Energy Conservation and Waste Heat Recovery
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Lecture - 56
Energy Storage Systems – VI

Welcome back to the next lecture of Energy Conservation and Waste Heat Recovery. So, today we will continue our discussion on Energy Storage Systems. And what we are going to talk about today is a new one, is a new technology or new class of technologies called thermal energy storage. Recall we have so far talked about mechanical energy storage under which we studied pumped hydro, compressed air, energy storage, and flywheel. Then we also talked about superconducting magnetic energy storage.

So, the next class of storage device is thermal energy storage where the excess energy is stored in the form of thermal energy. Now what do I mean by that?

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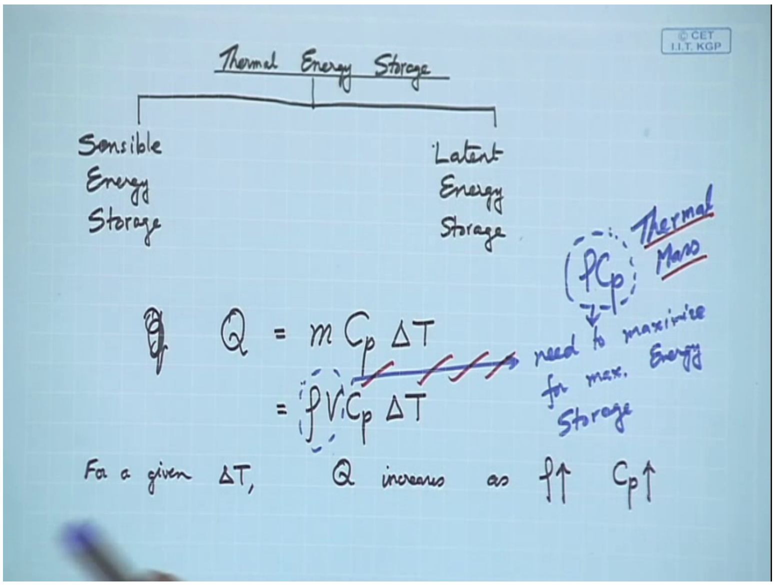

So first let us write down Thermal Energy Storage. So on the thermal energy storage we can further divide into 2 classes: the first one we will call sensible energy storage, and the second one is latent energy storage. So I believe from your already from what you know from our knowledge of thermal sciences and heat transfer we can figure out what this means. So sensible energy is when you heat up a material and it is temperature rises, so you can sense that heat gain. So that is where the word sensible comes from. And as a temperature rises definitely the internal energy of that body of that system or whatever we are heating up increases.

So, now if we have a device by which we can maintain that body at that elevated temperature then it stores the heat. And later, when we need that energy thermal energy we somehow extract it out we remove that thermal energy. So that sensible heat. And as we remove the thermal energy the temperature goes down again.

Latent energy storage however, as a name suggests deals with latent heat, which means there is a as we heat it up while storing energy or cool it down while extracting the thermal energy out of it the substance undergoes a change in phase. And typically when we say change in phase we talk we normally refer to solid to liquid or liquid to solid; so latent heat of fusion, latent heat of melting and therefore latent heat of solidification.

So, in this case what happens is the state of the matter changes from solid to liquid, but typically as we know that any phase change method happens ideally at it is melting temperature or saturation temperature; if you are talking about liquid to gas for example, then therefore the temperature during this change of phase remains constant. However, we store energy by changing it is phase and then extract energy vice versa right.

So that is what I am showing here thermal energy storage.

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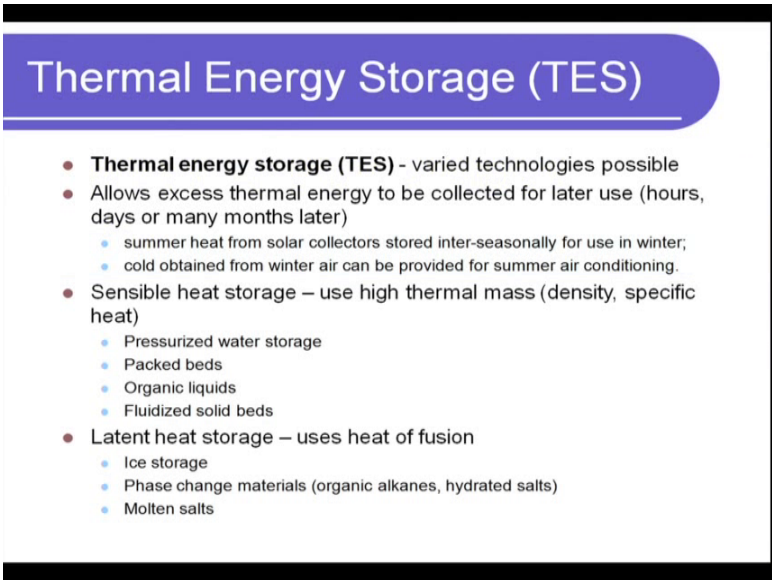

So what is Thermal Energy Storage? So, it allows excess thermal energy to be collected for later use. Now what is later use? Later use can be hours so within the day, later use can be within few days if you are able to insulate that you know that energy storage device appropriately or even months. So for example, the summer heat from solar collectors collected, it can be stored inter seasonally for use in winter; it is not easy but it is possible. And similarly cold obtained from winter air can be provided for summer air conditioning. Again not easy but it is possible, right.

So, this next 2 bullets is the sensible heat storage and latent heat storage which is exactly what we spoke about at the beginning. So what we will do next is, under sensible heat storage or energy storage what we do is we typically use a high thermal mass. So which means the amount of energy that we store if we know, if we recall is q sorry; let me do capital Q because we are talking about energy is m which is mass the specific heat times delta T. So let us say the volume is given, this I can even write as rho V C p delta T: where rho is the density, V is the volume so density times volume is mass.

So now, for a given delta T Q increases as rho goes up and as C p goes up. Therefore, what we need is we need this product of rho times C p right so we need to maximize for maximum energy storage clear so this is also means this also store is sometimes expressed as we need high thermal inertia or high thermal mass. Both of them go together sorry I am extremely sorry this is not rho V. So please ignore this what I wrote here we want to maximize rho C p, this quantity needs to be maximized. So this is the thermal mass. So this is what we need to maximize alright.

So, now so far if you remember we have already been exposed to one form of sensible energy storage and that is regenerative heat exchangers. So what happens there in regenerative heat exchanger, what happens is when you have a hot fluid go through then what happens is that is the materials inside the regenerative heat exchanger. Let us say a packed bed of sand or packed bed of pebbles, it absorbs the heat and cools down the fluid it retains that heat and we have to take care that it is adequately insulated. And later when a cold fluid passes through that same packed bed, it extracts the heat or rather this packed bed releases the heat to the cold fluid and heats it up clear. So this is how it is done.

So, this is one way of sensible thermal energy storage which we have already seen. So over here, if you see packed beds is 1, organic liquids what happens is here we what we will do is again in a regenerative manner we will have a hot fluid exchange heat with an organic liquid and we will the liquid will be chosen such that it is thermal mass is high and later on it is going to be released.

Fluidized solid beds is another example but however, today what we will focus on is, the first one which is pressurized water storage. We are going to talk about this in detail and latent heat energy storage uses heat of fusion as we talked about and we will see some examples. So right now I have written something we will see more examples later alright.

So with that introduction let us go to thermal energy storage the sensible energy storage and take up the example of pressurized water.

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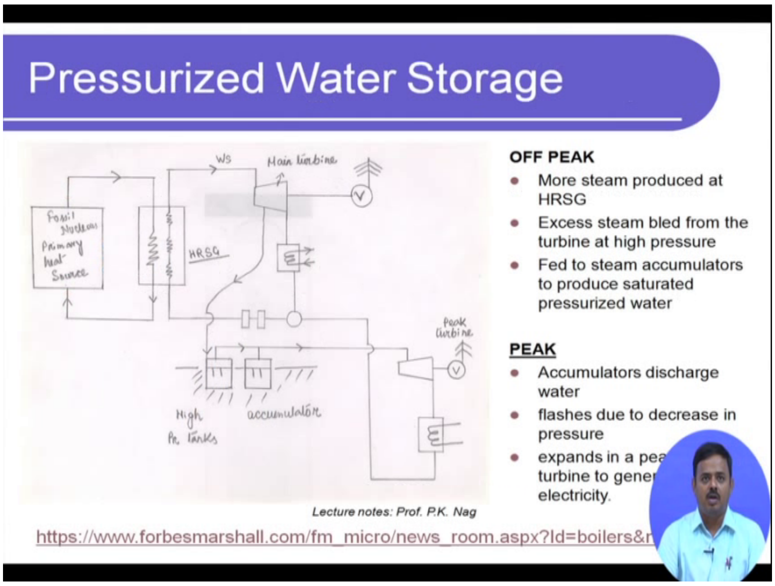

So, pressurized water storage again I am showing a schematic and this again is I express my gratitude to my former teacher Professor P.K. Nag, this is from his notes again something that I learnt many years back, but it still used very it is a very good, it is a very attractive technology that is being used quite regularly.

So, what I have also shown at the bottom is a link which will which also nicely explains the functioning of pressurized water storage. So I would encourage you to go through this link and read about pressurized water storage and this write up is more in the industrial you know is written more from an industry point of view by forbesmarshall. So it will also give you a nice feel us to how they are using it.

Now, let us come here water storage pressurize water storage what do I mean by that:- so the way it is done is when we have excess energy production or basically when the energy that is produced. Let us say by a steam turbine over here is more than what I need so during off peak hours. Then what is done is part of this high pressure steam that enters the turbine before it is expanded at the high pressure stage itself part of the steam is extracted out.

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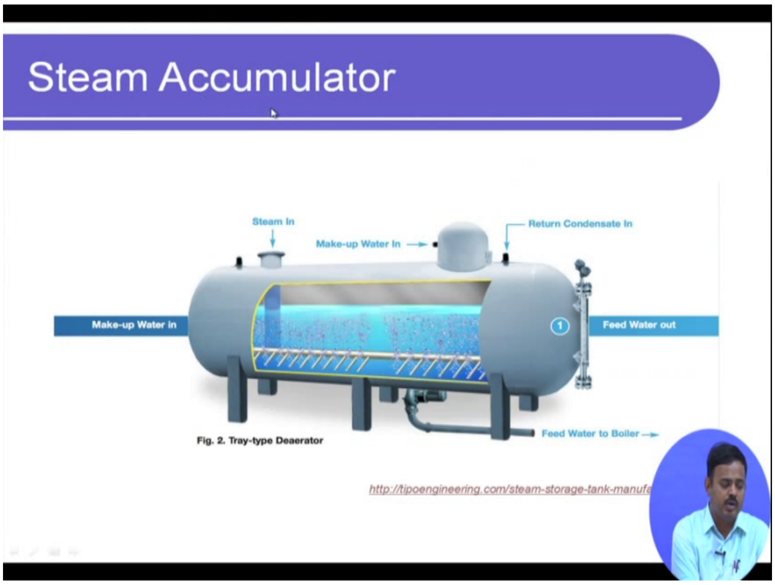

So, as it is extracted out it is fed into what is called a Steam Accumulator? A Steam Accumulator as you can see is actually a cylindrical vessel, it can be quite large with and where the steam is injected through these injecting nozzles that go through it. It is actually the steam accumulator is a big vessel that consists of water typically at a high temperature and in that the steam is injected through these nozzles.

So, let me go back to the previous slide again. So these are the steam accumulators where the steam is injected; so this steam that is injected can be either at the saturated temperature or can be superheated does not matter. So now as the steam comes and mixes with the water then what happens the temperature of the water also increases and the pressure is already high. So the pressure also goes up and typically. Finally, what you have is the water at that elevated pressure and at a temperature corresponding to that saturation temperature. So that is what the accumulator actually are high pressure tanks which consists of water and steam at the saturation temperature clear. So this is during off peak hours what happens.

So, during peak hours what happens is the accumulators they discharge the steam and it goes to a what we call a peaking turbine right. So as the steam is discharged to a lower pressure what happens or as this accumulator is subjected to a lower pressure what happens there will be a flash evaporation. So therefore, the steam will go here and will be expanded in this peaking turbine thereby, generating additional electricity and the pressure of the water is going to go down. So this is going to happen and during the peak hours and the peaking turbine is going to give us the additional electricity generation that we require over and above the base load clear.

And then during off peak hours what happens is the same steam again during off peak hours again what happens when this energy that is required from this turbine is less than what this volume flow rate of steam or mass flow rate of steam can provide part of the steam will again be bled into the accumulators. So this off peak and peak like in previous cases keep going in a cyclic manner in a sequential manner one after the other so alright.

So, let us now go through these bullet points after this discussion. So during off peak the more steam is produced at the HRSG. What is HRSG? HRSG is heat recovery steam generated by now I think you are already familiar with the term HRSG, is where the steam is being produced from water using the primary heating fluid or the combustible gases whatever you want to use alright.

Then the Excess steam, steam is bled from the turbine at high pressure again remember high pressure this at high pressure is important because if you bleed it out at the exhaust of the turbine then it does not help it is already at low pressure it will not be a pressurized storage anymore alright. So that is why we need it to be discharged or bled out at high pressure at the initial stages of the turbine and it is fed to steam accumulators to produce saturated pressurized water clear alright.

Now, during the peaking hours, peak hours what happens is that the accumulators discharge. So they are exposed to is discharge the water and as a result what happens is: Due to sudden decrease in pressure there is a flash boiling or flash evaporation and part of the steam will escape and go through this peaking turbine still at relatively high pressure and it will produce additional electricity and then similarly the condensed steam goes to a condenser and is fled back into the main loop clear alright.

So, now what we will do next is we are going to do a little bit of a exercise or mathematical exercise as to:- How we can I mean let us get a feel for numbers as to how much is energy that we can store.

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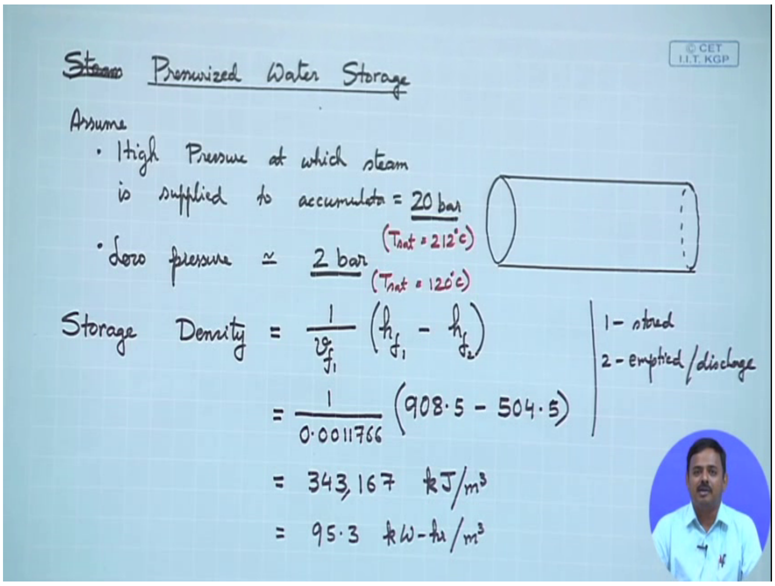

So for that what we will do is, let us say we are discussing steam accumulator or let us say Pressurized Water Storage. iSo what we will do is we will represent the pressurized water storage in the form of a cylinder. The accumulator rather in the form of a cylinder. Now let us assume that the high pressure I mean at which steam is supplied to accumulator is equal to 20 bar and the low pressure when it is discharge is 2 bar. So 20 bar 2 bar.

So, therefore I can define a term called Storage Density. And this will be equal to 1 over the specific volume. So 1 over the specific volume of 1 at point 1 divided by h f of the fluid, h f because it is liquid water and minus h f 2 or this is rho f or the density of the fluid at the high pressure clear. So again if we just take the these values and look up the steam tables which you can do what happens is you will see that a 20 bar the saturation pressure is actually 212 degrees centigrade and here the saturation pressure is 120 degree centigrade.

So, if you now look at the enthalpies from the steam tables or using e e s whatever you are comfortable with we will see that first of all the specific volume is 0011766 at the saturation temperature and pressure under saturated conditions, the liquid specific volume at 20 bar and the enthalpies 908.5 and 504.5 alright.

So, let us say 1 is under stored condition or high pressure and 2 is under emptied condition or discharged. So what this turns out to be is 343167 kilo Joules per meter cubed or this also turns out to be 95.3 kilo watt hour per meter cubed not a whole lot because kilowatt hour. If you recall any of our most of our home appliances like, a Toaster or a Microwave they are rated at 1 kilowatt around that. So therefore, a kilowatt hour is running such an appliance of course, you do not run a microwave for 1 hour directly by heating at least or a Toaster for 1 hour that matter.

But any appliance like that it is not a very high power appliance 1 kilowatt if you run it for 1 hour that is 1 kilowatt hour, so it is not a very large quantity, but it is per meter cubed so this gives you a feel of that if you want to really store energies in the in the you know of the range of 1000 megawatt hour daily few 1000's megawatt hour daily, then the size of the accumulator that you require you can get feel for that alright.

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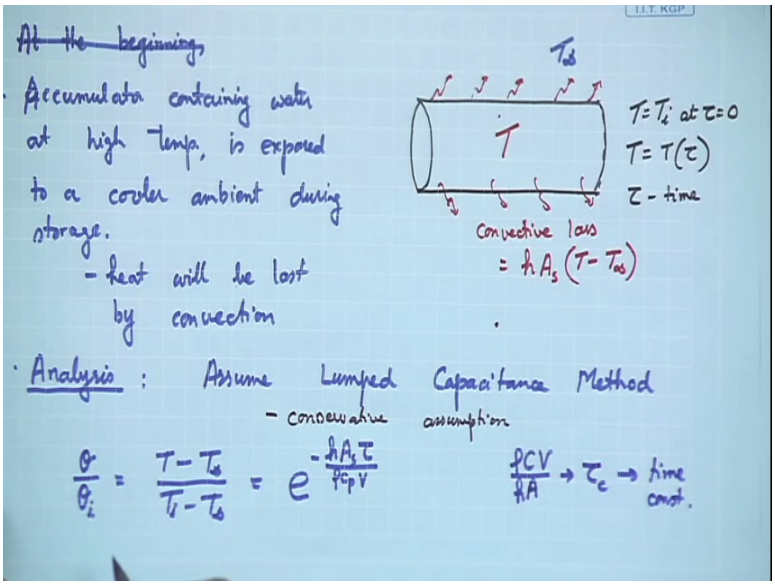

So, we will do a do an analysis on that as well so this is storage density is 1. Now what happens is maybe let me draw this again the cylindrical vessel right. So now, what happens when we actually heat it up or when we store the pressurized water this is at a high temperature and then we are not going to utilize it use it right away or discharge it right away we will discharge it later during the peak hours.

So, therefore what happens is when I store it so let me write it at the beginning, accumulator containing water at high temperature is exposed, let me remove that the beginning I would say accumulator is exposed to a cooler ambient during storage clear. So which means let us say my initial temperature or the temperature of the accumulator is T and the outside have a cooler ambient which is T ambient so therefore, what is going to happen there will be convective losses from the surface, so there will be convective loss and that is going to be h A s T minus T infinity clear.

So, what we will do is? So therefore, what I would say is heat will be lost by convection, so therefore, when it comes to discharge and extracting the stored energy during peaking hours I am not going to get the amount of energy that I stored and the loss is due to this. So how do we calculate so for analysis what we will do is assume lumped capacitance method.

Again, recall what is lumped capacitance method a lumped capacitance method in heat transfer in transient analysis we assume that the entire body which is being cooled is at an uniform temperature right and if you recall with that happens when bio number is much lesser than 1 point 1 and so on which also indirectly means that either the heat transfer coefficient on the outer surface is very low or the thermal conductivity of the material is very high clear.

So you can use lump capacitance under these conditions of course, a mathematical condition is there is a bio number which should be less than 0.1. But physically what it means is that there is no spatial variation across the body that we are analyzing for transient cooling.

So, which can mean primarily 2 things, one is the heat transfer coefficient outside is very low or the thermal conductivity of the material effective thermal conductivity of the material is very high of course, a third-one is the volume is very very small so that the spatial variation is negligible say that is a third-one. But for a given volume these are the 2 conditions.

Now for this case to be satisfy that we do not know probably it will be the h will be low I can say, but this is water which is really in a cylindrical vessel which is really not a very high thermal conductor or which is not known to be a very efficient thermal conductor. But still why do I use it I use it because what does it mean it would mean that there will be some variation in temperature and at the surface at most it will be lower.

So, if I use lump capacitance and use the maximum temperature then I am actually over estimating the losses and therefore it is a conservative assumption clear so I would say this is a conservative assumption. So with that assumption, we will go ahead I am not going to go to the details of lump capacitance analysis. I hope you all know from your heat transfer knowledge or you can just refer to any standard textbook what I would do is therefore, T minus theta over theta I, which is given as the T minus T infinity over T i minus T infinity.

So, what is T i, so I would write it down over here T is equal to T i or initial temperature at time equal to 0 clear and T is definitely a function of time tau, tau is time clear so this one it is known that lump capacitance method will give me e to the power minus h A s time divided by rho C p V. So many a times this one is also known as constant with the or the time constant. So this term which we write as rho C V or m C p over h A is I will denote it by T c or time constant.

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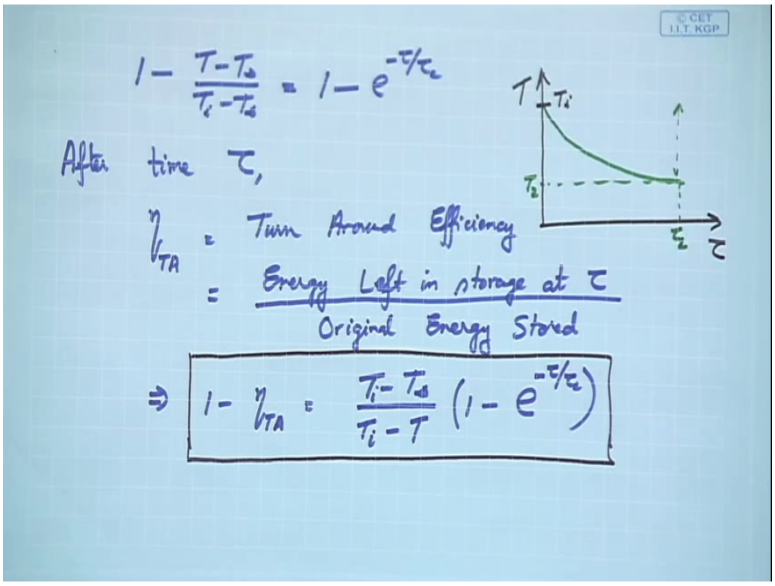

So, therefore I can write it as 1 minus T minus T infinity over T i minus T infinity is going to be equal to 1 minus e to the power minus tau over tau c clear. So therefore, after time tau what do we have we have this expression the time the temperature at that time tau is given by this expression alright. So after time tau I would also say I would define a term called turn around efficiency which as we have known as we have seen before is energy left in storage at tau divided by original energy stored and it can be shown that 1 minus eta T over A is going to be T minus T infinity divided by or T i minus T infinity divided by T i minus T at that time 1 minus e to the power minus tau by tau c. And if I have to plot it graphically it would come out to be something like this, if this is my temperature and this is my time then I started with T i and with time my temperature actually falls exponentially and probably at this point this is my let us say tau equal to tau 1 this is tau 2. Let us say this is T equal to T 2 clear.

So, this is the amount of temperature that has dropped and therefore the amount of energy that has been lost due to convection can be calculate here using lumped capacitance method and this is the expression that we get alright. So that brings us to the end of this lecture where we have looked at thermal energy storage and with details to pressurized water storage it is 1 example of sensible thermal energy storage. what we will do in the next lecture is we will take up some other examples of thermal energy storage.

Thank you very much.