Solar Energy Engineering and Technology
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Lecture - 29
Sensible Heat, Latent Heat and Thermochemical Energy Storage

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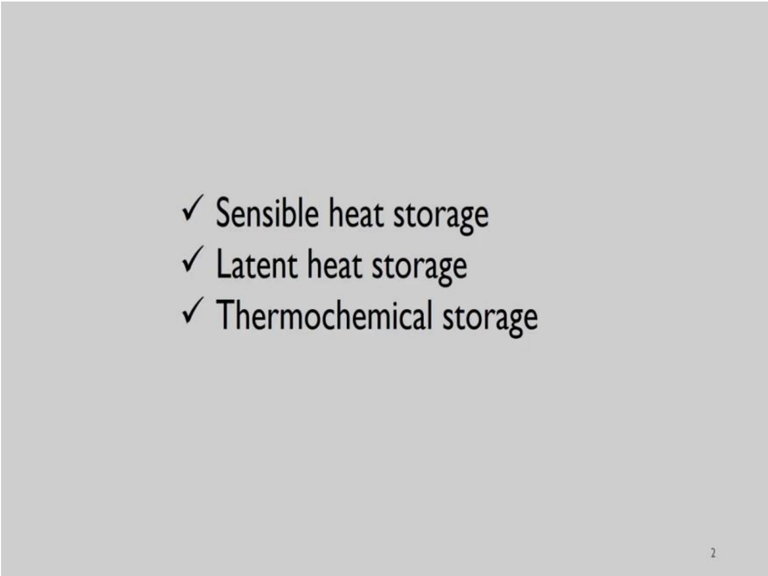

Dear students, today we will be discussing about thermal energy storage system, which includes sensible heat storage, latent heat storage and thermochemical storage system. So, before we study in details about these three technologies, let us learn the need of this kind of storage system.

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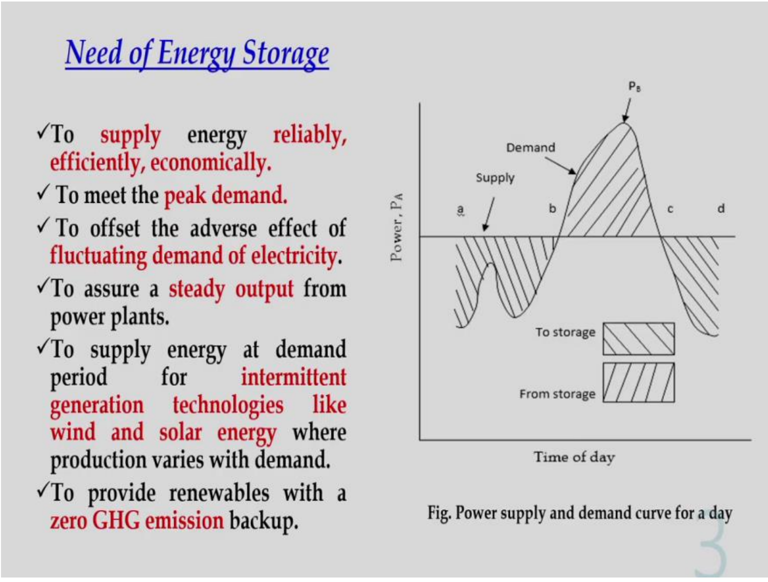

So, this includes to supply energy reliably, efficiently, and economically, first. Followed by to meet the peak demand. To offset the adverse effect of fluctuating demand of electricity. To assure a steady output from power plants, to supply energy at demand period for intermittent generation technologies like wind and solar energy, where production varies with demand. And to provide renewable with a zero greenhouse gas emission backup.

So, if we look into this figure, it tells about the relationship between power supply and demand curve for a day. So, as you can see, this constant line, which is parallel to the horizontal axis, it tells about the supply. Supply is fixed and then demand as you can see, it varies with time. So, at certain period of time, demand is very, very high than supply and certain period of time, the demand is lower than the supply. So, from this figure, we understand that in order to provide consistent power supply, we need to have a reliable storage system.

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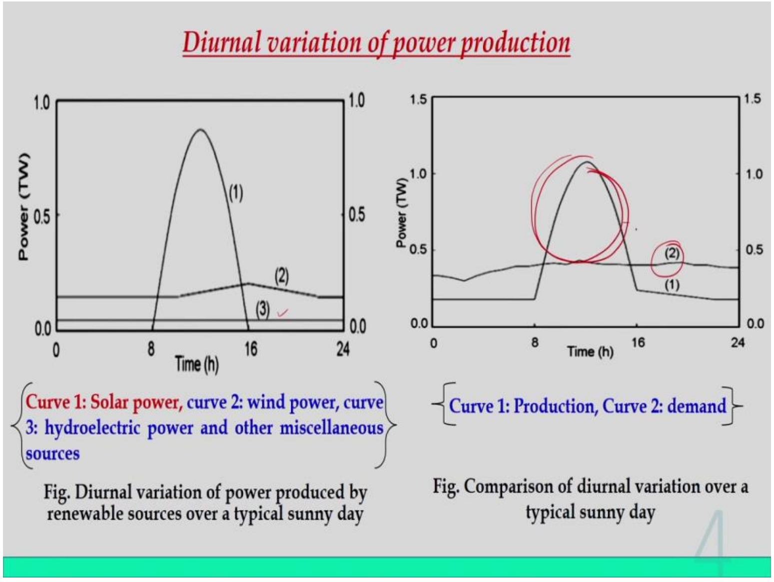

This figure shows the diurnal variation of power production by renewable sources over a typical sunny days. So, this 1 indicate the energy produced by solar energy and then, 2 marked in the curve shows the variation of energy generated by wind power and then 3 in the figure 1, shows about the power generation by hydroelectric power and other miscellaneous sources. So, this is more or less constant.

And as you can see, this variation of solar is increases and reaches a value at solar noon, and then it decreases. So, this window is from 8:00 to 4:00 p.m., so during that time, wind generation will be there. So, beyond that time, we do not have energy generation from wind energy. So, we need to store this energy to meet the demands at other periods.

So, next figure what is shown here is, the comparison of diurnal variation over a typical sunny days. So, one represents the production and then two represents the demand. So what you can see here, till 8 o'clock very nominal power generation or almost negligible. And then it reaches a peak in a solar noon and then it decreases and reaches a very minimal value at around say 4:00 p.m. on a particular day and then again decreases.

Now, what happens, if you look into the figure 2 or line 2, it shows the demand. So, demand is decreases sometimes, there is increases but more or less, it is constant. But here, supply is more, so if we can store this energy for certain period of time and that energy can be supplied to meet the demands for other time. So, that is a very good business. So, we will give more attention about this storage of energy.

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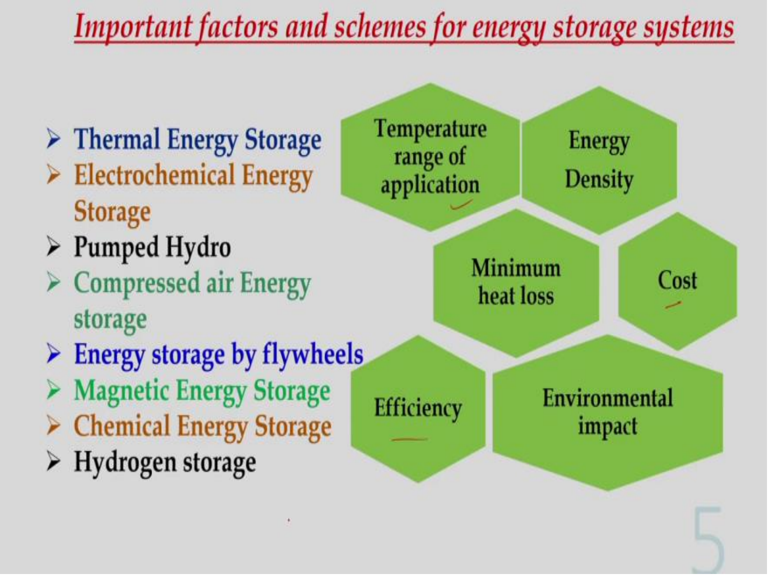

Now, let us pay attention about different schemes and what are different factors which influences the energy storage system. So, if we consider the factors, these are the factors which influences the performance of a energy storage systems. Like temperature range of application, then energy density, minimum heat loss, then cost, efficiency, then environmental impact.

So, what are the different schemes? We have, we have thermal energy storage, then electrochemical energy storage, pumped hydro energy storage, compressed air energy storage, energy storage by flywheels, magnetic energy storage, chemical energy storage and then maybe hydrogen storage. So, in our discussion today, we will emphasize on thermal energy storage.

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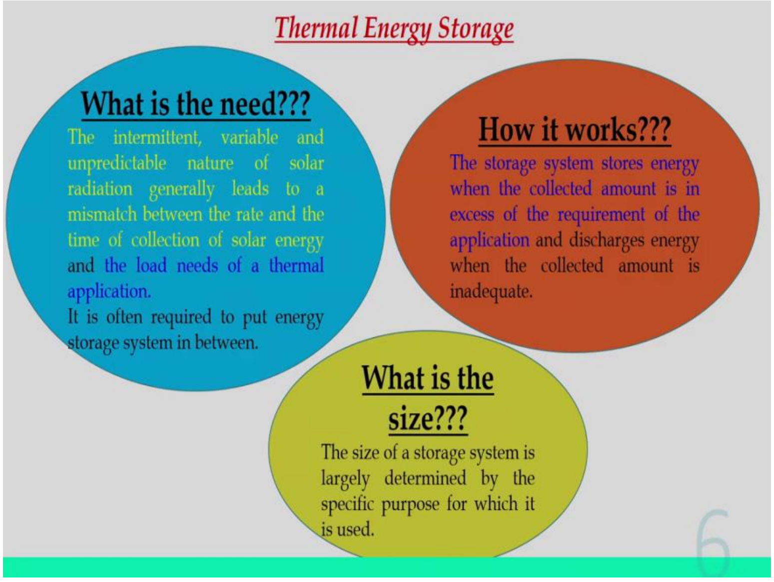

So, what is the need of this thermal energy storage system? As you have understand the background, now we will specifically study about thermal energy storage. The intermittent, as you can understand from the previous curves, the variable and unpredictable nature of solar radiation generally leads to a mismatch between the rate and the time of collection of solar energy and the load needs of a thermal application.

So, since there is a mismatch between the demand and supply, so we need to do something in between. So, it is often required to put energy storage system in between. So, the kind of curve, what we have discussed, that was purely on sunny days. So, if we consider on the cloudy days, as you can see, it is a lot of peaks and valleys, so we will not get a standard peak which has appear in case of sunny days.

Then for that condition, we need some kind of autonomy. So, how it works, the storage system stores energy when the collected amount is in excess of the requirement of the application and discharges energy when the collected amount is inadequate. So now, look into the sizing. So, the size of a storage system is largely determined by the specific purpose for which it is used, so kind of system or maybe the scale. So, if it is very large then we have to think of some other configuration. If it is very small then we have to think for another configuration.

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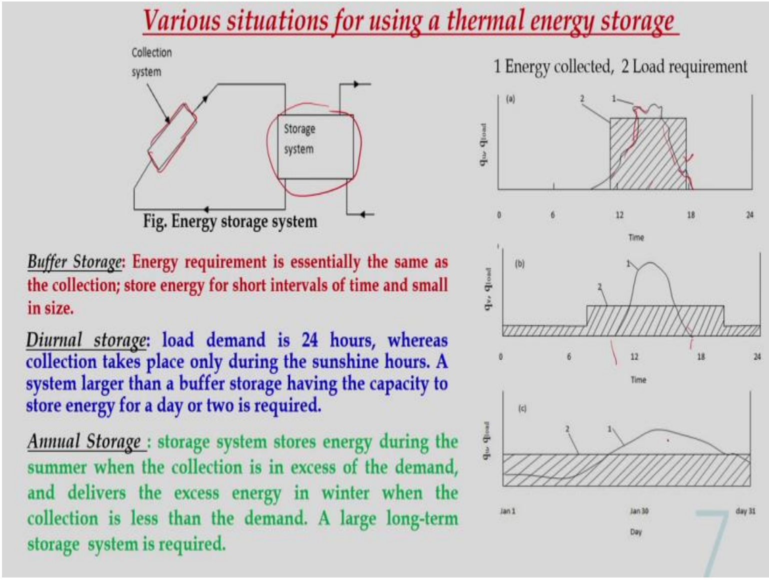

So, so what are different situations for using thermal energy storage? As you can understand now, if you consider this kind of system where one flat plate collector is involved where solar radiation is received and useful heat is generated and that can be stored at a particular time and whenever required that can be utilized.

So, there are different situations. Let us consider the first situations about buffer storage. As you can see in the figure for this buffers storage, here energy requirement is essentially the same as the collection. So, during this period, energy requirement is there, this shaded area and then this variation of energy collection is shown here. So, we are concentrated about this portion or this time only.

So, as you can see, this one means this is the portion where energy is collected and the shaded portion is the load requirement. So, store energy for short interval of time and small in size. Let us study the next situation, is the diurnal storage.

What happens, our energy collection is in this period and then requirement is throughout the day. So, for this kind of configuration, a system larger than a buffer storage having the capacity to store energy for a day or two is required. And the third situation is for annual storage, so long term storage is required. There are many configurations for long-term storage.

As far as thermal energy is concerned, this storage system store energy during the summer when the collection is in the excess of the demand and delivers the excess energy in the winter when the collection is less than the demand. A large long-term storage system is required for this kind of situation. As you can see here, so storage will be for six month and then delivery will be for another six months.

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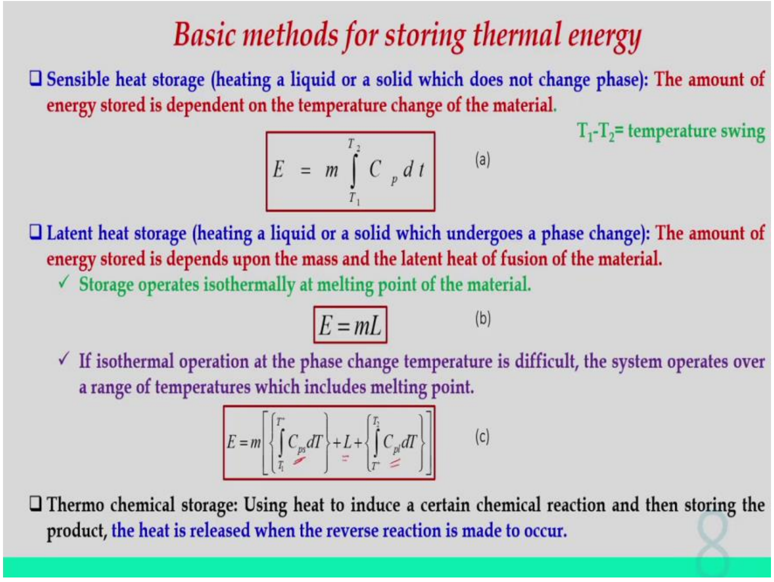

So now, let us study about basic methods for storing thermal energy. So, what are different methods? As you can understand now, so we have sensible heat storage, then we have latent heat storage, and thermochemical storage. So, for sensible heat storage, where there is no phase change occur, only temperature rise will be there. The amount of energy stored is dependent on the temperature change of the material.

So, if water need to be heated from say ambient, say, 20^{o} to maybe 70^{o}, so that range is nothing but sensible heat and the way we can store is known as the sensible heat storage. So, this can be represented by this. So, if E is the energy and m is the mass of the substance and temperature change is from T_1 to T_2 and C_p is the specific heat and that's a time. So, this T_1 minus T_2 is also known as temperature swing.

And the next situation is latent heat storage. So, heating a liquid or a solid which undergoes a phase change. The amount of energy stored is depends upon the mass and the latent heat of fusion of the material. So, mathematically, this can be represented by two situations. In the first situation, storage operates isothermally at melting point of the material.

Normally what happens, this isothermal condition cannot be achieved when we use sensible heat storage system. For in case of latent heat storage, we can provide isothermally, or constant temperature heat. And this can be represented by $E = m \times L$, m is the mass of the substance and L is the latent heat of fusion.

And the second situation is if isothermal operation at the phase change temperature is difficult, the system operates over a range of temperature which includes melting point, then mathematically we can represent something like this. So, m is common and then T_1 to T_2 is a first change. Maybe if we consider from, say, -15 to 0 and 0 to again, say, 60^o. So, 0 to 0 that phase from solid to liquid phase change will takes place. So, this L will come into play and then we will have this, again change of temperature from 0 to 60 and this is for specific heat of the solid, specific heat of liquid.

So, the final category is thermochemical storage. So, using heat to induce a certain chemical reaction and then storing the product, the heat is released when the reverse reaction is made to occur. So, that way, energy storage can be done.

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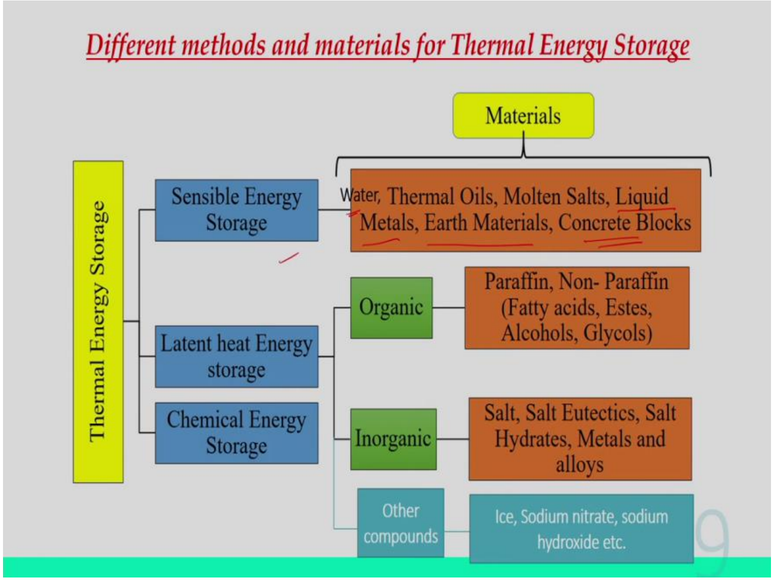

And if we see that the kind of material used for all these thermal energy storage system, we can see what are the different materials can be used for sensible energy storage. We can use variety of material like water, then concrete blocks for solids, and for high temperature application, thermal oils, molten salts, liquid metals, then earth materials.

And in case of latent heat storage system, we can have variety of substances. May be organic, maybe inorganic, or maybe other compounds. Under organic, we may have, paraffin, which is a very good phase change material; non-paraffin is also there like fatty acid, esters, alcohols, glycols. And under inorganic we will have salt, salt eutectics, salt hydrates, then metals and alloys. And for other compounds, we may have ice. So, ice can also be used as energy storage material. Then sodium nitrate, sodium hydroxide, and many more materials.

And for chemical energy, as we can see, there are different chemical reactions like methane reacts with water vapor, it produce hydrogen plus carbon monoxide. So that way, we can have reactions and that will be forward reaction and then backward reactions. That way, we can store the energy.

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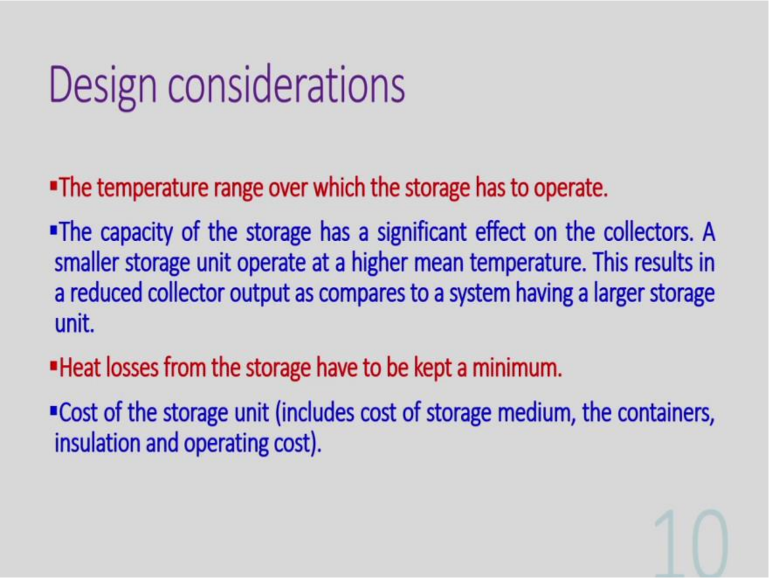

So, there are design considerations we need to follow like the temperature range over which the storage has to operate. So, when we have to design, first we should know at what temperature the system will operate. So accordingly, we will decide the kind of material to be used. The capacity of the storage has a significant effect on the collectors. A smaller storage unit operate at a higher mean temperature.

This results in a reduced collector output as compared to a system having a larger storage unit. And then heat losses from the storage have to be kept at a minimum value. And finally, we must see the cost, which includes cost of storage medium, the containers, insulation, and then operating cost. So, these are the design considerations.

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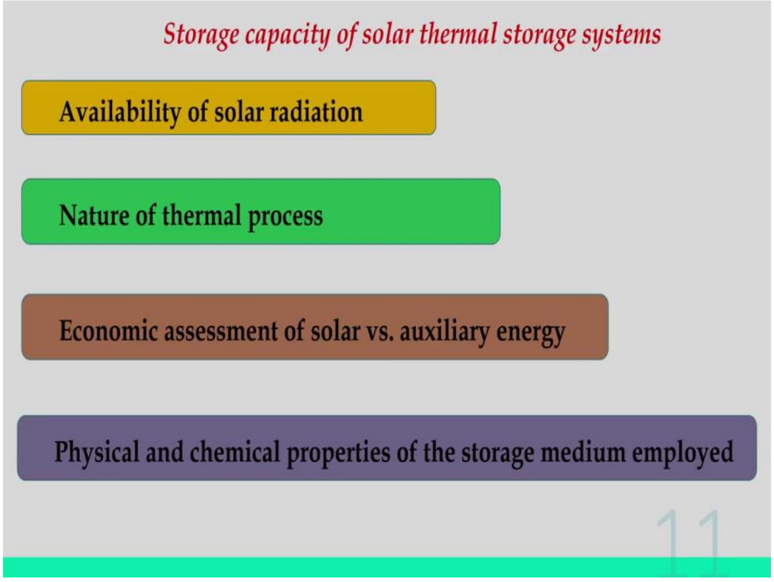

So, this storage capacity of solar thermal storage systems depends on availability of solar radiation, nature of thermal process, economic assessment of solar versus auxiliary energy, then physical and chemical properties of the storage medium, which are going to be employed.

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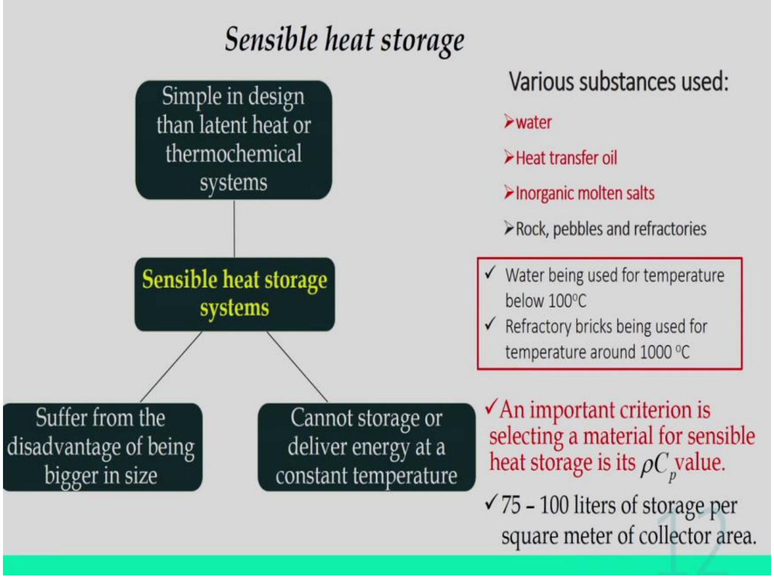

Now, come to the sensible heat storage system, which is simple in design than latent heat or thermal chemical storage system. But it has got some disadvantages, like it requires a bigger size of systems. And it cannot store or deliver energy at constant temperature, that is the major drawback.

And then what kind of material can be used as a sensible heat storage? First thing, if we talk about liquid then of course, we will go for water and if the temperature requirement is less than 100 °C. And if our temperature requirement is more than that, then we will go for other heat transfer fluids like oils, molten metals, inorganic molten salts. And sometimes, we can go for solid materials for sensible heat energy storage, like rocks, pebbles, and refractories.

For example, if we are interested to use water, then water being used for temperature below 100 °C. And if we are interest of to use the refractory bricks, then this refractory bricks being used for temperature around 1000 °C. That way, you can see the distinction between the use of liquid substance or use of solid substance for energy storage as far as sensible heat storage is concerned.

An important criterion for this sensible heat storage system is the selection of material for this storage, which is defined by ρC_p value. ρC_p is nothing but heat capacity of a particular substance. And for a system of having 1 m^2 collector area, we need to have a storage unit of about 75 to 1000 L. That means, if we have to store 75 to 100 L, then the collector size should be 1 m^2.

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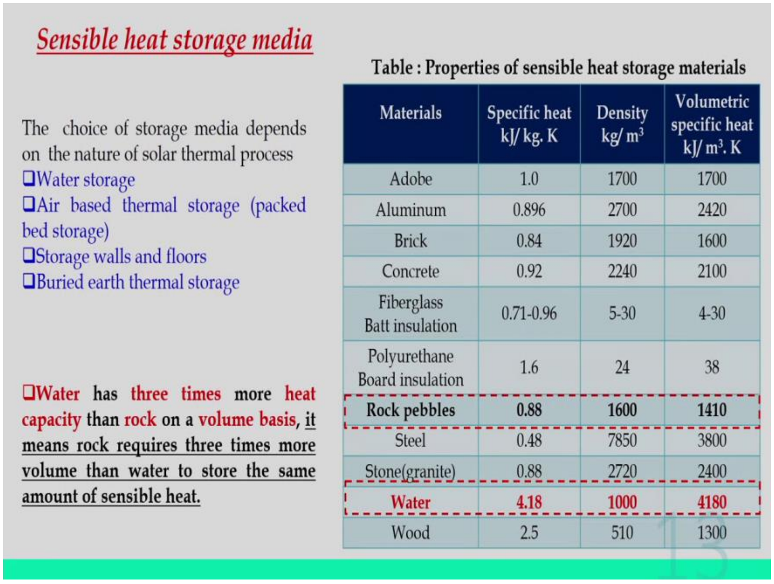

Materials	Specific heat kJ/ kg. K	Density kg/ m³	Volumetric specific heat kJ/ m³. K
Adobe	1.0	1700	1700
Aluminum	0.896	2700	2420
Brick	0.84	1920	1600
Concrete	0.92	2240	2100
Fiberglass Batt insulation	0.71-0.96	5-30	4-30
Polyurethane Board insulation	1.6	24	38
Rock pebbles	0.88	1600	1410
Steel	0.48	7850	3800
Stone(granite)	0.88	2720	2400
Water	4.18	1000	4180
Wood	2.5	510	1300

The sensible heat storage medium is very, very important. The choice of the storage media depends on the nature of solar thermal process. It maybe water storage, maybe air based thermal storage, which is done in packed bed storage, maybe storage walls and floors, maybe by earth thermal storage.

The table shown here is the properties of sensible heat storage material. Different kinds of materials are used for storage of energy. So, first column is the material, second column is the specific heat, and third column is density. So, if we multiply the specific heat then density, it becomes heat capacity. So, that is a volumetric specific heat, which is represented by kJ/m^3 K.

So, in this case, if we compare two substances, like rock pebbles and water, so if we see the properties, in case of rocks pebbles, specific heat is about 0.88, and density is about 1600. If we multiply these two then what we will get is 1410. So, in case of water, specific heat is 4.18 and the density is 1000, if we multiply this will become 4180.

So now, if we look at this value, 1410 for rock pebbles and 4180 for water, so if we divide 4180 by 1410 is about 3 times. So, that means what, this water has 3 times more heat capacity then rock on a volume basis. It means, rock requires three times more volume than water to store the same amount of sensible heat. So, this is important observations that tells about the kind of or size of vessel required for storage of same amount of energy.

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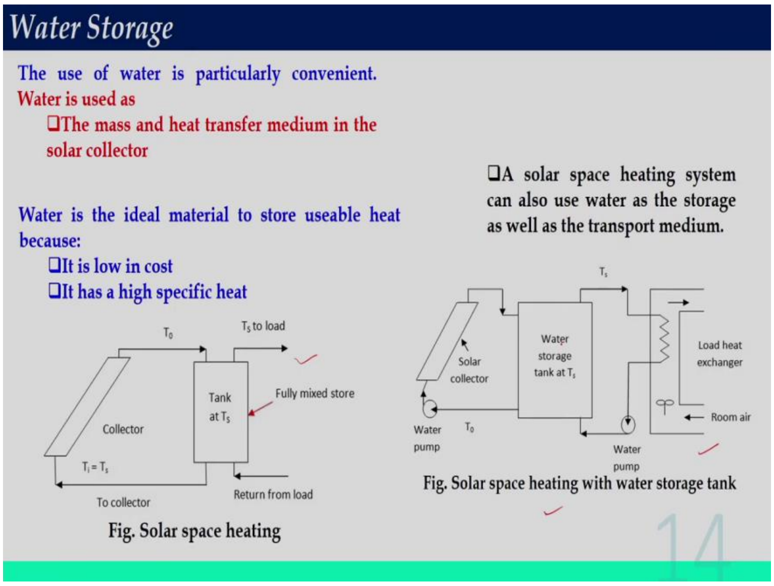

So normally, water is used in most of the cases and this water is used as heat and mass transfer medium in the collector. And also it is used because, it is low in cost and has a high specific heat. So, these are the configurations by which solar energy can be stored in a storage tank and that can be used based on the applications.

So, second figure, what is shown here is solar space heating with water storage tank. So here, this is a solar collector, and we have a storage tank, and finally, we can have this room heating arrangement. So, a solar space heating system can also be use water as the storage as well as transport medium.

So, this collector is liquid flat plate collector. So sometimes, we will discuss about solar air heater. So, air will introduce and then that air will be stored in a packed bed and that can be applied for other applications.

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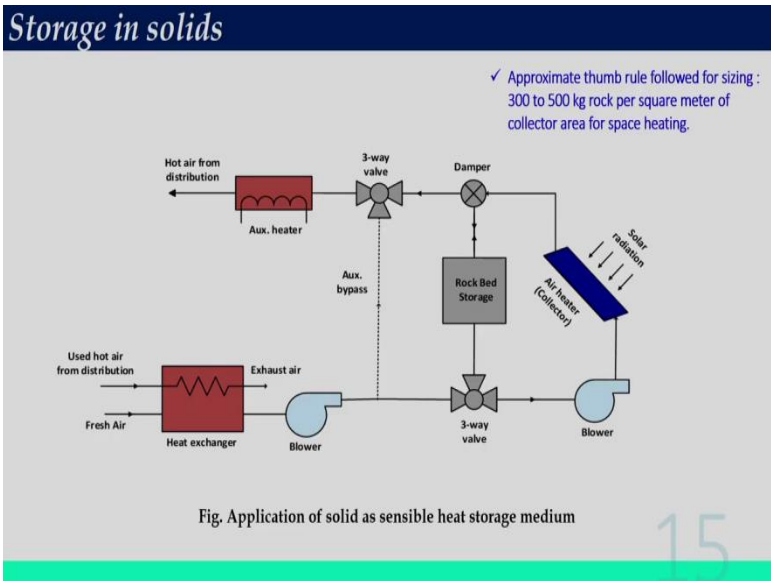

So, this is the case what we are discussing about. So here, this is our solar air heater where air is heated and that can be stored in a rock packed, or rock bed storage, that is a packed bed. And whenever required, that can be used based on the applications.

So, as a thumb rule, as far as sizing is concerned, about 300 to 500 kg rock per m^2 of collector area for space heating is required. So, we must know the quantities of rock required for this kind of heating applications.

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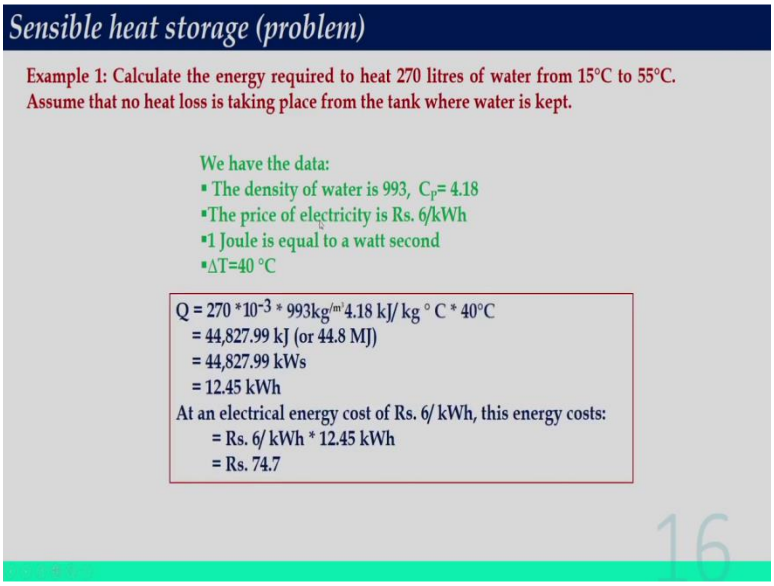

Now, we will discuss one very basic problem, how this sensible heat storage can be calculated. So, calculate the energy required to heat 270 L of water from 15 to 55 ^{o}C, assuming that no heat loss is taking place from the tank where water is kept. So, values given are density of water is 993, Cp is 4.18 kJ/kgK, price of the electricity is 6 kWh; then 1 J= 1 Ws. And ΔT = 40 ^{o}C.

So, Q can be calculated by $mC_p\Delta T$. So, this is 270 L$\times10^{-3}$ again this 993 kg/m^3. And if we multiply with 40, then what we will get, is the amount of heat stored that is 12.45 kWh. So, as you know, the price of electricity is Rs 6 per kWh then at an electrical energy cost of 6 Rs per kWh, this energy cost will be about 74.7 Rs.

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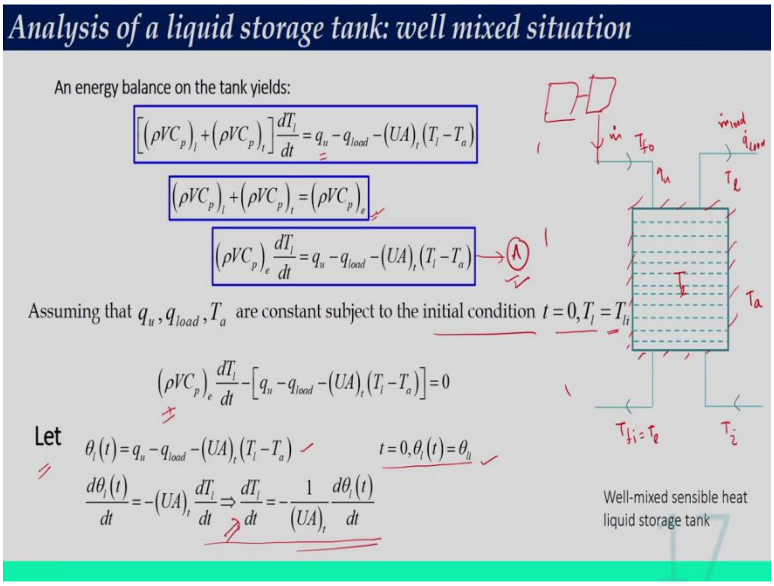

Now, we will analyze one very important aspects of well mixed storage tank. So, what does it mean? So, this is a liquid storage tank. So, this is insulated tank, where liquid is placed inside the tank. So, let the tank is at T_l and say, for example, these are the arrays of collectors. These are connected in series and parallel to achieve to a required temperature and that is supplied to this storage tank, and let $\dot{m}$ is the mass of the water, which is introduced in the tank. And this is coming from the collector.

And maybe this T_{fo} is the fluid outlet temperature of the collector which is introduced in the insulated tank. And this $T_{fi} = T_l$, which we will introduce again into the collector. And maybe $\dot{m}_{load}$, I will write, which is connected to the load, so that we can use it. And this may be T_i, and T_a is the ambient temperature and this temperature is at T_l. So here, T_l is the delivery temperature.

So, well mixed situation means, here it is assumed that temperature of the fluid is at T_l. There is no variation of the temperature. Now, if I am interested to develop an energy balance on the tank, then how we can write it? So, this $(\rho CpV)_l$, this is for liquid and (ρCpV) for the tank. If tank is very large, then we need some kind of angles to attach to hold the structure. So, heat capacity of those structures or angles need to be considered.

So, dT_l/dt because this will vary with time and then q_u is the useful heat gain. So, this is q_u, which is coming from the collector and I can write this as q_{load}, q_{load}, when required we can again collect it from the storage tank. And UA is the overall heat transfer coefficient which is multiplied by the area of the tank. And T_l is the temperature of the fluid and T_a is the ambient temperature.

So, these two can be coupled and we can give an effective. So, which combines both, the $(\rho C_p V)_l$ and $(\rho C_p V)_t$. And this can be represented by $(\rho C_p V)_e$, equivalent. So, this can be reduced to this form. So maybe, I can give an equation name, maybe A. And these equations need to be solved by using this initial conditions.

So, at T = 0, this $T_l = T_{li}$. At initially, the condition is something like that. And if we rewrite this equations, it will be something like this and if we define it a term, $\theta_l(t) = q_u - q_{load} - (UA)_t (T_l - T_a)$, and we use the initial conditions at T = 0, $\theta_l(t) = \theta_{li}$. Then if we differentiate with respect to time this equation, then we will get this kind of expression. Now, what we will do, we will substitute this dT_l/dt here in the equation A. Then let us see how we can get the solution of this ODE.

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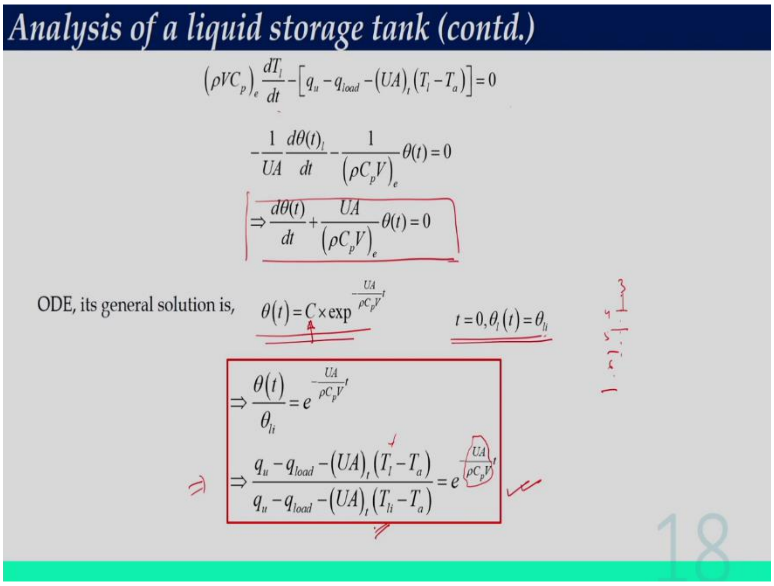

So, on substitution, we will get this expression. And then finally, we will have this expression. And this is nothing but a ordinary differential equation. And we will get the solution of something like this. And this constant value can be calculated by using the initial conditions. So, at T = 0, this exponential of 0, it will be 1. So, C = θ_{li}.

So, if you substitute here, then what we will have, so we will have this kind of solution of the ODE. Now, this expression is very important. So, we need to find out the T_l value at different time. So, if we start, say for example, say morning 3 o'clock, we have started something and we are interested to know the T_l value after every 1 hour; say, 4 o'clock, 5 o'clock, 6 o'clock. Then know, we need to use this expression for calculation of temperature at different times. Because these values will be constant. And T is, for this case, it will be 1 hour. So, from that we can calculate, what will be the value of T_l, since we know T_{li} and T_a.

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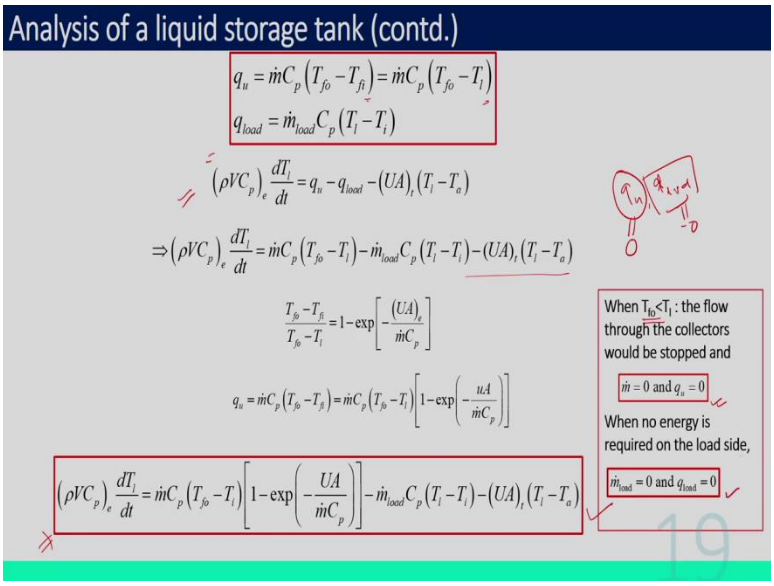

Now again, we can relate this q_u and q_{load} with respect to inlet and outlet fluid temperature. So, $q_u = \dot{m}C_p\left(T_{fo} - T_{fi}\right) = \dot{m}C_p\left(T_{fo} - T_l\right)$. And $q_{load} = \dot{m}_{load}C_p\left(T_l - T_i\right)$. So, T_l maybe T_a. So that way, we can relate this q_u and q_{load} in terms of inlet and outlet fluid temperature.

So, if we recall the expression, if we substitute then we will get this expression. And this expression you will get first and then if we substitute these values, then it will be something like this. And then finally, our expression in terms of this fluid inlet and outlet temperature, it will be something like this.

So, with this knowledge, let us solve one numerical problems on this well mixed tank when temperature is fixed. And also, one more observation; sometimes what happens, this q_u and q_{load} maybe 0 when no heat is required. Then this $q_{load} = 0$. If no useful heat gain is there from the collector array, then this will be 0. Then what happens?

When $T_{fo} < T_l$, the flow through the collector will be stopped, and $\dot{m} = 0$ and $q_u = 0$. So, this the condition at which $q_u = 0$, if $T_{fo} < T_l$. And when no energy is required on the load side; that means $q_{load} = 0$ and $\dot{m}_{load} = 0$. So, these conditions are required to understand the different situations.

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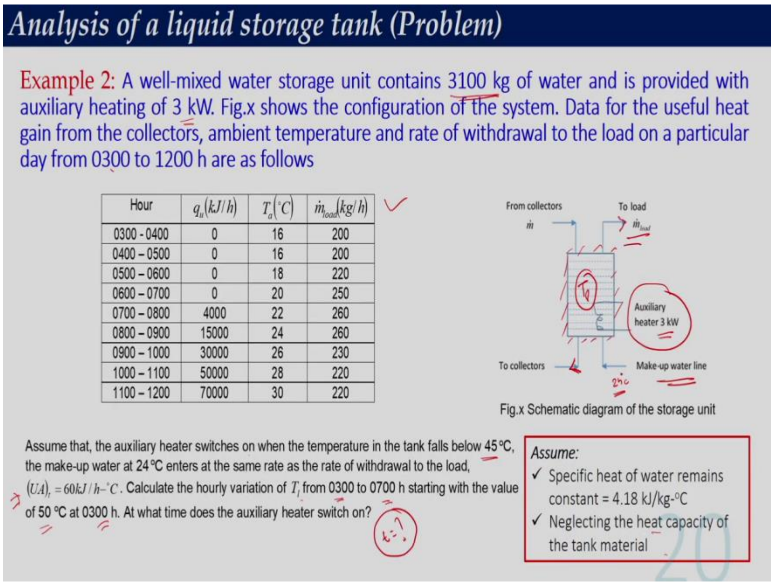

So, this problem goes something like, a well mixed water storage unit, means that T_l, if you consider is T_l, T_l is constant for 1 hour duration, contains about 3100 kg of water. And is provided with auxiliary heating of 3 kW. So, this 3 kW auxiliary heating is given here. So, figure x shows the configuration of the system. So, $\dot{m}$ is the mass flow rate from the collector and introduced in the tank.

So of course, this is insulated tank and no heat loss is taking place, ideally. Of course, practically, some heat loss will be there. And this makeup water line is here, and it goes something like this and it is a $\dot{m}_{load}$.

So, data for useful heat gain from the collector ambient temperature and rate of withdrawal to the load on a particular day from 3 o’clock to 12 o'clock are as follows. So, this data is given. So, q_u = 0 from 3 to 4, because collector will be off at that time, no solar radiation will be there, so this q_u = 0. So, till this 7 o'clock q_u = 0, and T_a how it varies it is given here, and $\dot{m}_{load}$ is given because system is on.

Assuming that the auxiliary heater switch on when the temperature in the tank falls below 45 °C. The makeup water at 24 °C enters at the same rate as the rate of withdrawal to the load. So, means that is entered at 24 °C and this same rate, this heat is collected. And this value, overall heat transfer coefficient multiplied by area is given as 60 kJ/hr °C. And now, we need to calculate the hourly variation of T_l from 3 to 7 hour starting with the value of 50 °C at 3 hours. So, at what time does the auxiliary heater switch on?

So, we need to find out the time, when this auxiliary heater need to turn on. This is quite interesting problem and very very practical. And we need to assume the specific heat of the water remains constant, because temperature variation is not much and neglecting the heat capacity of the tank material.

So here, we are not considering the tank material even though, it requires some kind of angles to hold the structure. So, we are not considering that. Of course, we can consider, so just so we need to add this component in the heat capacity part. But now, for the time being, we are not considering it.

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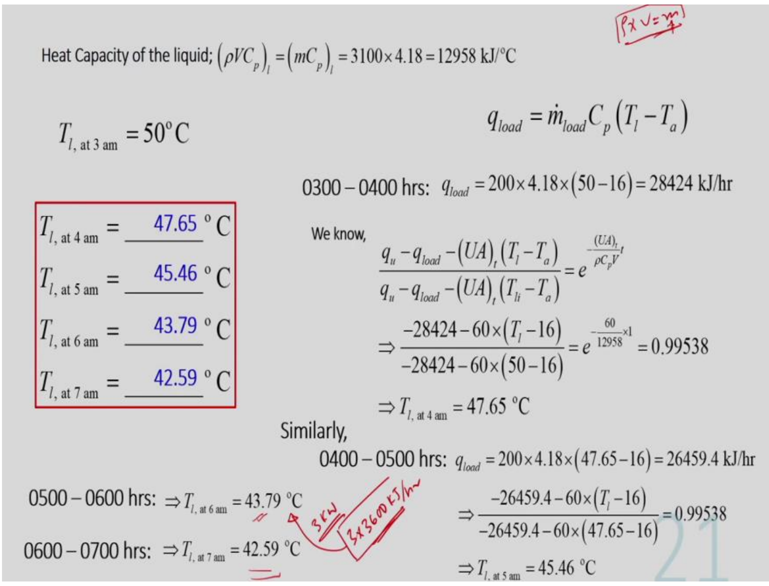

Now here, in this case, the heat capacity of the liquid can be calculated by $(\rho C_p V)_l = (\dot{m} C_p)_l$, because ρ×V is nothing but mass. Since mass is known to us, so that is why, ρ×V=m is considered in this problem. So, this m is 3100 multiplied by specific heat is 4.18, so it is comes around 12958 kJ/°C.

So, what is given to us? The temperature at 3 a.m. is 50 °C. So, what we need to calculate? At different times, at 4 a.m., 5 a.m., 6 a.m., and 7 a.m. So, in order to find out temperature at 4 a.m., so first we need to calculate what is load. So how to calculate the load? $q_{load} = \dot{m}_{load} C_p (T_l - T_a)$. T_l is the liquid tank temperature and T_a is the ambient temperature.

And if you consider this range, 3 to 4 hours, q_{load} can be calculated something like this. Because this value is known to us, 200 kg/hr and 4.18 is the Cp value and this is the temperature difference. 50 is the T_{li}; initially, it is given as 50 ^oC, so 50 is considered here, minus 16 is the ambient temperature. So, this is found to be 28424 kJ/hr.

Now what is next? We know the solution of this problem is something like this and we can substitute the values. So, at this time, $q_u = 0$, so because of that $q_u = 0$, here not considered. And q_{load} we have calculated, we have substituted here. And $(UA)_t$ is given to us, this is 60, and $(T_l - T_a) = 16$, and this values are known, because $T_{li} = 50$. And we can substitute the values here. And this is also known UA, $\rho C_p V$, these values are known. And this t = 1 hour, so this will be about 0.99538.

So, only unknown is T_l. So, this calculation is 4 a.m. So, T_l at 4 a.m. will be 47.56 ^oC. Similarly, we can do the calculations, for 5 a.m., what will be the temperature? So, for 4 to 5 hours, q_{load} the can be calculated based on the data given to us. And also, we can use the similar expression and we can get the value of temperature at 5 a.m., which is equal to 45.46 ^oC.

So, this is very close to 45. So, we need to find out at what time our heater has to be turn on. So first, we need to calculate in the next step, what will be the T_l at 6, then we have to rectify it, the correct values of T_l at 6. So here, so after corrections, what we get is 43.79. So, what I mean to say, when we do the calculation for T_l at 6, then we have to confirm that, know what is the temperature. Once it is found that, it is less than the temperature 45 ^oC at which heater has to be turn on, then it is confirmed that we need to turn on the heater after 5 hours.

So that way, we need to find out what will be the value of T_l exactly at 6 a.m. while considering the 3 kW heater when it is turn on, 3 × 3600, this will be kJ. So that, we need to add or which will be hour. So, that you need to add in the q_u part and then we have to do the calculation. And once you do the calculation, then what we will get, a value T_l at 6 a.m. will be 43.79. So, then at 7 a.m., similarly, we can do the calculations and the value found to be 42.59 ^oC.

So, what we got now, T_l at 4 a.m. is 47.65 ^oC; at 5 a.m. 45.46 ^oC; at 6, 43.79 ^oC; at 7, 42.59. So, it is confirmed that heater has to be turn on in between 5 to 6. Then we have to find out the exact time, at what time we need to turn on the heater.

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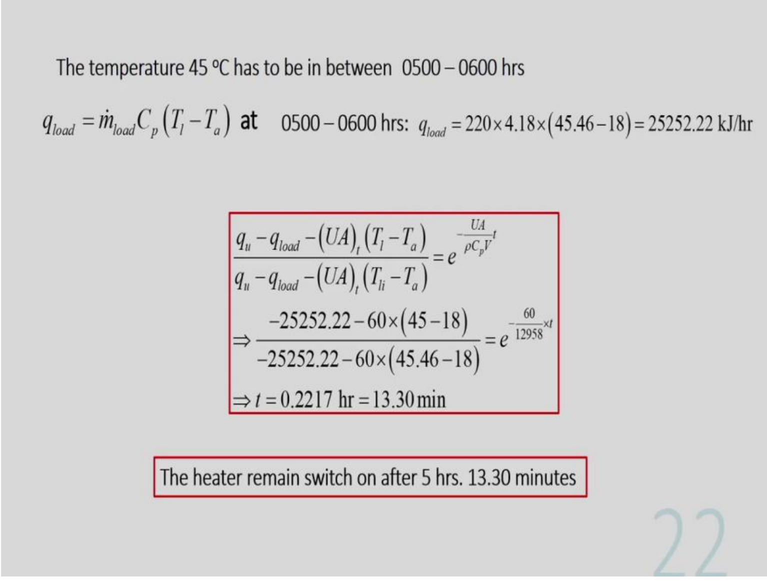

So, the temperature 45 °C has to be in between 5 to 6 hours and we need to find out the q_{load} by using this expression between 5 to 6 and it is found to be about 25252.22 kJ/hr. So, we can find out the time.

So now, these values are known. All these values are known because this is 45 T_l, T_{li} = 45.46; previous values we need to consider and then from that we can calculate what is the value of T, which is equal to 13.50. So, this heater will be remained turn on after 5 hours 13.30 minutes. So, once we are done with this, then we can calculate the timing, means what is the temperature for T_l 6 and T_l 7.

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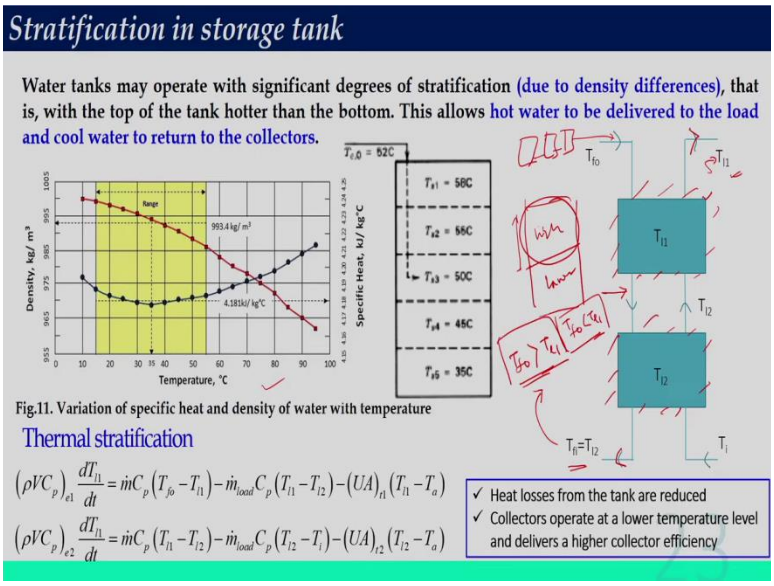

So now, let us consider the case for stratification in storage tank. This water tanks may operate while significant degree of stratification due to the density difference, that is, with the top of the tank hotter than the bottom. This allows hot water to be delivered to the load and cold water to return to the collector.

Normally, what happens in case of flat plate collectors, when storage is there, so in the storage in the upper portion hot water will be there, in the lower portion of cold water will be there. So, if we can take the hot water which is required say at say 45 ^oC, so at 45 ^oC, it is closer to the utility and maybe ambient, maybe 20 ^oC or 30 ^oC, which is at the bottom, which can be circulated in the flat plate collector.

So that way, if this temperature is significant or temperature difference is significant, that is required temperature and then ambient temperature, so then this stratification is very, very important. And this plot shows the variation of density with temperature and variation of specific heat with temperature. As we can see, density is decreasing with increasing temperature, but specific heat is increasing with increasing temperature. That means if we have to operate at higher temperature, then mC_pV will be higher or that way, our losses will be more.

Now, if we analyze this thermal stratification process, so we can analyze by making two different well stirred tank, or well mixed tank. Normally what happens, when we are talking about stratifications? If we take a single tank, so maybe in the upper portion having higher temperature and this is the lower temperature. So, analysis is very complex. So, in order to make the analysis very, very simple. So, it is divided into two part. Then upper part is the hot part, this is something like this, of course, this is a insulated tank. And this is normally installed near to the utility point, because T_l is the required temperature or T_{l1} is the required temperature. And this is the lower part.

So here in this case, these are the arrays of flat plate collectors and it is introduced here and it fills the hot water. And then in goes down and finally, this T_{fi} is nothing but input to the flat plate collector. So, these two are well mixed tank and utility is near to this upper tank, which is delivered at a temperature of T_{l1} which is higher than this T_{l2}.

So, we can use this kind of expression for solving T_{l1} and T_{l2}. So finally, we can get solution for T_{l1} and T_{l2}. So in this case, only what we have considered, fluid is introduced from the top of this arrangement. So what happens here, this is $T_{fo} > T_{l1}$. So, this phenomena will active when $T_{fo} > T_{l1}$, then this will be receiving the heat. This tank is receiving the heat from the source. And if $T_{fo} < T_{l1}$, no heat flow will be there from the source.

So, we can make this kind of arrangement here also. We can have some kind of inlet in this portion also. So, under the conditions, we have to use different approach for calculation of, or development of the conditions for usability. So, what benefit we will get by doing this? Heat losses from the tank are reduced and these collectors operate at a lower temperature level and delivers a higher collector efficiency.

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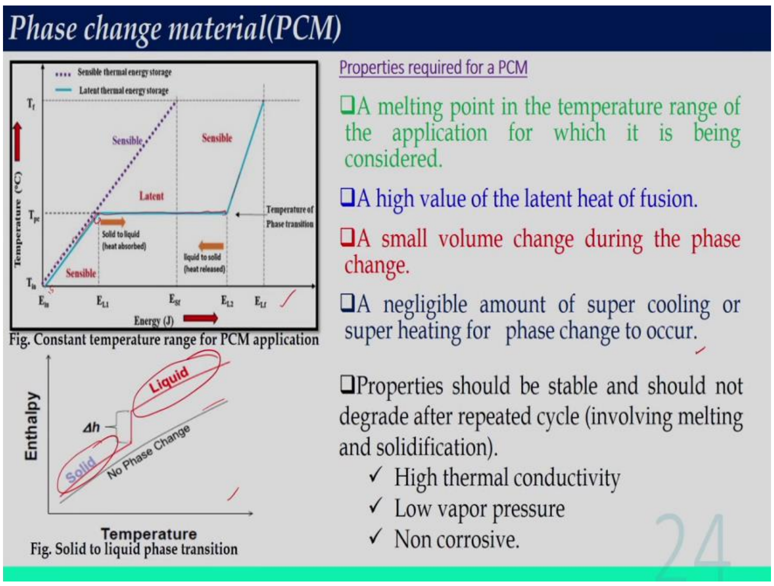

So, now come to the phase change material. Here what we can see in the first figure, so this dotted line shows the sensible heat storage system. So, there is no change of phase. So, if we look into this blue colored line, so first, this is similar to the sensible heat storage and then phase change will be there. So this may be, if you consider, say, ice at -15 to 0, it will go something like this; from 0 to 0, solid to liquid, and it will go something like this. And then from 0 to maybe 50 or 60, it will go something like this. So, that is how it works.

And this plot shows the enthalpy versus temperature. So, if no phase change is there, then it will go something like this and if there is a phase change at certain temperature, so this much of enthalpy rise will be there. This is something called latent heat of fusion. And then again, it will go something like, and this part was solid and other part is liquid.

So now, the kind of material which is used for phase change applications, it has got some kind of properties. So, these properties are something like, a melting point in the temperature range of the application for which it is being considered. Say, for drying of paddy, we need to maintain at, say, 60 ^{o}C. So, accordingly, we need to find out, which PCM best for depth temperature range.

So, at that temperature range, that has to melt so that that latent heat of fusion can be transferred to the paddy for drying. A high value of latent heat of fusion is always important or required. A small volume change during the phase change is important because if we make a tray and if volume change is taking place significantly, then it will be very difficult to accommodate. So, this is one of the very important properties of a phase change material.

A negligible amount of super cooling or super heating for phase change to occur, this is also important. The properties should be stable and should not degrade after repeated cycle. Like this cycle involves melting and solidification. So, this includes high thermal conductivity, low vapor pressure and non corrosive. So, these properties are very important for a phase change material.

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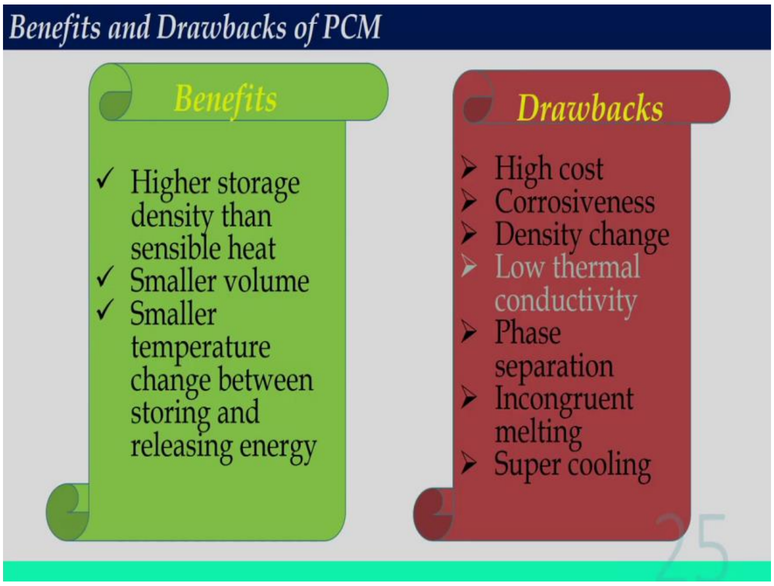

What are the benefits and drawbacks of PCM? So, this benefits includes higher storage density than sensible heat, smaller volume, smaller temperature change between storing and releasing energy. So, drawbacks are high cost, corrosiveness, then density change, low thermal conductivity, phase separation, and incongruent melting, that is not uniform, melting is there, then super cooling; before it reach, the cooling is also taking place.

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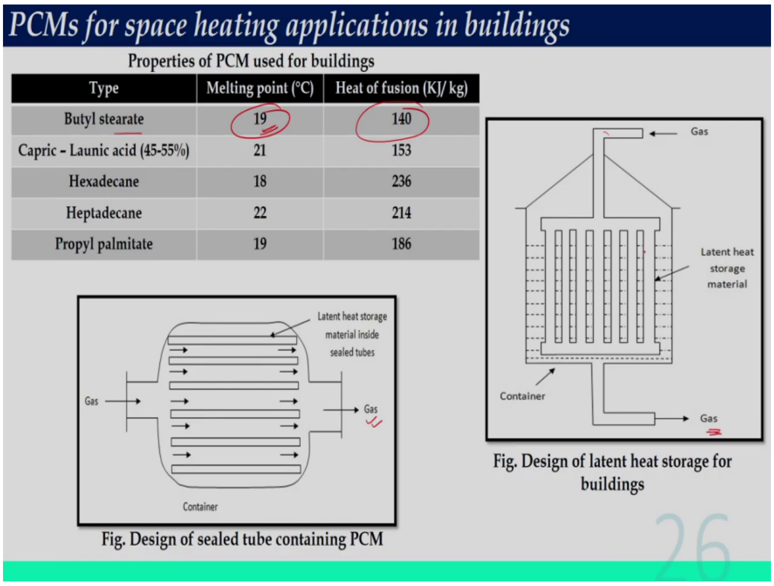

So, this table shows the properties of PCM used for thermal comfort in buildings. So, these are the different types of PCM used for building. Suppose we need to maintain at, say, $20\ ^{o}C$

or 21, then we need to go for this kind of materials, butyl stearate. So, where melting point is about 19 and then heat of fusion is about 140.

So that way, we can decide, the kind of material to be used for a specific application. This table shows different scopes of utilizing the material based on the availability and we can have different configurations for using this PCM. This may be horizontally we can feed it, so gas introduced here and then PCMs are placed in the tubes, so heat exchange will takes place and finally, we will have different heat at outlet and then at the inlet.

And also, we can have this kind of configurations. So, gas inlet is from the top and it moves around the tubes and then gas can be collected at the bottom and PCMs are placed inside.

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PCM options

	Compound	Melting temperature (°C)	Heat of fusion (KJ/ kg)	Thermal conductivity (W/ m . K)	Density (kg/ m3)
Inorganic	$MgCl_2.6H_2O$	117	168.6	0.057(liquid, 120 °C) 0.694 (solid, 90°C)	1450 (liquid, 120 °C) 1569 (solid, 20°C)
	$Mg(NO_3)_2.6H_2O$	89	162.8	0.490(liquid, 95 °C) 0.611(solid, 37°C)	1550 (liquid, 94 °C) 1636 (solid, 25°C)
	$Ba(OH_2).8H_2O$	48	265.7	0.653(liquid, 85.7 °C) 1.225(solid, 23°C)	1937(liquid, 84 °C) 2070(solid, 24°C)
	$CaCl_2.6H_2O$	29	190.8	0.540(liquid, 38.7 °C) 1.088(solid, 23°C)	1562(liquid, 32 °C) 1802(solid, 24°C)
Organic (paraffin) ★	Paraffin wax	64	173.6	0.167 (liquid, 63.5 °C) 0.346(solid, 33.6°C)	790(liquid, 65 °C) 916(solid, 24°C)
	Polyglycol E600	22	127.2	0.189(liquid, 38.6°C)	1126 (liquid, 25 °C) 1232(solid, 4°C)
Organic (non-paraffin)	Palmitic acid	64	185.4	0.162(liquid, 68.4°C)	850(liquid, 65°C) 989(solid, 24°C)
	Capric acid	32	152.7	0.153(liquid, 38.5°C)	878(liquid, 45°C) 1004(solid, 24°C)
	Caprylic acid	16	148.5	0.149(liquid, 38.6°C)	901(liquid, 30°C) 981(solid, 13°C)
Aromatics	Naphthalene	80	147.7	0.132(liquid, 83.8°C)	976(liquid, 84°C) 1145(liquid, 20°C)

And also, there are different components, different compounds which are normally used to for phase change applications. So, it’s a exhaustive list what you can see here. So, different compounds; this is inorganic compounds, then we will have organic paraffin, which include paraffin wax and poly-glycol E600. Then, we will have organic non-paraffin compounds, palmitic acid, then capric acid, and caprylic acid, and then we will have aromatics.

So, you can see the range of melting temperatures and then heat of fusion. So, based on the requirements, we can select the best material to meet the demand.

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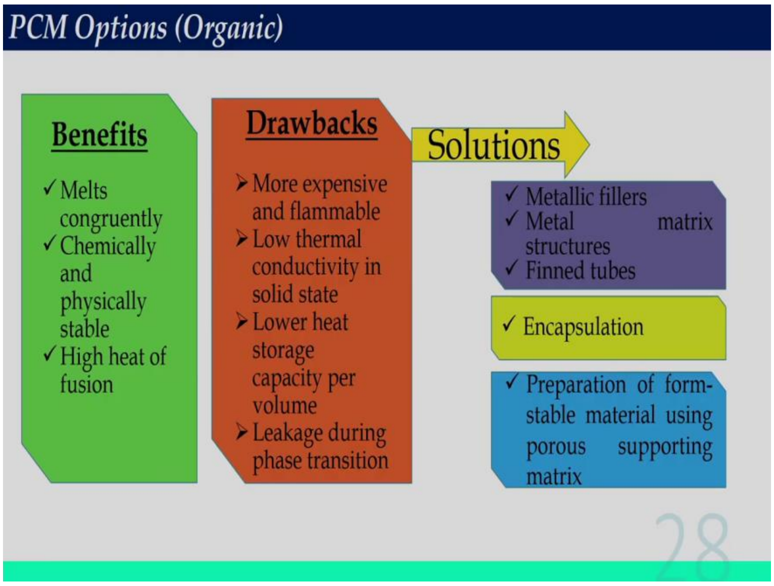

Now, let us pay attention about organic PCM, what are benefits and demerits. So, it melts concurrently, and chemically and physically stable and high heat of fusion in case of organic material. And drawbacks are more expensive and flammable, and low thermal conductivity in solid state. And lower heat storage capacity per volume. And leakage during phase transition. These are some of the drawbacks.

And how to mitigate those drawbacks, we have options or solutions. The solutions are something like metallic filters, then metal-matrix structures, we can make; fin tubes, we can make; encapsulation is a solution and preparation of form-stable material using porous supporting matrix. So, these are the solutions to use organic PCM.

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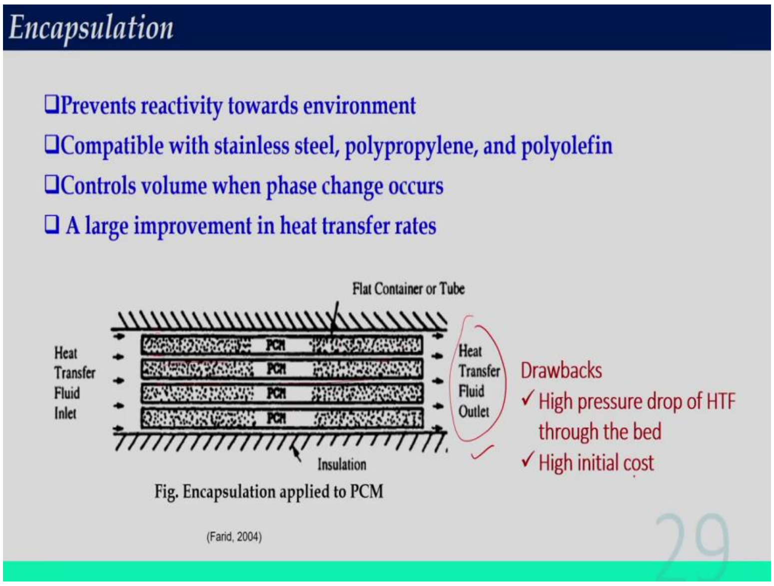

So, encapsulations is done to prevent reactivity towards environment. Then compatible with stainless steel, polypropylene and polyolefin. Controls volume, when phase change occurs, which is very, very important. A large improvement in the heat transfer rates, if we make this kind of arrangement.

So, this figure shows about the arrangement. Heat transfer fluid inlet, you can see in arrows. So, these are channels through which the flows and these are the encapsulation. So, PCMs are contained in this tube, so we can get the heat transfer outlet here. And again, we will have drawbacks like, for this kind of arrangement, high pressure drop of heat transfer fluid through the bed and then high initial cost. So, these are drawbacks that this kind of system have.

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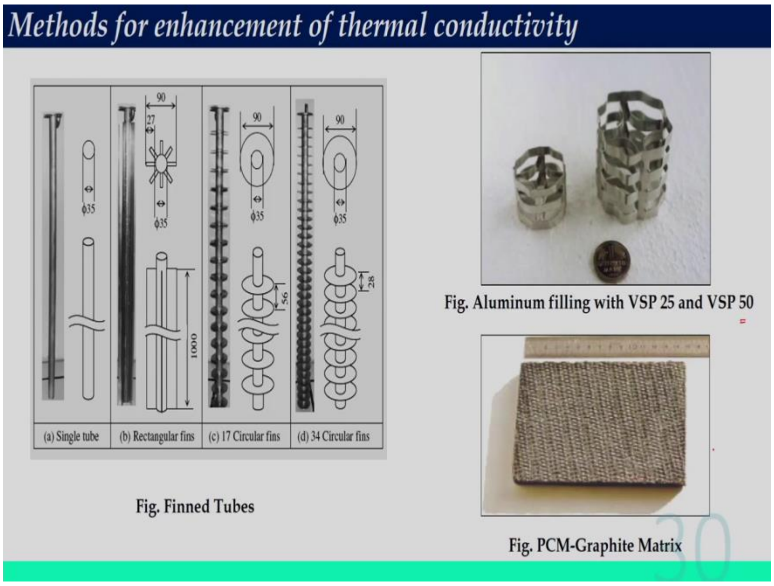

And also, there are different other enhancement method like finned tubes. So, this kind of fin, we can make and we can insert there, to increase the thermal conductivity of the system or maybe effectivity of the PCM system.

And also, this aluminum filling with VSP 25 and VSP 50 are also seen. This VSP means Vegetative Storage Protein, and this 25 is 25 kD and this is 50 kD; that is why is the name. And this kind of matrix, graphite matrix with PCM is also in practice.

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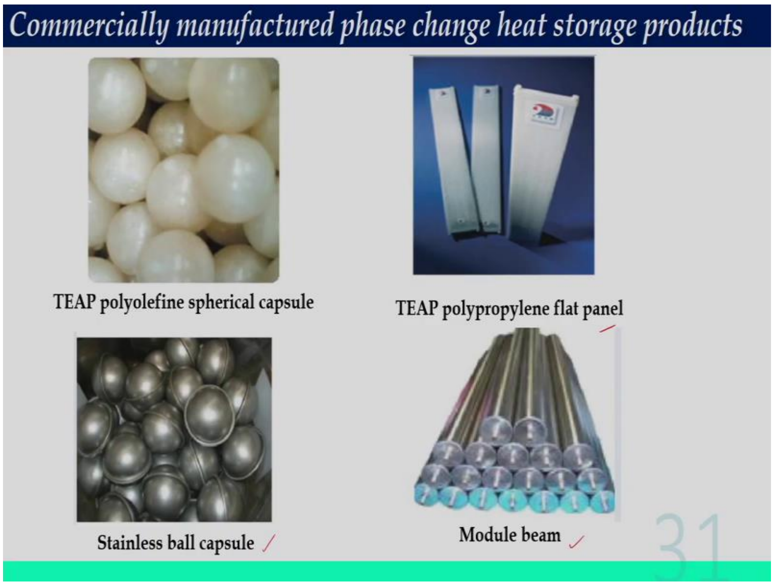

And this kind of systems, thermal energy encapsulations, polyolefin spherical capsules are also available. So, this can be used in packed beds. So, these are introduced there and then air is introduced from the bottom and heat exchange will takes place. These are found to be very, very effective and these are stainless steel balls. And this is polypropylene flat panels and we have module beams.

There are many configurations based on the applications, which are already in the market. But we need to compromise, if we use this kind of balls, then pressure drop will be very, very high.

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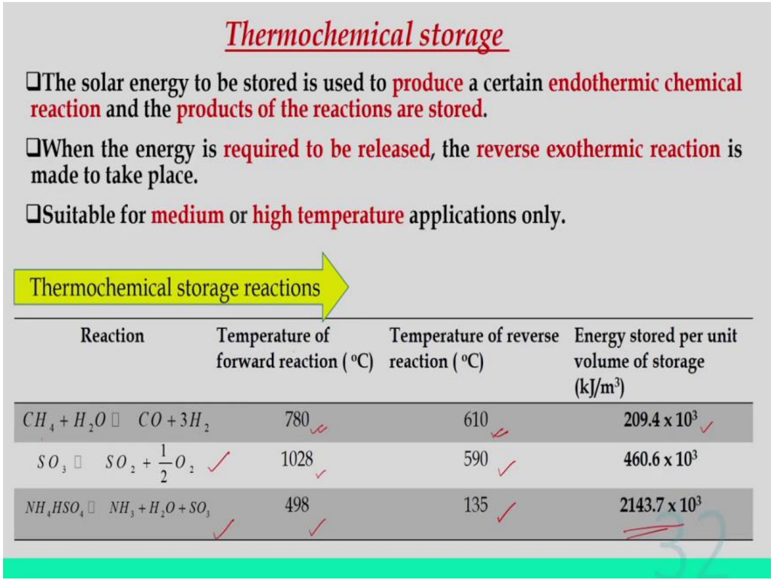

And we will pay attention about thermochemical storage system. This, the solar energy to be stored is used to produce a certain endothermic chemical reaction and the products of the reactions are stored. So, when the energy is required to be released, the reverse exothermic reaction is made to takes place. This is suitable for medium to high temperature application only. So, other two what we have discussed, sensible heat storage and latent heat storage system, we cannot use it for very high temperature. So, this thermochemical energy storage is specifically for medium to high temperature applications.

And we can see different chemical reactions like methane reacts with water, it converted to carbon monoxide and hydrogen. So, in this case, this temperature of the forward reaction will be about 780 and this reverse reaction will be at 610. And also, we can see energy stored per unit volume of storage is about 209.4×10^3.

So, for other cases also, we can see how it varies. So, for this reaction, so forward reaction will happen at 1028 ^oC. And this reverse reaction happens at 590. And for the other reactions, we can see forward reaction is at 498 and it is about a 135 for the reverse reaction. Also, we can see the energy stored per unit volume of storage, which is represented in kJ/m^3.

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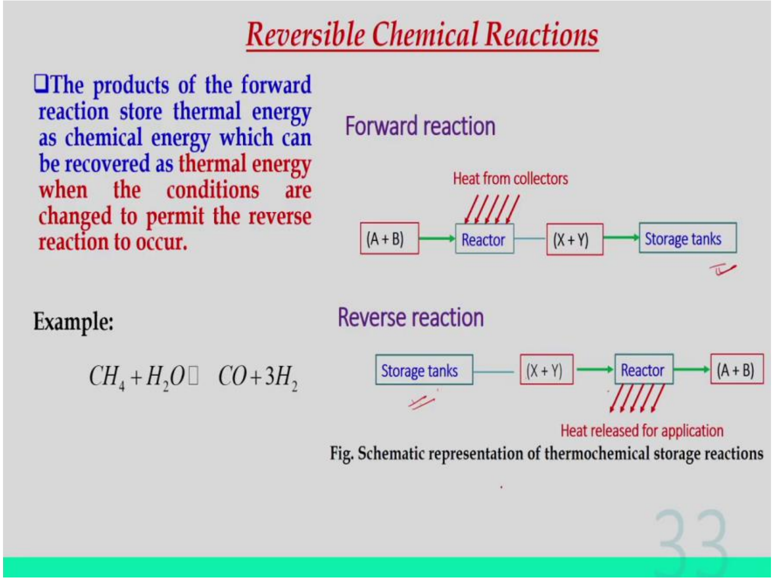

So, the product of forward reaction store thermal energy as chemical energy, which can be recovered as thermal energy when the conditions are changed to permit the reverse reaction to occur. So, already we have discussed the examples and this is the way it reacts.

If you consider two constituent (A + B), and if we get energy from the solar collector and it is converted to (X + Y), two other elements, and that can be that can be stored in a storage tank. And in the reverse reaction, this X Y Z will reacts with this and then we will have, so this in the storage tank from that we have to release the energy, so we can get the energy back from the storage system from X Y, (X + Y) → (A + B) by using this reverse reaction. So, this is what is shown as the schematic representation of thermochemical storage reactions.

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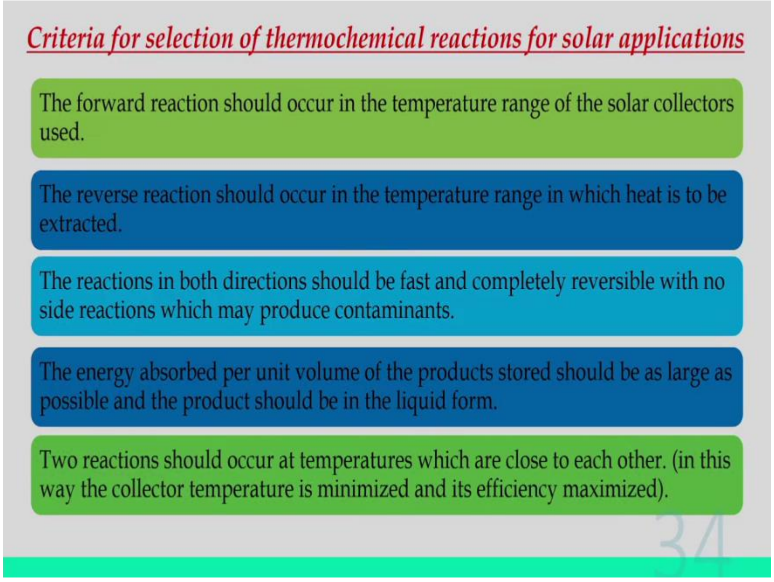

And there are some criterias for selection of thermochemical reactions for solar applications, like the forward reaction should occur in the temperature range of the solar collectors use. So, if we use solar concentrator then things will be different, if we use solar flat plate collector, if we use solar air heater, then things will be different.

The reverse reaction should occur in the temperature range in which heat is to be extracted. The reactions in both directions should be fast and completely reversible with no side reactions, which may produce contaminants, which is very, very important. The energy absorbed per unit volume of the products stored should be as large as possible and the product should be in the liquid form.

Two reactions should occur at temperatures which are close to each other. So, in this way the collector temperature is minimized and its efficiency can be maximized.

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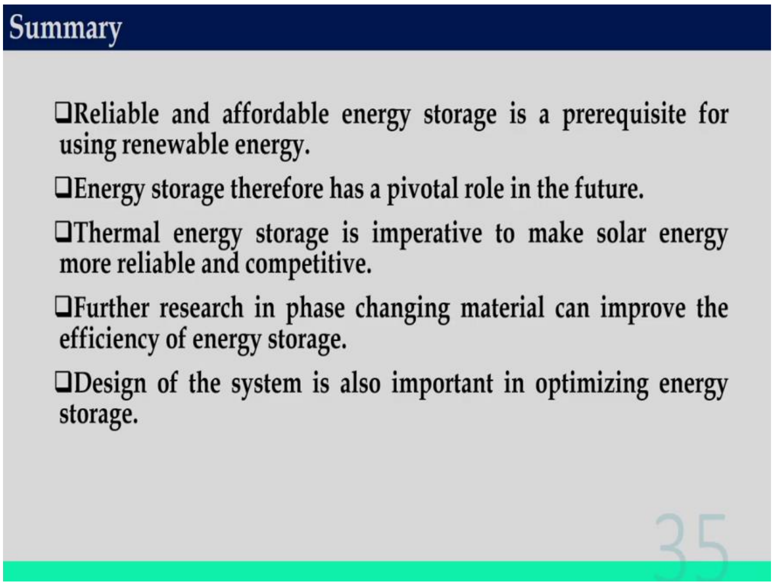

So, we can summarize what we have discussed today. So, we have discussed three different technologies for solar thermal energy storage, like sensible heat storage, latent heat storage and then thermochemical energy storage and we have studied different methodologies and at what condition, we can store what technology, that we have summarized.

Also, we have studied the reliable and affordable energy storage is a prerequisite for using renewable energy, that we understood clearly. Energy storage, therefore, has a pivotal role in the future. Thermal energy storage is imperative to make solar energy more reliable and competitive. Further, research in phase changing material can improve the efficiency of storage system. And the design of system is also important in optimizing energy storage.

Hope you enjoyed this video. Thank you for watching this video.