outer glass tube, the outer surface of the inner glass tube is now coated with selective absorption layer that means, there is the solar radiation which falls on the surface of the inner glass tube is now absorbed by the coating, which is there on top of the glass tube. The inner glass tube contains the water and it is connected to water storage tank. Typically, the water heater would have let us say 20 tubes of 1 to 2 meters long.

So, you have 20 tubes which are then connected and it is connected to water tank. And the efficiency is usually much higher than flat plate water heaters of the same collecting areas. So, if I remove let us say in the same 2-meter, 2 square area, I now replace the copper pipe work with vacuum tube collectors, their efficiencies will be much higher and typically for vacuum tube collectors, the efficiencies are approximately 80 percent or so.

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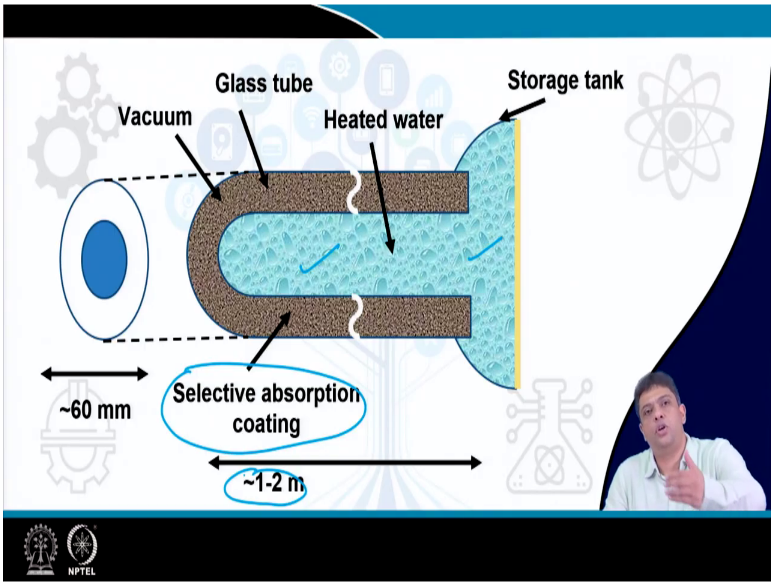

So, this is a schematic to explain the construction of vacuum tube collectors. And everything which was written in the slide previously would become much more clear to you. So, now, what you have, you have a selective absorption coating on the outer layer of the inner tube and the space in between the outer tube and the inner tube is evacuated and you remove air.

And the water is flowing through the inner tube which is connected to water tank. This is a typical design of the vacuum tube collectors and the length of the tubes are 1 to 2 meters and there are let us say 20 such tubes which are arranged so that the heating process is much faster and more efficient.

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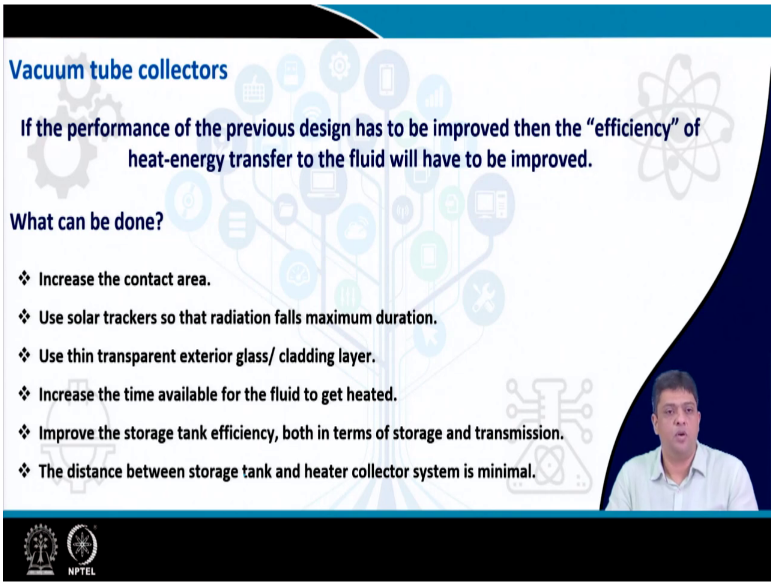

Now, if the performance of the previous design has to be improved, then the efficiency of the heat transfer process to a fluid will have to be improved. Because you see the overall process depends on the transfer of heat from the tube to the water. We are not concerned at this moment about heating of a plate, what is the end product which we are going to use is the warm water or the heated fluid.

So, I am more concerned about the heat energy transferred to the fluid. Now, what can be done, if I have to get a fluid heated at much faster rate and if the whole process has to be much more efficient. There are some solutions which you can see immediately, that you increase the contact area between the fluid and the tubes, use solar trackers, so that the radiation falls for the maximum duration.

Now, what are these solar trackers, these solar trackers track the movement of sun, and then they can ensure that maximum radiation falls as sun moves from east to west, your designing is such that you are installing this tube on a tracker and the tracker ensures that maximum radiation falls as the sun moves this also moves along with the movement of sun. So as to ensure that maximum radiation falls on the overall receiving plate or the tubes.

Use thin transparent exterior glass. This exterior class is preventing the convection losses but if you make it very thick what will happen, this thick glass will also have its own absorption, and the radiation which has to cross this thick glass and then hit the top of the inner glass tube will also be much reduced.

And if that happens, the intensity which reaches the inner glass tube will be much reduced and therefore, the heat transfer would be much lower because the inner tube will itself not get heated up and so, the water will also not get heated up as per our requirement. So, use thin transparent exterior glass and let maximum intensity to cross through it. Increase the time available for the fluid to get heated, you heat the fluid for more time or longer duration.

And we will have to improve the storage tank efficiency both in terms of storage and transmission. This will ensure that you do not heat from the storage area and when water is taken down from the storage tank to the tap from which I want to have the water which is warm, I do not allow the water to cool down. And the final idea which can be used to improve the efficiency of the heat energy transfer process is that the distance between the storage tank and the heater collector system is kept minimal.

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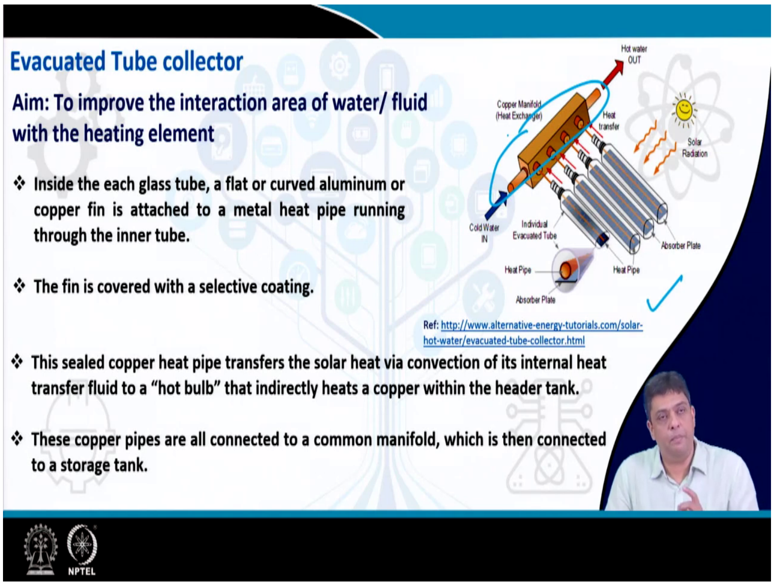

So, the wish list which we had proposed in the previous line is addressed in some of the designs which are more novel or have been proposed in recent past. And first one amongst them is the evacuated tube collector. And the aim of this design is to improve the interaction area of water with the heating element.

What do they do in this design, they have a flat or curved aluminum or copper fin which is attached to a metal heat pipe that runs through the inner tube, and the fin is coated with the selective coating which can absorb the solar radiation. This sealed copper heat pipe transfers the solar heat via convection of its internal heat transfer fluid to a hot bulb that indirectly hits a copper within the header tank.

So, you have a bulb which is connected to the copper which is running through the header tank and then this ball indirectly hits this copper. These copper pipes are all connected to a common manifold which is then connected to a storage tank. So, you connect all these pipes and then you connect the complete system to a storage tank. So, the main idea of evacuated to collector is to increase the interaction area of fluid with the heating element.

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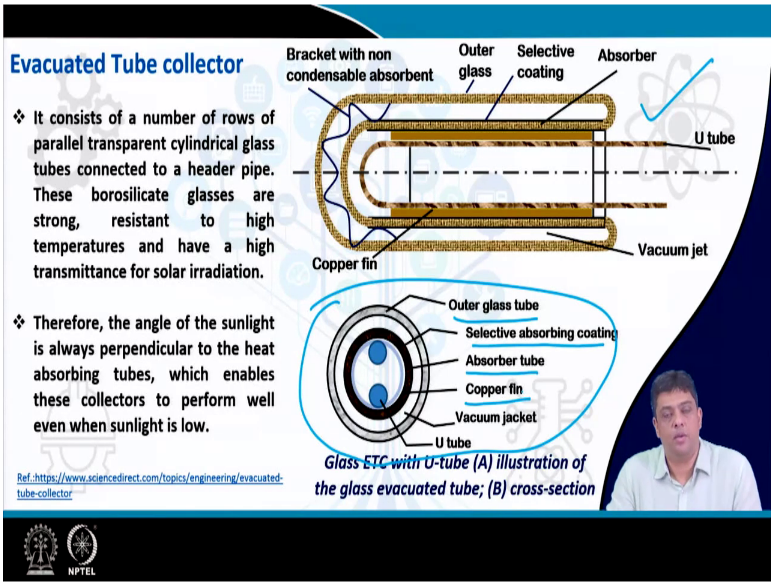

So, if you look into the same thing from other way, you have the rows of parallel and transparent cylindrical glass tubes connected to a header pipe. Now what type of glasses do we use? We use borosilicate glasses. Question is why do we use borosilicate glasses? We use borosilicate glasses because they are strong and they can withstand high temperatures, along with that they have high transmittance for solar radiation.

So, you have the glass which allows the passage of solar radiation while maintaining high strength. Now, because of this design, the angle of the sunlight is always perpendicular to the heat absorbing tubes which enables these collectors to perform well, even when sunlight is low, what do I mean by that? You see, now, every time even if the sunlight is low, you are able to capture the maximum light which is available and the result is the overall efficiencies are much higher and this is the cross-section view of the whole design.

So, what do we have in the overall design? You have the outer glass tube, you have the selective absorbing coating, I hope now, the need for using selective absorbing coating is very clear to you. Now, once you have the coating, you must have an absorber tube which will absorb this heat, you have the absorber tube, which is absorbing the heat.

Where will that heat go? It will have to be transferred to a copper fin and that copper will be connected to the bulb and then bulb can be connected to the main channel which is made up of copper and that copper is going to heat the water.

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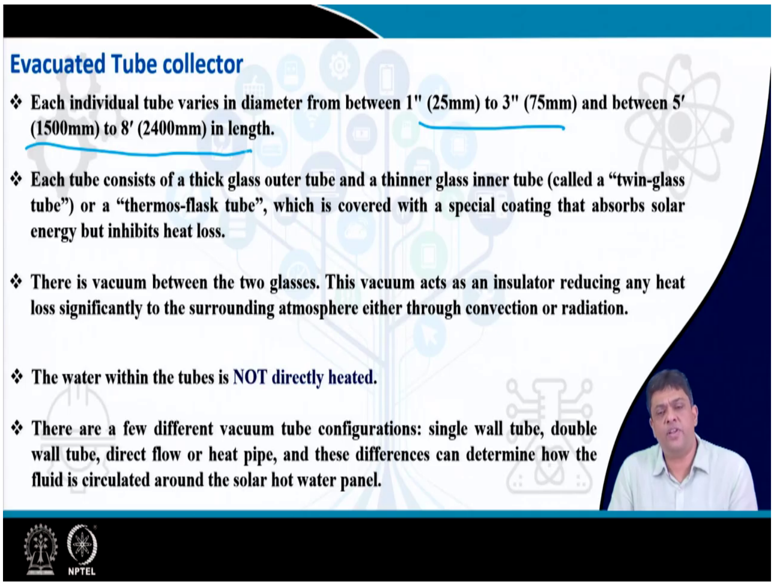

And typically, the evacuated tube collectors have tubes with various diameters and their lengths can also change. So, these are the typical values which are used for diameters and lengths. Each of these tubes consist of thick outer glass tube and thinner glass tube that is the inner side and this is called as twin glass tube or a thermos flask tube.

Now, you will understand when I had given you the example of a thermos flask. Here, the only additional thing which you should remember that the tube is covered with a special coating that is able to absorb solar energy, but it prevents heat loss. Now, there is a vacuum between the two glasses, why there is vacuum because you want to minimize the losses due to convection, conduction, or radiations.

The water within the tube is not directly heated. So, the water which is flowing inside the tube is not directly heated, it is indirectly heated. And there are few different vacuum tube configurations which can be investigated, this can be single walled tube, it can be double-wall tube, there can be direct flow or heat pipe, and the differences amongst them is mainly in the way the fluid is circulated around these solar hot water panels.

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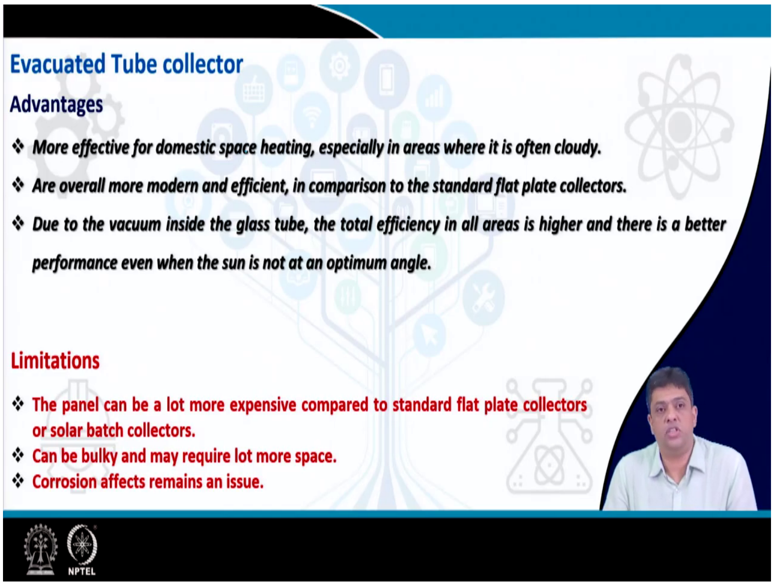

So, the major advantages of these evacuated tube collectors are that they can be used in areas where you can have cloudy skies on most days. So, they are quite useful because the designs are quite modern and the system is also quite efficient, you can have similar performance in much smaller areas than compared to flat plate water heaters, they are more effective for domestic space heating.

But there are certain limitations because they involve more number of fabrication steps than standard flat plate collectors they can be a lot more expensive and they can be quite bulky and may require a lot more space. So, overall, the efficiencies may be much higher, but the components which are used to fabricate such evacuated tube collectors may be much larger in number than flat plate collectors and therefore, they become quite bulky. And just like many of these solar-based systems, which are exposed to air, corrosion effects remain an issue even in evacuated tube collectors.

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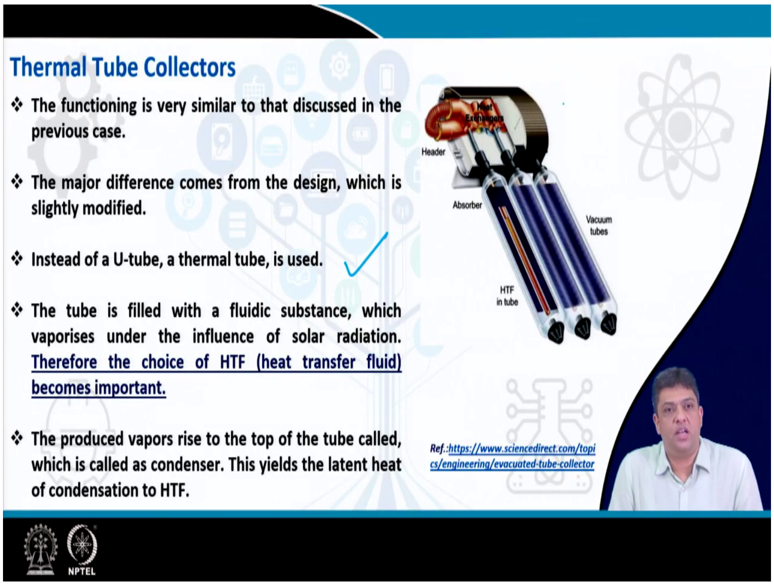

Next design which has been proposed more recently are the thermal tube collectors and the functioning is very similar to what has been discussed just previously. The only major difference is that the design is slightly modified, what is the modification, that instead of a U-tube you use a thermal tube.

And in this tube, what do you do, this thermal fluid is filled not necessarily with water, but a fluid substance which vaporizes under the influence of solar radiation. And because of this, the choice of this heat transfer fluid becomes critical in thermal tube collectors. So, the produced vapors rise to the top of the tube which is called the condenser. This yields the latent heat of condensation to the heat transfer fluid.

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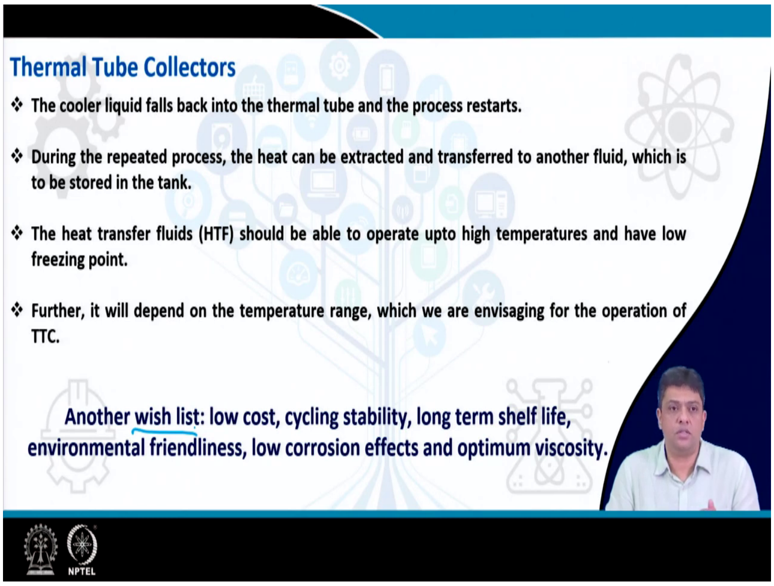

What happens, the cooler liquid falls back into the thermal tube and the process can restart. And overall temperature can be further increased for the fluid. Now, for all this system, we can again make a wish list which include low cost, you must have cycling stability, long shelf life, the construction, the installation, and operation, and also disposal should ensure that the system is environmentally friendly. And we should have low corrosion effects and optimal viscosity.

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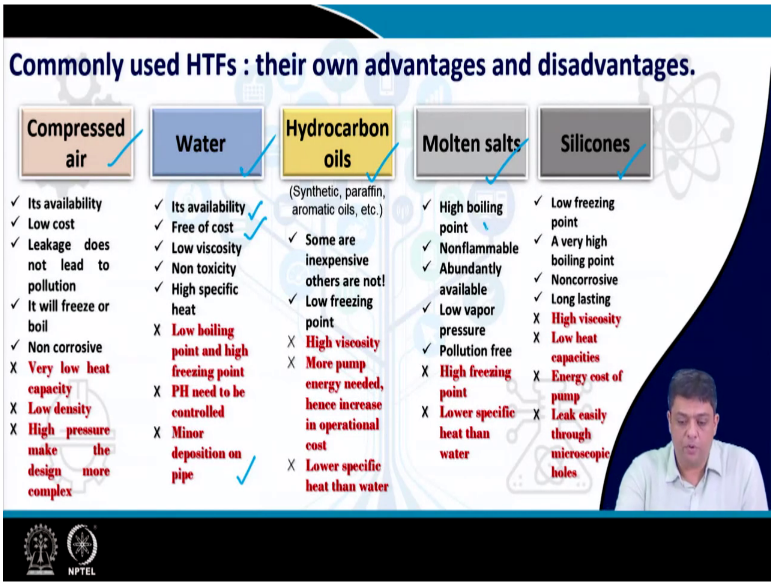

These are the common heat transfer fluids which are used compressed air, water, hydrocarbons, molten salts, or silicones and they have their own advantages or disadvantages. For example, water is easily available, cost you can say is minimal, but it has its own disadvantages like it can lead to a certain level of depositions on the pipe. In comparison, what you can see molten salts they have high boiling point, but the lower specific heat than water brings them to disadvantage condition.

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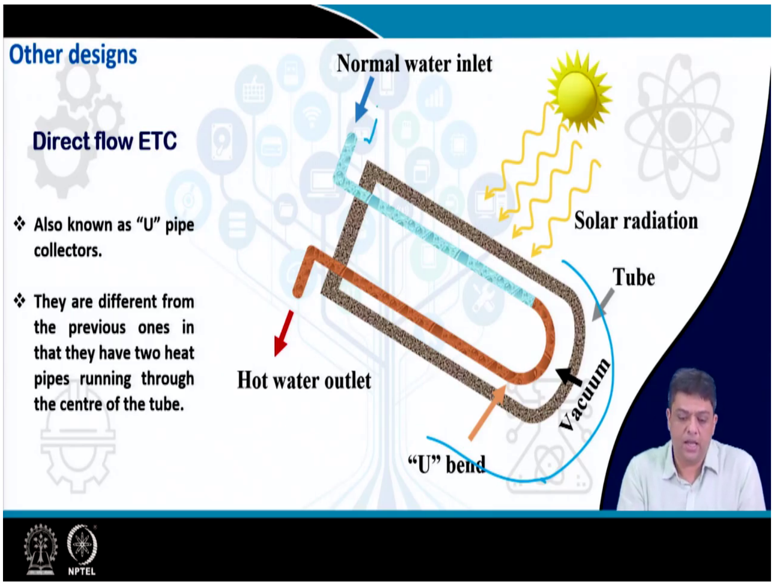

So, to improve the designs and the efficiency of these ETC that is evacuated tube collectors, there are other designs one of them is the U-pipe collectors, where the U-shaped bands are there. And it is a very simple design, what do you have, you have the normal water inlet area and the hot water outlet area and the interaction takes place in the inner tube, rest all the concept remains the same.

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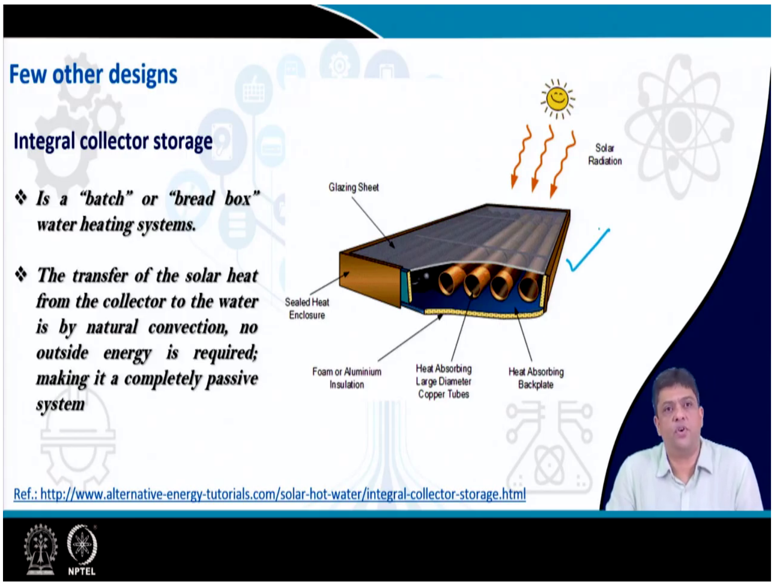

And one of the final designs which we are discussing is the integral collector storage, which is a batch or a breadbox type water heating systems, rest the functioning remains the same, it is only the design which is changing. And here the transfer of solar heat from the collector to the water is by natural convection, no outside energy is required making it completely passive system.

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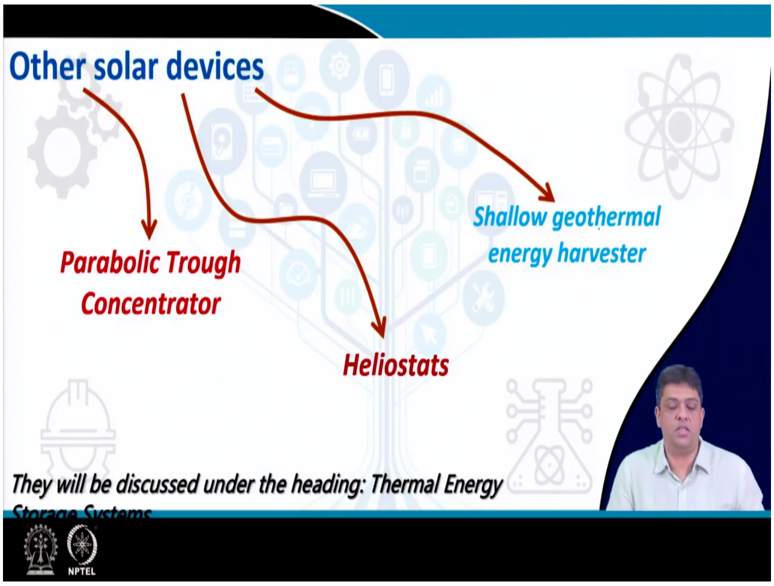

You may have also heard about other solar-based systems such as parabolic trough concentrators, heliostats, shallow geothermal energy harvesters, but these form an integral component of the thermal energy storage system. And they will be discussed when we start talking about the energy storage technologies. And when we talk about thermal energy storage systems, all these three types of solar-based systems will be explained to you.

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And I hope that after listening to today's lecture, you will have developed an understanding about solar heaters and what are various types of solar heaters and which one you would like to fabricate, and install at your homes. And you should while fabricating, you should also remain aware of the limitations which are integrally attached to these kinds of devices.

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These are the references from which we have used the data. And if I have taken some data from the published literature, those are also mentioned on these slides. And from next lecture, we will move on to the next module that is wind energy. I thank you for attending the lecture.