Renewable Energy Engineering Solar, Wind and Biomass Energy Systems
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Lecture – 12
Thermal Energy Storage Systems, Part I

Hi everyone today we are here for lecture 7 of this course renewable energy engineering solar wind and biomass energy system. This is about thermal storage systems for solar energy storage. So, before going into this week lecture we will review whatever we learnt till now.

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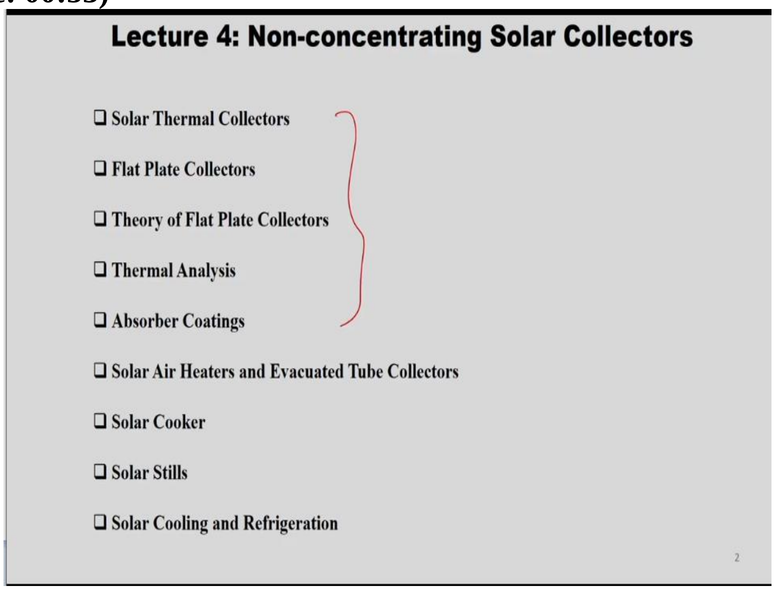

In the last week we had 2 lectures and one practice problem are in the first lecture we learnt about non-concentrating collectors. So, in that solar thermal collectors especially flat plate collectors in depth we had seen the theory thermal analysis and special coatings applied etcetera. And also we reviewed about solar air heaters and evacuated tube collectors. And on the application side using FPC the heat generated by FPC, how to design a solar cooker and solar stills and solar cooling and refrigeration units.

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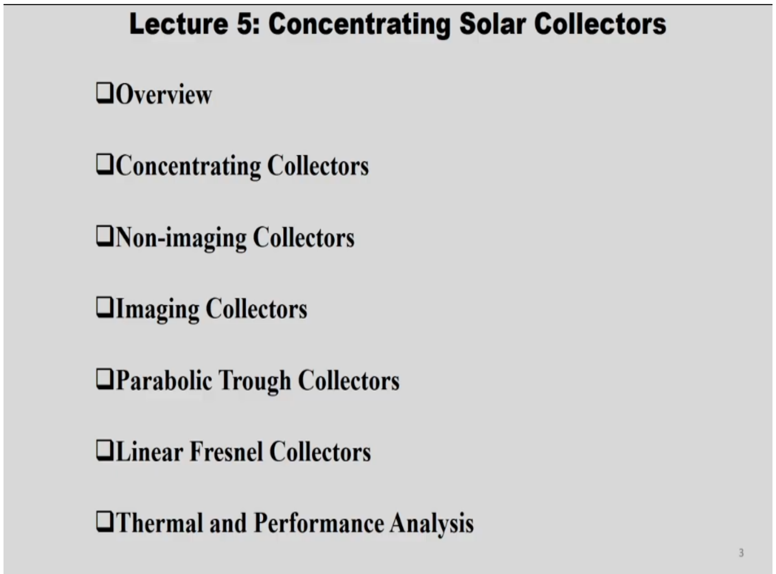

And in lecture 5 we learnt about concentrating solar collectors we reviewed about concentrating collectors, non-imaging collectors, imaging connectors and we also had seen various kinds of concentrating solar collectors and concentration ratio and how it helps in getting higher temperature and that higher temperature may be used to for solar power plant applications. And then we had seen parabolic trough collectors linear fresnel collectors and thermal and performance analysis of cylindrical parabolic concentrating collectors.

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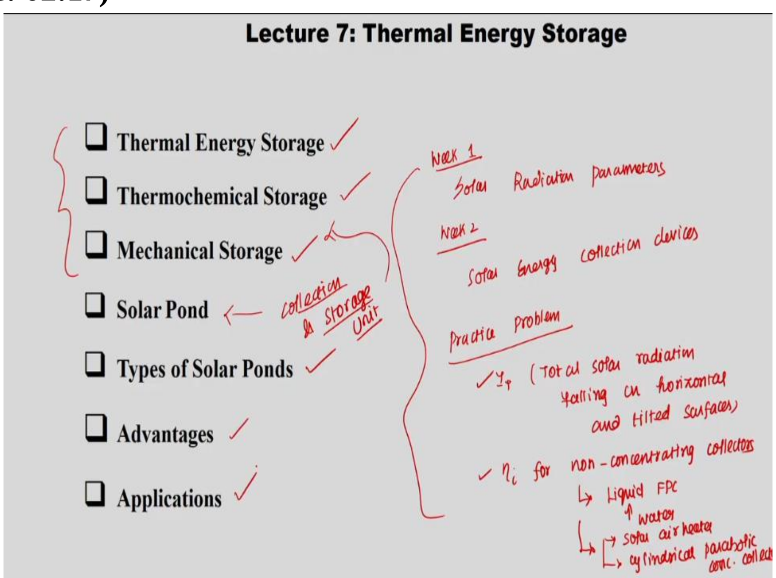

So, in today's lecture we are going to see about thermal energy storage system, so now we are comfortable with solar radiation parameters which we learnt in week 1 and week 2 we learnt about solar energy collection devices on practice problems side by now you are comfortable with how to calculate I T which is the total solar radiation for length on horizontal and tilted surfaces and the second one is how to calculate instantaneous efficiency for non-concentrating collectors.

So, we have done a problem on liquid flat plate collector using water and we have told how to calculate these performance parameters and how to do thermal analysis for solar air heater and cylindrical parabolic concentrating collectors. I hope all of you comfortable with this till now collection technology. So, now we are slowly moving on to storage in of sunshine hours how to use the excess energy which we got during sunshine hours.

In today is lecture we will see about thermal energy storage thermo chemical storage mechanical storage these are various types of solar energy storage systems and this is the solar pond which is a both collection and storage unit can do both the job it can collect solar energy as well as stores solar energy and types of solar ponds and its applications and advantages.

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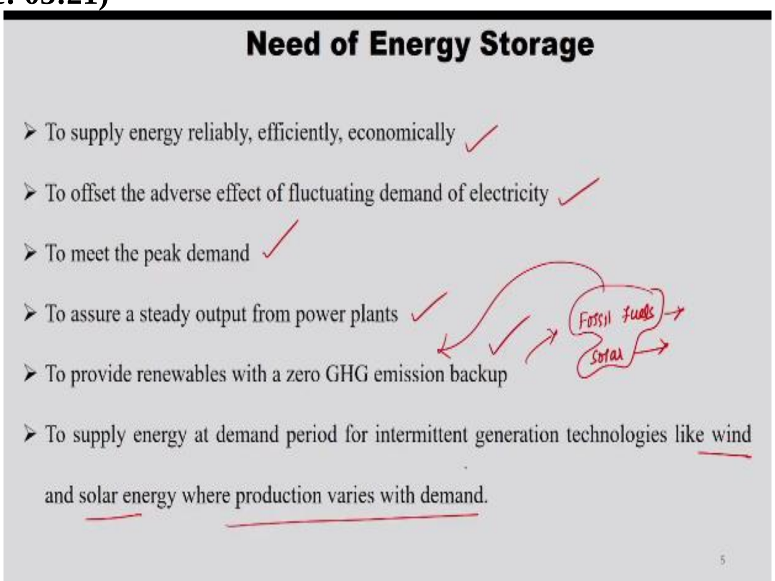

Why we need to have energy storage system to supply energy reliably efficiently and economically? Because whenever there is excess energy we can store it and whenever we have demand we can use it back so that we do not waste energy when it is an excess and we would not be in short of energy when there is a higher demand the offset of adverse effect of fluctuating demand of electricity sometimes we may require larger electric power for example, in the morning, everyone at home leaves to office school and electrical energy demand would be high.

So, we take bath and do iron throats and sometimes we cook an electrical cooker so, the morning hours would be peak hours for demand of electricity. So, such peak demands also can be sold using stored energy to meet the peak demand to assure a steady output from the power plants. So if we are changing non renewable energy to renewable energy the major crisis faced is this unsteady output.

If we are changing to solar power plants day our says but night how do we run the power plants without shutting it down such kind of steady output can be done using energy storage to provide renewable with 0 GHG emission backup. When non renewable energy power plants are going to be shifted to renewable energy power plants. So, this is the first step we will do so we will go for the mixed one the one with fossil fuels and with solar.

So, this will run for day hours and this will resolve the demand and the night hours so instead of going this kind of mixed one. So, we can directly use renewable rootle power plant working on solar kind of system. If we have energy backup that will reduce the number of hours of power plant operation using fossil fuels and to supply energy or demand period for intermittent generation technology like wind and solar, where production varies with demand.

These all points can be used for any energy storage but one of its pointers when we have the energy demand at period for intermittent generation technology. So, the wind we cannot have throughout the urine throughout the day we cannot extract same power from wind energy the same with solar energy. So, in such cases where production varies with the demand also we can use energy storage system.

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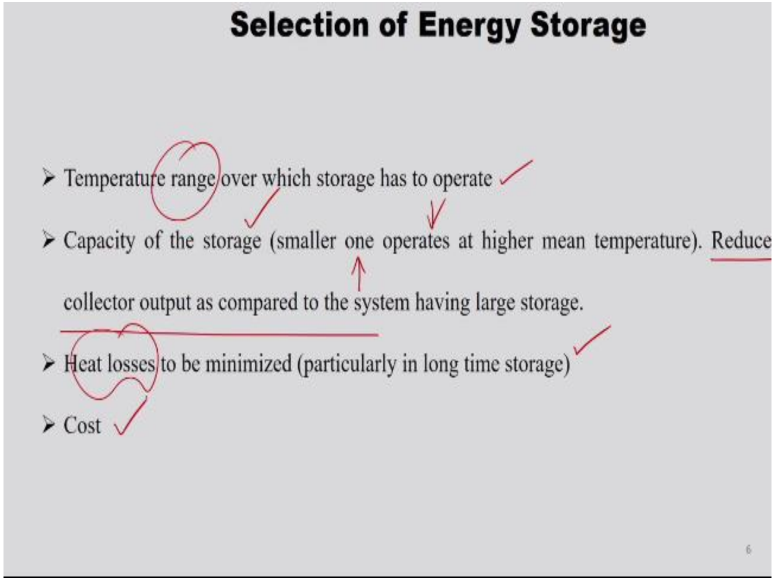

Selection of energy storage based on various parameters so here we are going to see about 4. One is temperature range over which storage has to operate, whether you need a low temperature storage system or medium temperature storage system or high temperature storage system. So, temperature ranges one of the parameter and capacity of the storage. So, normally smaller one operates at higher mean temperature that is what our goal is the volume should not be higher but at the same time it should serve higher mean temperature.

So, this reduces the collector output as compared to the system having largest storage. So, we would require a smaller one and the heat losses to be minimized particularly in longtime storage for example, if we have yearly storage or monthly storage. So, this would be the primitive parameter because heat loss has to be minimized it should be properly insulated and cost of the system also matters when we select the energy storage system.

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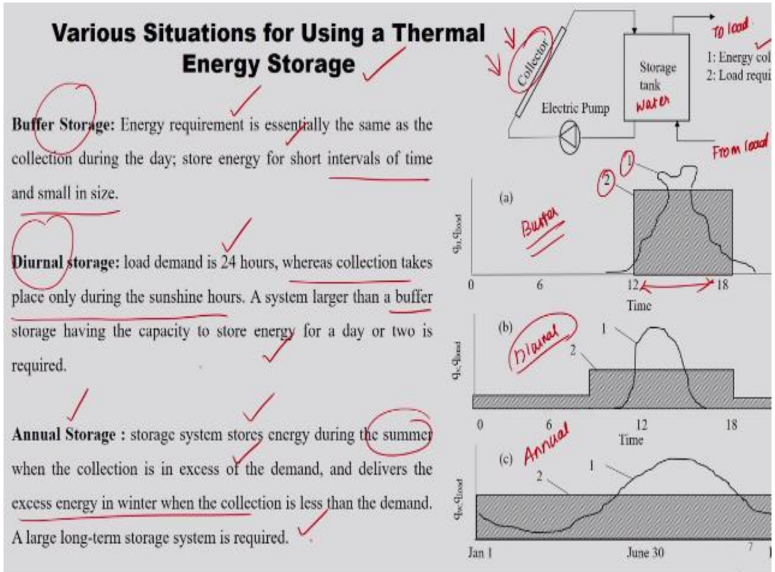

There are various situations for using thermal energy storage one is buffer storage, second one is diurnal storage, the third one is annual storage. So if you see buffer storage where energy requirement is essentially same as that of collection during the day. Here if you see in the figure, here it is a storage system so here is your collection device the water for example, if you are taking water heaters or fluid both in collector side as well as the load side.

So, the water is pumped using electric pump and it gets the energy in the collector and hot water is again goes back to the storage tank. Then the water from the load comes here and takes the energy and goes out so there are 3 kinds one is this one is buffer storage, this is the internal storage, this is and will storage one refers to energy collector 2 refers to the load requirement so if you see here in buffer storage both are almost same.

But at any instant there may be an imbalance between the energy requirement and the collection during the day. We probably record here in buffer storage, the total energy for a short interval of time and small in size for example here 12 to 18 almost 6 as we might require. So, in such case we can use buffer storage. So, this is the storage system which is very small in size and second one is diurnal here the load demand is for 24 hours whereas the collection takes place one way in the sunshine hours.

A system which is larger than buffer storage and having the capacity to store energy for a day or 2 is required. So, mostly solar energy we may use diurnal storage and third one is annual storage where storage system stores energy during the summer and when the collection is in excess at the summer we might require a storage system and it delivers the excess energy in the winter that collection is less than the demand. This is the long term storage system of about a year.

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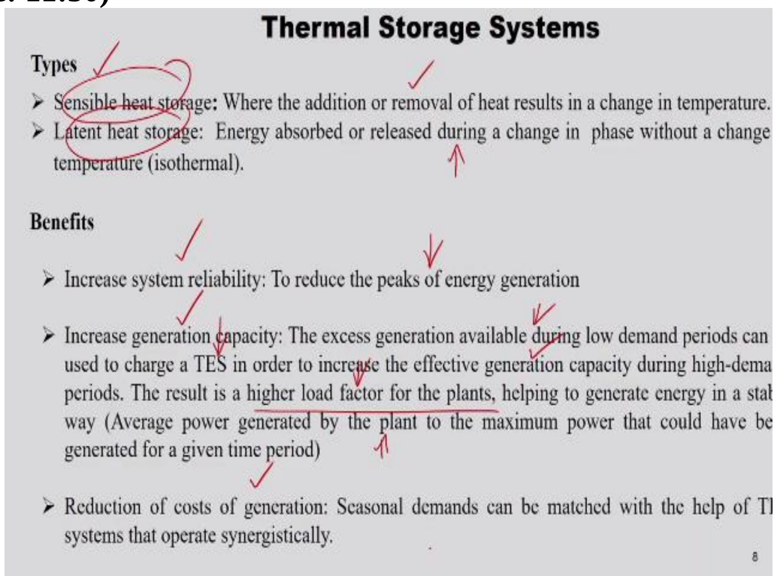

In types of thermal energy storage system, there are 2 categories one is sensible heat storage. Another one is latent heat storage sensible heat storage is nothing but where the addition or removal of heat results in the change in temperature but in latent heat storage energy absorbed or released during a change in phases so without a change in temperature so it is an isothermal process.

Benefits of thermal energy storage it increases the system reliability to reduce the peaks of energy generation and it also increases generation capacity the excess generation available during low demand periods can be used to charge the thermal energy storage in order to increase the effective generation capacity during high demand periods. This we have seen already this resultant high load factor for the plants helping to generate energy in a stable way.

What is load factor load factor is nothing but average power generated by a plant to the maximum power that would have been generated for a given period of time. So, it obviously increases the load factor for the plants and reduction of costs of generation. So, when seasonal demands can be matched with the help of thermal energy storage system which operates synergistically the cost of generation would go down.

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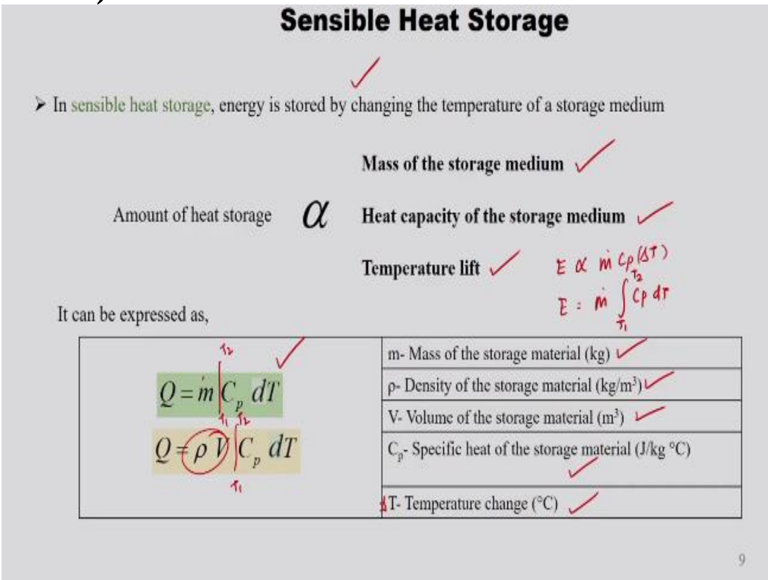

In the thermal energy storage we are going to see first about sensible heat storage system, in sensible heat storage system energy stored by changing the temperature of the storage medium here the amount of heat storage is proportional to mass of the storage medium, heat capacity of the storage medium and temperature lift. So, this energy is proportional to the mass of the storage media C p which is nothing but heat capacity and delta T.

E is m dot because C p is also a function of temperature dT so this spans between T 1 to T 2, so if you see here the storage tank so T 2 is a higher temperature and T 1 is a bottom temperature. Then you can write it us here the limits is T 1 and T 2. So, Q our energy is nothing but m dot C p dT T 1 T 2 and mass we can write it as a density into volume again T 1 to T 2, mass of the storage material density of the storage material is rho, volume of the storage material is V, specific heat of storage material is C p, T is nothing but delta T is nothing but temperature change in degrees centigrade.

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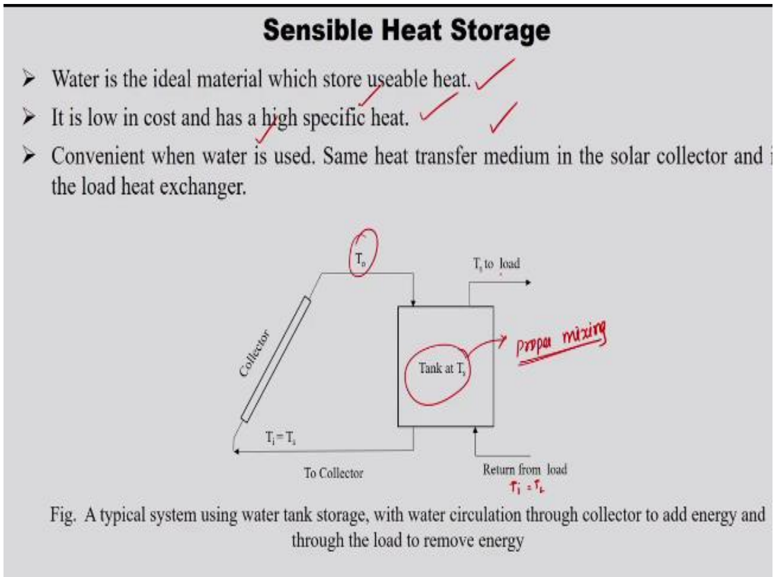

This is we have already seen this particular diagram so the tank is at T s if you have proper mixing. So, here water is an ideal material which store useable heat it is low in cost and has a high specific heat high specific it obviously yes but low in cost when there is water scarcity. So, we cannot say exactly like that. So, convenient when water is used to buy because if the heat answer medium in solar collector and the lower heat exchanger.

If both are water then it will be easy to handle from the collector it is at T naught which is at higher temperature when it goes to tank it leaves the heat and goes back as a T i which is equal and to T s if it is properly mixed. So, T i = T s which goes back to the collector from the load you will get T i which is equal to TL then it goes and when it comes out it should be T s because the tank is at T s temperature.

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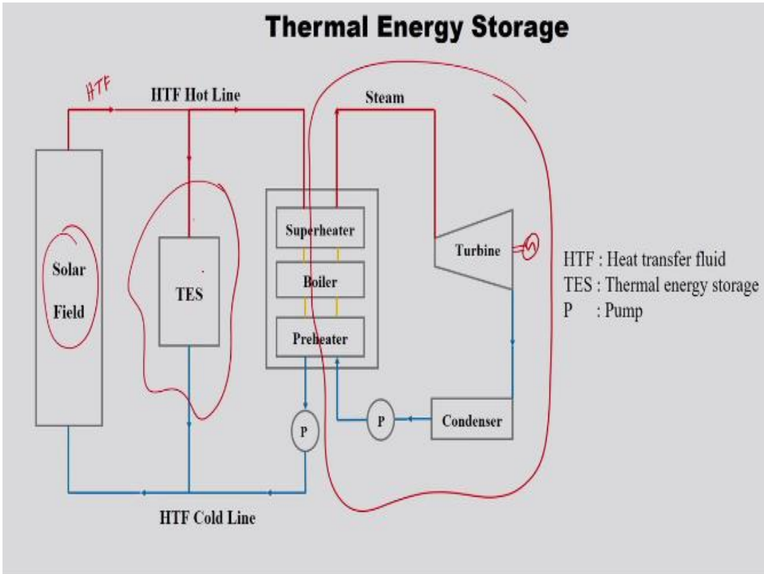

This particular system is for higher temperature applications, so this is normal power plant which consists of turbine condenser pump and pre heated boiler and superheated assembly steam generated from the superheated spread into the turbine then from there it goes to condenser and then it is the fluid is pumped back to the pre heater where it takes the heat from solar collector field heat transfer fluid from solar collector field to generate the steam.

So if there is no thermal energy storage system the solar field provides the heat transfer fluid at higher temperature which loses its heat in superheated boiler and pre heater assembly to generate steam. Which further used to generate the electricity then after losing its heat is pumped back and goes to the solar collected field but if we want to use TES system for example, in the solar moon you can produce the heat transfer fluid with much higher temperature. But that is probably not required in superheated boiler and pre heater assembly we can store some of its heat in TES and the rest of the heat transfer fluid can go to superheated boiler and pre heater assembly.

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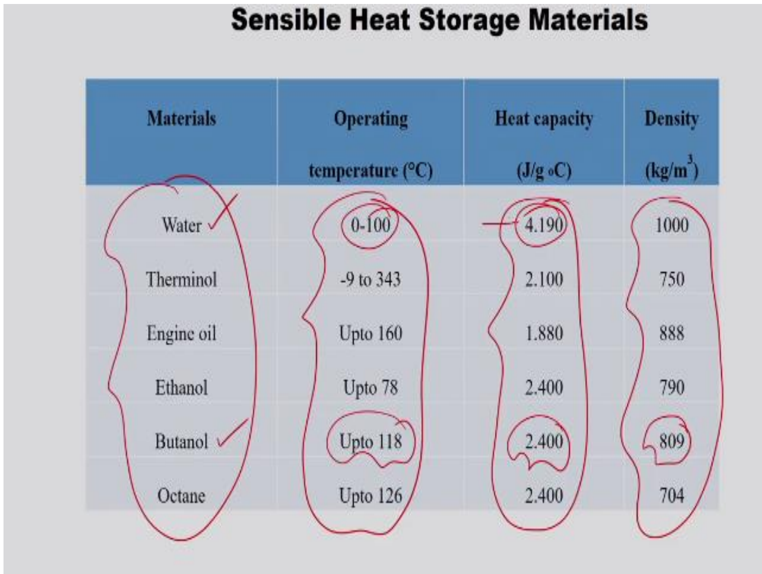

Sensible Heat Storage Materials

Materials	Operating temperature (°C)	Heat capacity (J/g ∘C)	Density (kg/m^3)
Water	0-100	4.190	1000
Therminol	-9 to 343	2.100	750
Engine oil	Upto 160	1.880	888
Ethanol	Upto 78	2.400	790
Butanol	Upto 118	2.400	809
Octane	Upto 126	2.400	704

So, these are some of the sensible heat storage materials water terminal engine oil ethanol butanol octane. So, it has their operating temperature range and heat capacity in joules per gram degrees centigrade is given and density is given. So, based on the requirement you can choose any one of them. So if you are operating temperature ranges around 0 to 100 then you can obviously go for water.

So, octane or butanol is very much favorable if you want your operating temperatures 120 degrees centigrade at the same time you need to say for the row as well as the heat capacity value. So, if you see the water has higher heat capacity heat capacity is nothing but the ability to hold the heat so this also it might require to see.

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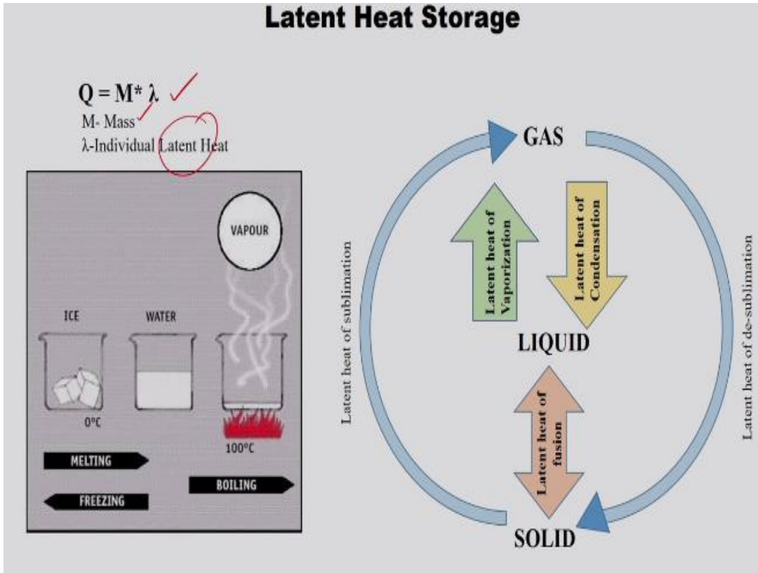

The next one is latent heat storage system so where Q = M lambda, so lambda is nothing but individual latent heat M is nothing but mass, there are 3 phase change available one is solid to liquid to gas. So, solid to liquid it is called latent heat of fusion from liquid to gas it is latent heat of precession from gas to liquid it is latent heat of condensation. If you are converting from gas to liquid and it is a latent heat of de-sublimation solid to gas it is a latent heat of sublimation.

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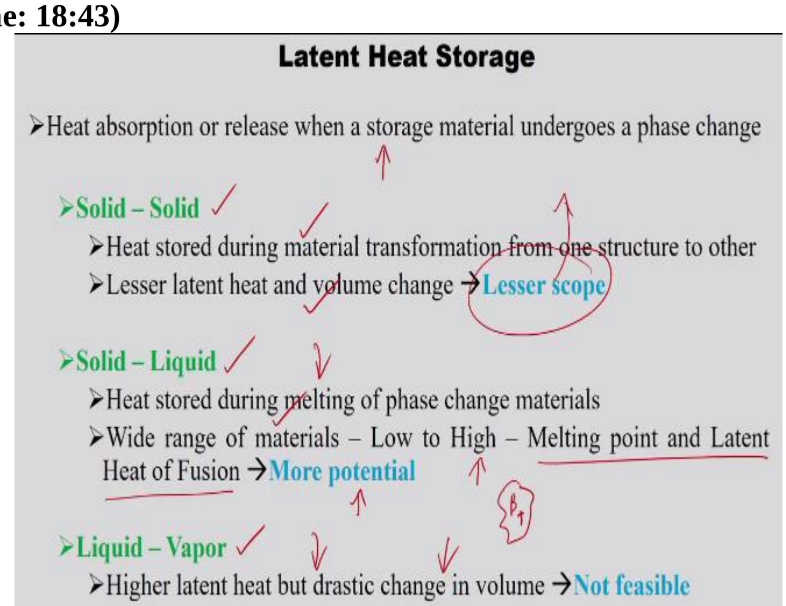

So, here we will see what are all the phase change whether that would be available or that kind of phase change would be compactable for the latent heat storage system. So, heat absorption or release when a storage material undergoes phase change is called latent heat storage. So, there are 3 kinds of exchange right solid to solid can happen solid to liquid and liquid to vapor. So, the solid to solid it is basically a structural change hits total during material transformation from one structure to another structure.

So, here the latent heat available would be very much less and volume changes also lesser so lesser hope for using them as a latent heat storage material solid to liquid heat stored during melting of the face change material. If it is a solid it takes the heat and melts as a liquid and when liquid releases its heat it becomes solid here wide range of materials are available low to high temperature range, melting point and latent heat of fusion based on this the more potential for latent heat storage system.

Liquid to vapor high latent heat is available but problem is drastic change in volume happens so this is also another important criteria when you need to check during thermal storage system because the change in volume should not cause much damage when you change the face for example you have a liquid and a bottle when it becomes solid. So, there should not be any greater volume change otherwise the capacity of the system may not meet that requirement. So that volume change that is nothing but beta T volume expansion coefficient that also has to be checked during selection of the storage material.

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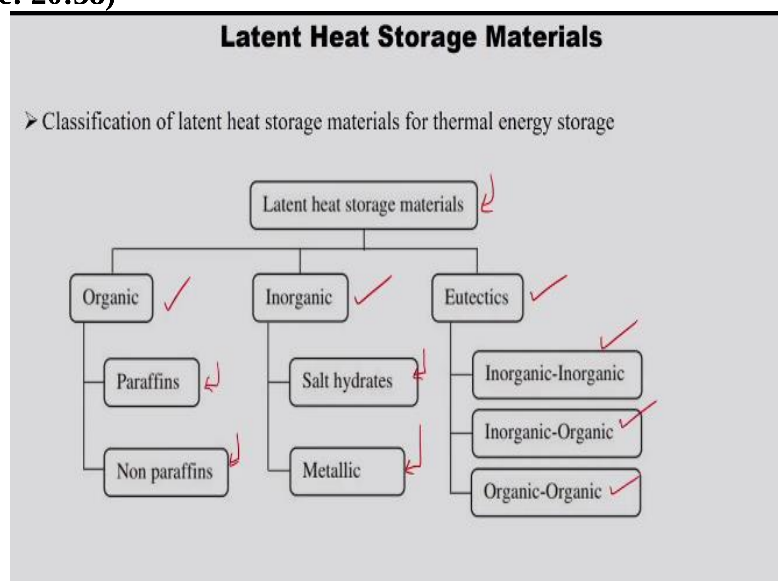

Based on latent heat storage there are 3 varieties one is organic PCM, inorganic phase change material, eutectics phase change material. In organic paraffins and non paraffin so come in inorganic salt hydrates and metallic hydrate eutectics inorganic-inorganic, inorganic-organic and organic-organic.

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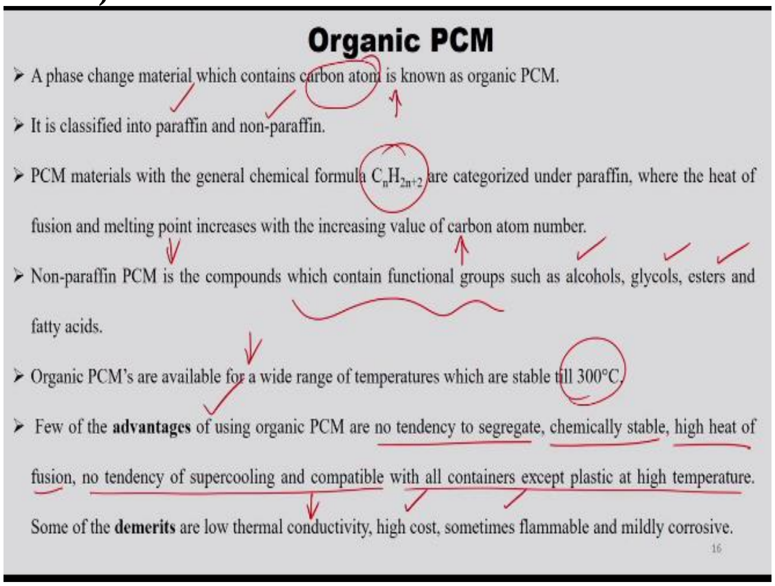

In organic PCM the phase change material which contains carbon atoms it is classified into paraffin and non paraffin PCM materials with general chemical formula of C nH 2n + 2 are characterized add the paraffin. Where the heat of fusion and melting point increases with increasing carbon atom number C 2 is lesser heat of fusion and melting point then C 4. Then in non paraffin PCM category which contains the functional groups of alcohols glycols esters and fatty acids.

Organic PCs are available for a wide range of temperatures which are stable till 300 degree centigrade advantage of organic PCM is nothing but no tendency to segregate there would not be any phase separation and chemically stable high heat of fusion and no tendency of super cooling and compatible with the containers except plastic at high temperature. This is also important because the material what we choose should not cause the corrosion. If it is then you need to change the system frequently. Some of the demerits are low thermal conductivity as I said; this is also important and high cost sometimes flammable and mildly corrosive.

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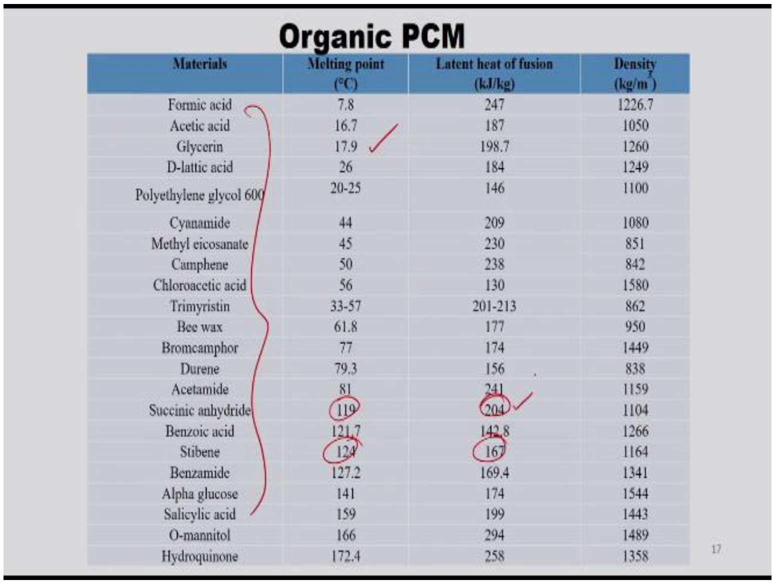

Organic PCM

Materials	Melting point (°C)	Latent heat of fusion (kJ/kg)	Density (kg/m^3)
Formic acid	7.8	247	1226.7
Acetic acid	16.7	187	1050
Glycerin	17.9	198.7	1260
D-lattic acid	26	184	1249
Polyethylene glycol 600	20-25	146	1100
Cyanamide	44	209	1080
Methyl eicosanate	45	230	851
Camphene	50	238	842
Chloroacetic acid	56	130	1580
Trimyristin	33-57	201-213	862
Bee wax	61.8	177	950
Bromcamphor	77	174	1449
Durene	79.3	156	838
Acetamide	81	241	1159
Succinic anhydride	119	204	1104
Benzoic acid	121.7	142.8	1266
Stibene	124	167	1164
Benzamide	127.2	169.4	1341
Alpha glucose	141	174	1544
Salicylic acid	159	199	1443
O-mannitol	166	294	1489
Hydroquinone	172.4	258	1358

These are organic PCM materials based on their melting point, the melting point is nothing but your system temperature what you require. So that has to be chosen based on their melting point and latent heat of fusion sometimes you require a temperature of 120 but temperature of 120 material is available with for example, here 167 and same material is available for around 120 what we are having is 204. So, obviously you choose higher latent heat of fusion material and this is density is given.

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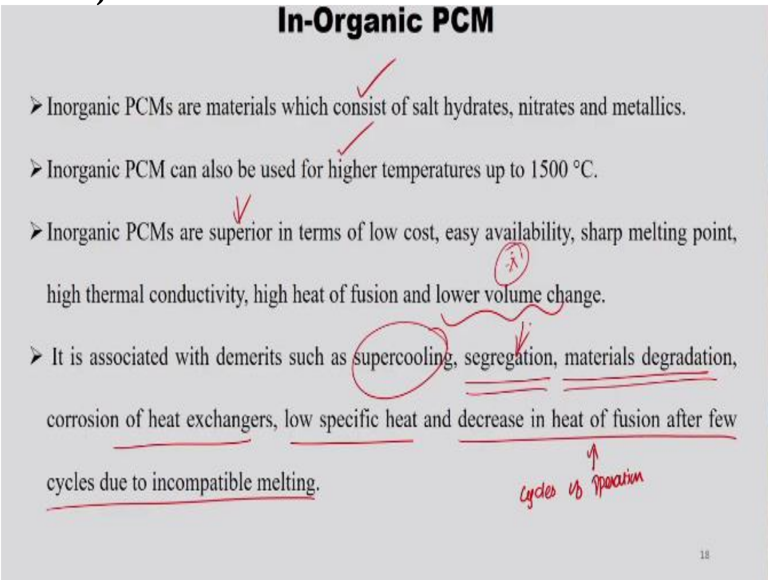

In inorganic PCM, so these are the materials which consists of salt hydrates nitrates and metallic's, inorganic PCMs can also be used to for higher temperatures up to 1500 degrees centigrade. Inorganic PCMs are superior in terms of low cost easy availability short melting point and high thermal conductivity high heat of fusion and lower volume change this is important it is associated with the demerits such as super cooling and segregation that is phase separation and materials degradation and corrosion of heat exchanger.

Because it is mostly salts and low specific heat and decrease in heat of fusion after few cycles due to incompatible or in congruent melting. So, this is also another property to look into cycles of operation. How many cycles you can use that particular material for stories that is also important but inorganic PCM are not good for that because there is a decrease in heat of fusion after few cycles and also the phase separation that is also a problem in using inorganic PCM.

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In-Organic PCM

Materials	Melting temperature (°C)	Heal of fusion (kJ/kg)	Density (kg/m^3)
$NaNO_3$	306	182	2260
$RbNO_3$	312	31	3685
KNO_3	334	266	2109
KOH	380	149.7	2044
$CsNO_3$	409	71	2500
AgBr	432	48.8	1100
$PbCl_2$	501	78.7	5600
$Ca(NO_3)_2$	560	145	2113
LiCl	610	441	2070
$FeCl_2$	677	337.9	3160
$MgBr_2$	711	214	3720
CaI_2	783	142	3956
NaCl	802	482	2160
KF	858	468	2370
$BaCl_2$	961	76	3856
$PbSO_4$	1000	133	6200
$MsSO_4$	1130	122	2660
MgF_2	1263	938	3150
BaF_2	1320	119	4890
CaF_2	1418	391	3180
$BaSO_4$	1512	188	4500
$SrSO_4$	1605	196	3960

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So, these are certain inorganic PCM materials and its melting point is given and heat of fusion is given and density of the material is given. So, these are all famous ones sodium nitrate and potassium nitrate salt which are being used to for thermal storage system.

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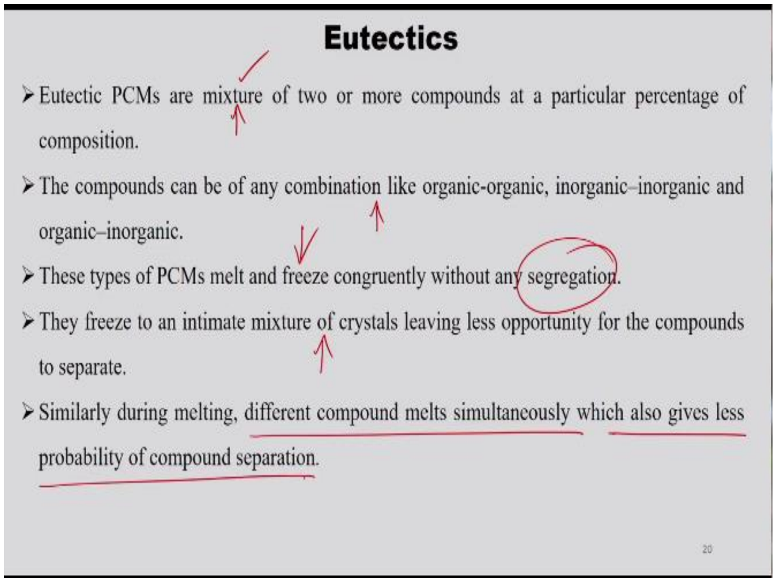

Then the next material is eutectics, eutectics are mixture of 2 or more components at a particular percentage of composition. These components can be any combination like organic-organic inorganic-inorganic and organic-inorganic. These types of PCMs melt and freeze congruently without any segregation. They freeze to an intimate mixture crystals leaving less opportunity for compounds to separate though it is a mixture when it melts and when it freezes their own way any freeze separation.

Similarly, during melting different compound melts simultaneously which also gives less probability for compound separation in that way it predicts at best even though it is a mixture of PCMs.

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Examples of Eutectic Phase Change Materials

Material composition (Mt)	Melting temperature (°C)	Heat of fusion (kJ//kg)	Density (kg/m^3)	Thermal conductivity (W/m-K)
NaF--MgF_2 (75 + 25)	832	650	4660	2.68
NaF-MgF_2 (67 + 33)	832	616	4650	2.14
LiF-MgF_2 (67 + 33)	746	947	-	2.63
NaF-CaF_2-MgF_2 (65 + 23 + 12)	745	574	-	1.58
LiF-NaF_2-MgF_2 (33.4 + 49.9+17.1)	650	860	1150	2.82
LiF-NaF_2- MgF_2 (46 +44 + 10)	632	858	1200	2.24
Na_2CO_3-Li_2CO_3 (56+44)	496	368	2110	2.33
$NaCl$-$MgCl_2$ (50 + 50)	450	429	0960	2.24
Li_2CO_3-K_2CO_3-Na_2CO_3 (31 + 35+34)	397	275	2040	2.31
$MgCl_2$-$NaCl$-KCl (63+ 22.3 + 14.7)	385	461	950	2.25
$NaCl$-Na_2CO_3-$NaOH$ (7.8 + 6.4 + 85.5)	282	316	-	2.13
$LiCl$-$LiOH$ (37 + 63)	262	485	1100	1.55
KCl-$NaCl$-$CaCl_2$ (5 + 29 + 66)	504	279	1000	2.15
KCl-$BaCl_2$-$CaCl_2$ (24 + 47 + 29)	551	219	950	2.93

So, these are certain material compositions as a eutectic phase change material and they are melting temperature heat of fusion density and then thermal conductivity values are given.

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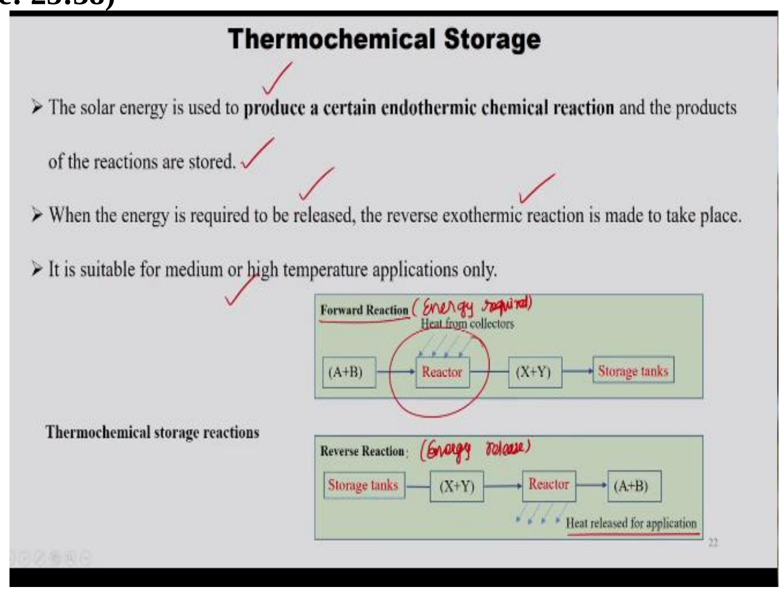

The next comes is thermo chemical storage system so here till now what we have seen us thermal energy storage system. So, there are 2 types one is sensible and other is latent heat storage system and various materials used to facing latent heat storage and sensible heat storage we had seen. So, the next one is thermo chemical storage system the solar energy is used to produce a certain endothermic chemical reaction. So, which takes the heat from the solar energy and the products of the reactions are stored.

When the energy is required to be released the reverse exothermic reaction made to takes place, it is suitable for medium and high temperature applications only because the conducting the reaction it is not advisable if you require low temperature applications because low temperature applications you have wide variety of storage systems. So, what happens in the forward reaction so A + B put into reactor take the heat from solar energy and converts into X + Y with this product and it is stored in the storage tank.

Whenever the reverse reaction happens which is nothing but energy release so this is nothing but the energy required. So, whenever energy release is required the products have been taken from storage tanks and goes back to the reactor which releases the heat for the thermal application. Which is basically an exothermic reaction and goes back to A + B which are nothing but reactants.

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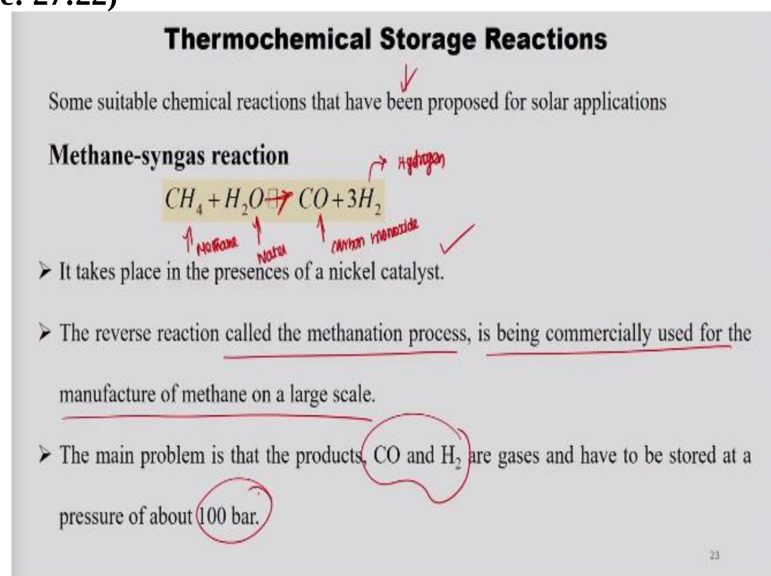

So, some suitable chemical reactions that have been proposed to her solar application the first one is methane-syngas reaction this is a give simple it takes place in the presence of nickel catalyst. So, here methane reacts with water use carbon monoxide and hydrogen so the reverse reaction is called methanation process where CO and H 2 combines and gives the maintainer water which is being commercially used for the manufacture of methane on a larger scale.

The main problem is that the product CO and H 2 what we have seen here so you take reactants and made them to react by taking the solar energy and convert them into product and store it in storage tanks. So to store CO and H 2 is not that easy because they have to be stored at a pressure of about 100 bar it is not a disadvantage but it is difficult to manage. But if your requirement is high temperature application, obviously you can go for everywhere the trade off should be there what application you record to do or apply that particular technology.

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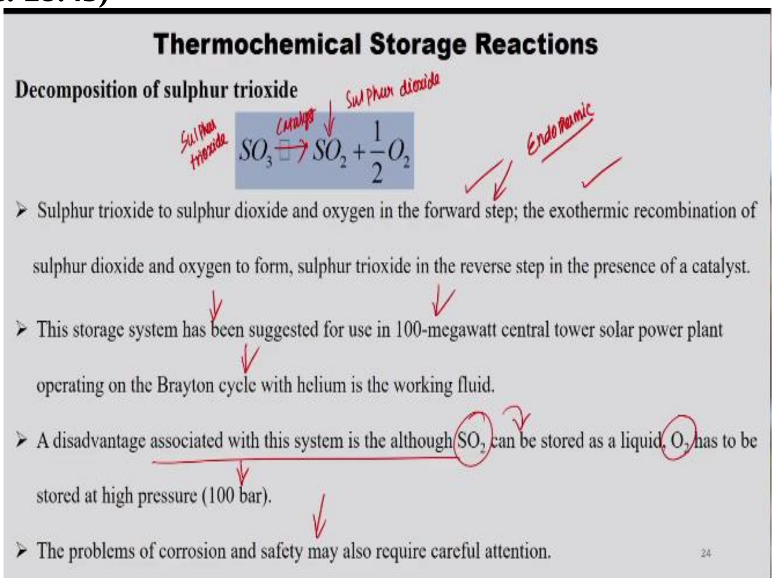

The same thing with decomposition of sulphur trioxide, so sulphur trioxide to sulphur dioxide this is sulphur dioxide reactant is sulphur trioxide. So, sulphur dioxide to sulphur dioxide and oxygen is the forward reaction which is exothermic recombination of sulphur dioxide and oxygen to form sulphur trioxide is the reverse step in the presence of a catalyst. So, this is forward step, forward step is nothing but an endothermic step, exothermic step is nothing but sulphur dioxide and oxygen to form sulphur dioxide.

Sulphur dioxide and oxygen to form sulphur trioxide in the reverse step in the presence of catalyst. So, this storage system here that catalyst would be there. They also if you see the reserve catalyst which is nothing but nickel. This story system has been suggested to use in 100 megawatts central tower a solar power plant operating on the brayton cycle with the helium is the working fluid that is the example where this particular reaction is being used for thermal storage application.

The disadvantages associated with the system is again how to store SO 2 add water SO 2 can be stored as a liquid but O 2 has to be stored at gas only which requires higher pressure. The problem of corrosion and safety may also require careful attention when we use such kind of thermo chemical storage system.

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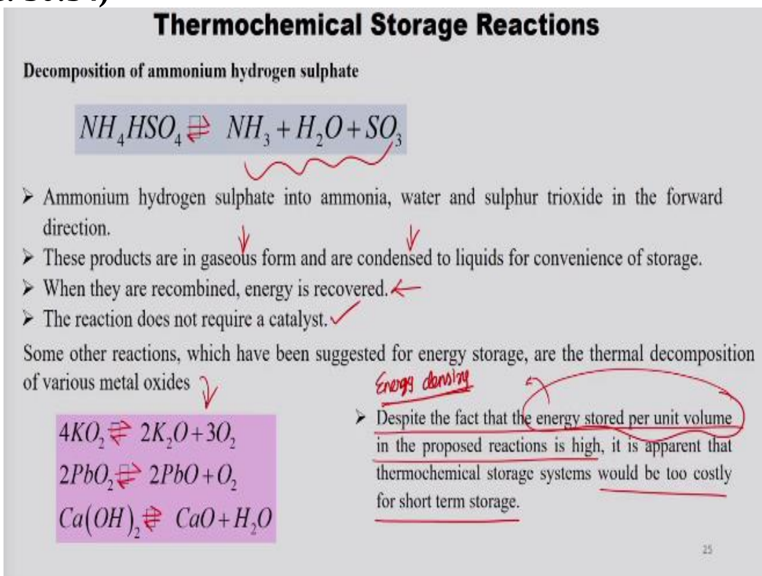

The next one is conversion of ammonium hydrogen sulphate into ammonia water and then sulphur trioxide these products are in gaseous form again the ammonia and then sulphur trioxide, some of them can be condensed to liquids for convenience of storage. Even ammonia can be stored in terms of liquid but when they are recombined energy is recovered the reverse reaction. So, here I should have done something like this because the forward as well as the reverse reaction happens the same thing here forward reverse reaction.

So, the reaction does not require a catalyst here we do not require a catalyst so some of the other reactions also can work for energy storage system thermal decomposition of various metal oxide. So, here KO 2 which again forms K 2 O + 3O 2 then lead oxide which gives 2PbO+O 2 then calcium hydroxide which gives calcium oxide and water. So, one problem is how to store them in the storage tanks and use them when energy requirement is there the storage if it is a liquid.

It may be C but if it is a gas it has to be stored at higher pressure that is bit difficult unless otherwise you require a high temperature application. So, despite the fact that energy stored per unit volume of the proposed reaction is high, this is what I told you energy stored per unit volume. So, this is we call it as a energy density this should be high for energy storage material for these proposed reactions this particular factor is high but the problem is this would be too costly for short term storage because of the fact that you need to store gases at high pressure.

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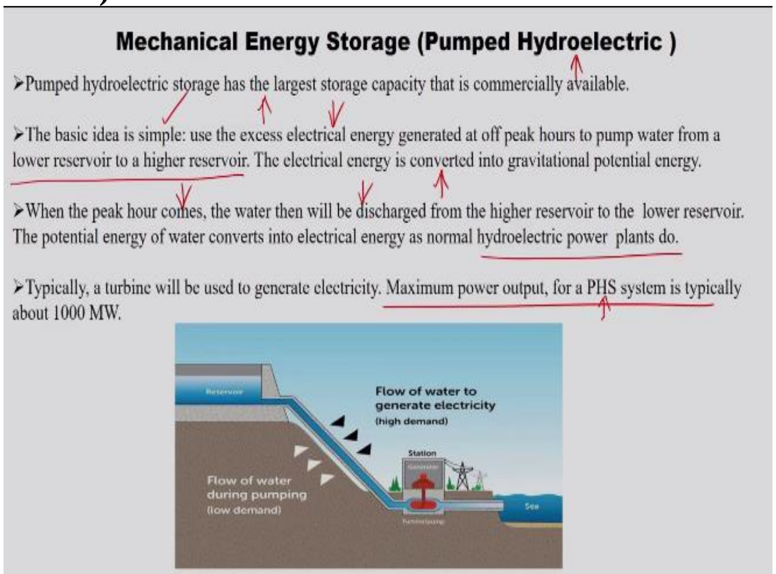

The next one is mechanical energy storage system or pumped hydro electric storage system. The pumped hydro electric storage system has the largest storage capacity that is commercially available. The basic idea is simple here what we do is we use the excess electrical energy generated at off peak hours to pump the water from lower reservoir to higher server that is what it is being done. So, we pump the water from lower reservoir to hire a surveyor using the electricity generated and which is not used.

So, that is nothing but off peak hours generation of electricity so this particular electrical energy is converted into gravitational potential energy. So, during this storage when the peak hour comes water then will be discharged from the higher surveyor to lower stress or where this potential energy of water converts into electrical energy as normal hydroelectric power plants do. In hydroelectric power plant, this is the working principle so when water flows from higher reservoir to lower a server.

That potential energy is being used to run the way that way you generate the electricity so, the reverses this one, the forwarders you use off peak covers generated electricity to pump the water for lower reservoir to higher a reservoir typically a turbine will be used to generate electricity maximum power output for a PHS system that is pumped hydro electric storage system is typically about 1000 megawatt.

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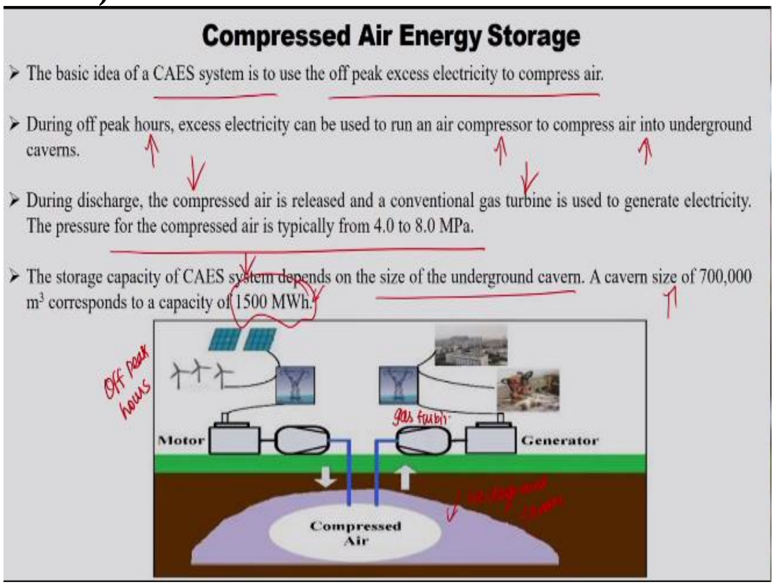

Next one is compressed air energy storage system the basic idea of CAES system is to use the off peak excess electricity to compress air. During off peak covers what we do is we use the excess electricity to run the air compressor and to compress air into underground caverns. During discharge, this compressed air is released and a conventional gas turbine is used to generate the electricity. So, the same principle there we used normal turbine here we use gas turbine so which takes the compressed air to generate electricity.

The pressure for the compressed air is typically 4.0 to 8.0 mega pascal the storage capacity of CAES system depends on the size of the underground cavern. This cavern sizes around 700,000 lakh meter cube corresponds to capacity of 1500 megawatt hour. I hope you are now comfortable with these units because that is what we have done in lecture one. So, this is nothing but here the off peak electricity comes here and runs the motor and compress the air and stores it in underground cavern. This is off peak covers and when demand comes the compress tiaras sent to the gas turbine in a way it generates the electricity.

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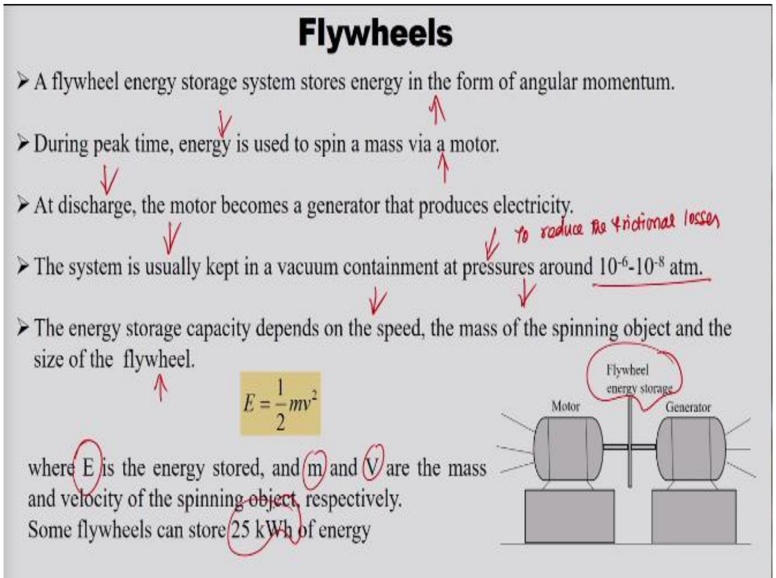

The next one is flywheel storage system this stores energy in the form of angular momentum here is the flywheel energy storage. So, this is the mass during peak times the energy is used to spin a mass via motor this particular mass is connected to the motor which spins at discharge, the motor becomes generated and that produces electricity whatever the energy stored during spinning so that will be released this motor is used as a generator to generate the electricity it is not motor exactly used as a generator.

What I am telling here is this motor is used to spin this flywheel so when the energy release comes the mass rotates back and that rotational energy is given to the generator to generate electricity. The system is usually kept in the vacuum containment had pressures around 10 to the power of minus 6 to minus 8 atmosphere this is to reduce the frictional losses. The energy storage capacity depends on the speed and mass of the spinning object. And the size of the flywheel which is nothing but half mv square is the energy stored m and v are the mass and velocity of that spinning object and some flywheels can store around 25 kilowatt hour of energy.

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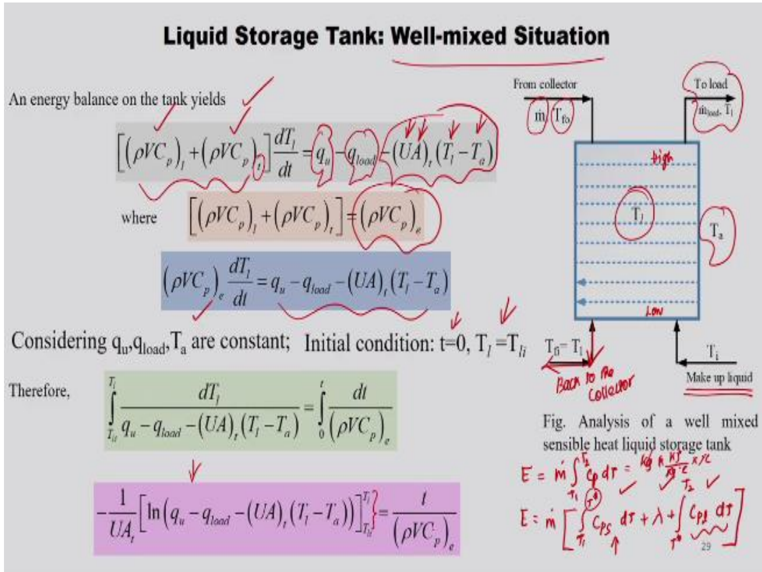

Till now we have discussed about thermal energy storage system in that category sensible and latent heat energy storage system using sensible heat storage materials and then phase change materials and one more thing we need to remember for sensible heat it is just that m dot integral T 1 to T 2 C p dT but if you are using latent heat energy storage system even though it is said isothermal.

So, it cannot operate because you need to take your heat transfer fluid to the melting temperature and then after melting happens during phase change then it becomes liquid there also you have some sensible heat it is nothing but m dot T 1 to T star which is nothing but a melting temperature of the material T 1 is normal temperature. So, C ps dT first you need to increase the solid temperature from T l to melting temperature and then melting happens.

So that is nothing but light and heat of fusion once the melting is over then from T star to T 2 it has nothing but C pl dT. So, these 3 regions first take to melting temperature after melting this also holds some of the sensible heat. So, this part of sensible heat from melting or to liquid and then this pot of sensible heat from the initial temperature of the solid to melting also to be accounted at is not simply m lambda.

This dot is nothing but like rate of heat if you calculate mC p delta this is kg kilo joules kg degrees centigrade into degrees centigrade so it comes in kilojoules. So if you use dot which is mass flow rate it is kilojoules per second nothing but kilowatt during thermo chemical storage also system operates at isothermal temperature but the reverse reaction temperature and forward reaction temperature may be different.

So, here we are going to see energy balance for a liquid storage tank which is under well mixed situation well mix the situation in the sense there would not be any stratification layer the total fluid inside that tank would be in the T 1 temperature. So, normally what happens is stratification happens so this will be at higher temperature and this will be at lower temperature it is not that much temperature difference but probably 5 or 10 degrees centigrade.

But if you mix it properly then it will be a uniform temperature of T l from the collector the mass flow rate of fluid comes with the T f naught from the collector and it leaves its heat while there should be going back to the collector. When it goes back to the collector it should be at T f which is nothing but T l tank temperature here is the makeup liquid which comes with T i and goes to the load m dot off load mass flow rate of load to the T l.

Because when it comes out it should be in tank temperature T l the atmospheric temperature is t here rho VC p of liquid and rho VC P of tank material into dT of T l which is equivalent to useful heat gain minus whatever the heat it gives to load and what is the heat which is contributed as a loss convection loss UA t is nothing but tank. This is the overall heat transfer coefficient and area of the tank T l is nothing but the liquid inside the tank T a is atmospheric temperature.

So if we combine both of them rho VC p of the liquid and the rho VC p of tank we call it as rho VC p of e this is nothing but mass into C p mass we are writing as a density into volume. So, rho VC p e d dt of T l which is equivalent to q u - q l UA t T l - T a. If we take initial temperature of t = 0 T l is to T l i and integrate the time component from 0 to t and temperature component from T li initial temperature to T l that is the final well mixture temperature.

So, we combine all the temperature terms at one side dT l upon q u - q load - UA t T l - T a and time component the side which is nothing but one upon rho VC p e dT which is integrated to 0 to t what do you get is minus 1 upon UA t ln of qu - q load - UA t T l - T a the temperature differences T li to T l which is equal to t upon rho VC p e.

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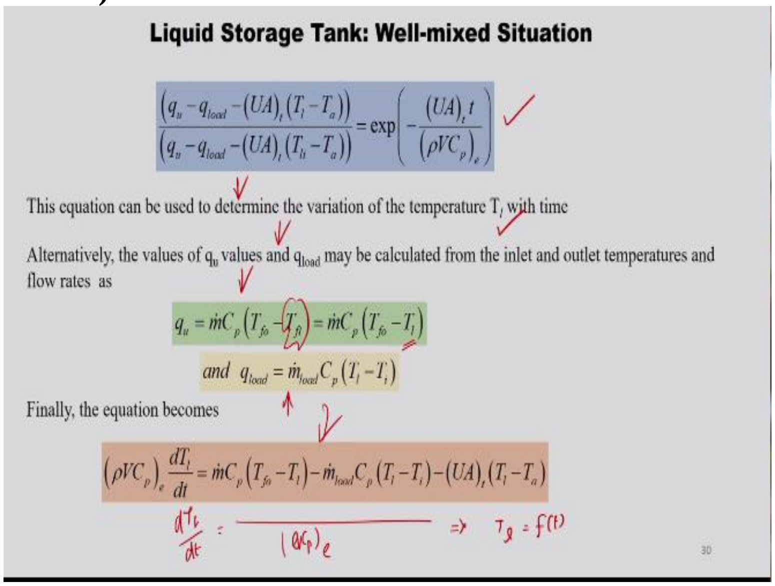

So, further simplification this turns out to be q u - q load UA t T l - T a upon q u q l UA t T li - T a which is equal to the exponential of minus UA t into T upon rho VC p e. So, this equation can be used to determine the variation of temperature T l with time how the inside temperature of the tank varies with respect to time. Alternatively one can use the definition of q u and q load in the basic equation of 1 and then do energy balance as well.

So if you remember whatever the useful heat gained which is nothing but m dot C p T f naught - T fi. So, T fi initially it is T l and then q load is nothing but m dot load C p T l - T i, if you substitute and calculate dT l upon dt the whole value divided by rho VC p of e, then also you can get T l as a function of time. Till now, whatever we discussed us energy storage system purely of energy storage. The next one is solar pond, so which has collection and storage unit.

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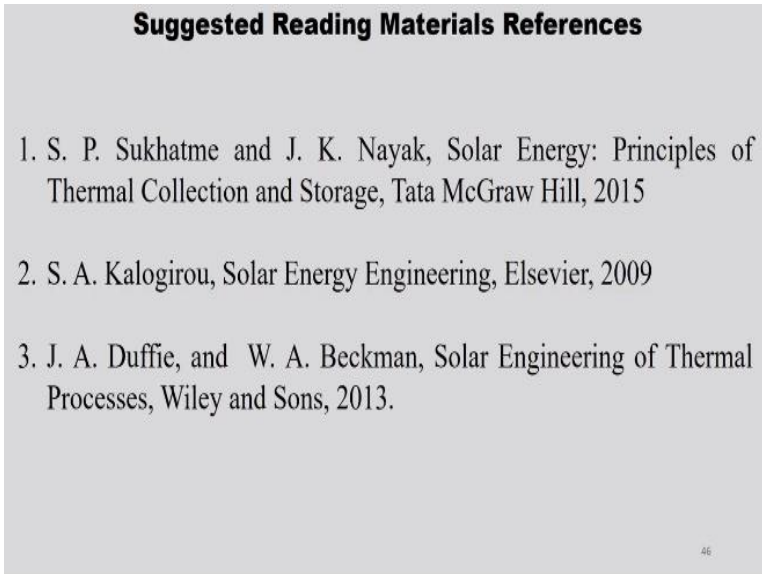

For today's lecture you can refer these books alright the thermal collection and storage unit which is nothing but a solar ponds. We will discuss in next lecture. Thank you.