POWER PLANT SYSTEM ENGINEERING

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Module 4

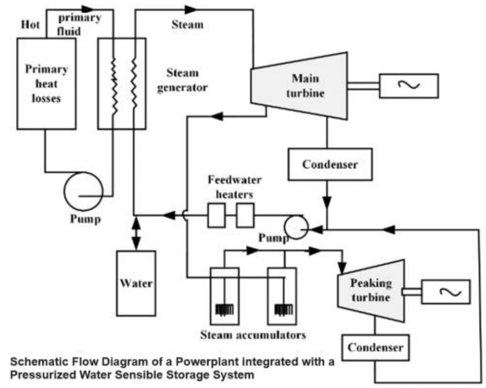
Lec 9: Energy Storage-II

Dear learners greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering module 4 that is Hydro and Renewable Energy Power Generation System. So, in our previous lecture we are focusing on energy storage part 1. In this lecture we will be focusing this energy storage part 2, where we will be discussing about two important energy storage systems, thermal sensible and latent heat energy storage. And in particular we will be discussing about the pressurized water based sensible storage system, which is a very common type of applications and we call this as a steam storage. So, first thing I need to emphasize is that we need energy storage because it is the only option that can cater the peak demands for any kind of power plants.

We know that renewable energies are always intermittent in natures; they vary hourly, daily, monthly. So, in order to run this plant continuously with steady energy, we require the main plant to operate at a base load and during the off peak hours energy can be stored and this stored energy is utilized further to cater the peak demands by the users. So, for that energy storage is the only option. However, this energy storage is possible mainly in two methods, one is electrical part & other is the thermal storage. In our previous lecture we talked about this electrical storage or we call this as electromechanical systems, in which the storing is mainly based on potential energy. For that we discussed about pumped hydro storage and compressed air storage systems.

Now, in this lecture our focus will be on thermal energy part and in this thermal energy part we will be talking about 1) sensible heat based thermal energy storage & 2) the latent heat based energy storage system. And in any case we say that primary plant operates at base load, whether it is electrical mode or thermal mode, but the peak load plant has to cater the need of the user at the time of demand. So, the advantage of this thermal energy storage system is that we can have a wide choice of system materials and they can operate in the range of refrigerating temperature to 1250℃. By refrigerating temperature, I mean it is not exactly 0℃ which is for water, but there are some materials which has capability to store the energy maybe below sub 0.

So, for that things, the possible method we can talk about is pressurized water storage. So, this is nothing, but we call this as steam storage and this is very common in large scale power plants. Other methods involved are like organic liquid storage, packed solid bed storage and fluidized solid bed storage. And this pressurized water based systems is called as steam storage and this is something similar to case where we store air to run an air turbine. Here we store steam with certain techniques, which can run the peaking turbine at the time of need.



Schematic Flow Diagram of a Powerplant integrated with a Pressurized Water Sensible Storage System

Another advantage of this system is that it can be integrated with any kind of power plants or base plants which can be operated through nuclear reactor or any fossil fuel furnace. Here entire idea is that base load plant supply steam during low demand, so that excess steam can be bled at high pressure turbine extraction. This is something we call as a feed water heating systems or regenerative mode of operating in a steam turbine for a conventional power plant. So, whatever steam you tap at low pressure that can be stored. So, this is how the system operates.

Let us see this a thermal circuit diagram. So, what we see is that we have two turbines one is the main turbine & other is the peaking turbine. Main turbine runs at base load. Now, from this main turbine we tap some heat at certain locations and this is something called as regenerator mode of operations. And we are storing that steam in an accumulator or in a large structure, which we call as a steam accumulation system and in fact, these two units are called as steam storage unit. So, this is stored at certain pressure and temperature. When the steam is stored it is packed with water, so that steam is mixed in water medium and we call this as saturated conditions, it can be either saturated liquid or vapor. So, these steam accumulator operates at saturated conditions. So, we have steam generator that runs from the primary heat sources and rest of the things are same except the fact that we have one unit which is called a peaking turbine. So, these two turbines are to be operated separately because this peaking turbine work on saturated vapor which expands in the turbine, whereas the main turbine has superheated steam. So, during the demand hours whatever steam stored in that manner gets pumped back to the peaking turbine to generate power.

Now some of the silent features are that peaking turbine operates when there is a peak demand which means that accumulators are discharged in this small peaking turbines. The operating limits typically fall in the range of 20 bar for which the saturation temperature of water is 212℃ & lower limit is 2 bar for which saturated temperature of water is 120℃. So, range of temperature is 120℃ to 212℃. So, that at any point of time we will find only steam and maybe dryness fraction should not come below one.

The main important parameters to quantify this peaking turbine, steam generator assembly are 1) thermal turnaround efficiency & 2) peaking turbine generator efficiency. So, typically this peaking turbine generator efficiency is kept at low because we are operating the steam at only saturated region. So, it is in the range of 20-25 % and also the base load plant operation falls in the range of 30-40%. So, these are the conditions and this is mainly because of variable inlet conditions, low temperature of saturated system, small size and many other factors.

However, our main analysis is charging and discharging the steam, for that we need this thermal turnaround efficiency. And this thermal turnaround efficiency is a complex function associated with the sensible heat transfer to and from the steel wall. That means, steam is stored in a container which is made out of steel and idea behind this is that the rate of heat loss should be minimized. So, steam contains energy and the wall material is also made out of steel. Hence, the conditions are such that the heat losses are minimized and also other losses are from structural members, interconnecting pipe. But the main loss that comes out or the main parameter for thermal turnout efficiency is the time dependent convective heat loss which we are going to analyze. So, to quantify this pressurized water sensible storage systems, we have some parameters. First parameter is called as storage density. So, storage density for a pressurized water storage medium can be expressed as a function of product of temperature difference specific heat and thermal density of the materials.

So, what we see is that the steam accumulator is made out of steel and whatever heat that gets stored in the steam is supposed to get conducted out of this accumulator through this wall and the heat capacity of the wall is nothing but combination of temperature difference, specific heat and density of the material. Storage thermal density is utilized in the peaking turbine per unit volume of high pressure saturated water which means if you look at this expressions we are trying to express this storage density as a function of power generating factor.

Storage density, $\rho_s = \frac{1}{v_{f1}}\left(h_{f1} - h_{f2}\right) = 95.3\,\frac{\text{kWh}}{\text{m}^3}$

Subscripts1&2:Stored pressure and discharge pressures

h & v:Enthalpy and specific volume of saturated water

For stored pressure 20 bar $\left(h_{f1} = 908.5\,\frac{\text{kJ}}{\text{kg;}}\right);\ v_{f1} = 0.0011766\,\frac{\text{m}^3}{\text{kg}}$

& discharge pressure 2 bar $\left(h_{f2} = 504.8\,\frac{\text{kJ}}{\text{kg}}\right)$

So, for example, in this case if your system operates between 20 bar and 2 bar, so correspondingly we can find out the saturated value of enthalpy at 20 bar and saturated liquid enthalpy value that is 504.8 kJ/kg at 2 bar. So, correspondingly at storage pressure, specific volume of water would be around 0.0011766 m^3/kg. Now, from this we can define the storage density as a function of stored capacity of volume of water required per kWh. So, in this case we can say for this enthalpy difference and or for this pressure difference between 2 bar and 20 bar, the storage capacity could be as high as 95.3 kWh/m^3. So, that means, if your storing limit is 20 bar to 2 bar, then the steam has a capacity to store about 95.3 kWh of energy per m^3. So, larger the m^3 higher will be the capacity.

The accumulator has wall which has certain thickness *t* and the diameter and length of this accumulator is defined as *D* and *L*. So, steam is stored here and it has energy and that energy will try to get convected out of this wall. So, there are 2 parameters here, one is wall material in which steam is stored and typically it is steel. And the other one is the steam which is stored closely at about 20 bar pressure. So, there are 2 factors, one is energy dissipated at the solid wall and the energy stored in the accumulator in the steam.

Energy dissipated at the solid wall(steel), $E_d = (\pi DLt)\rho_s c_s; t = \frac{Dp}{2\sigma}$

Energy stored in accumulator (cylindrical steel container), $E_s = \left(\frac{\pi}{4}D^2L\right)\rho_f c_f$

$$\Rightarrow \frac{E_d}{E_s} = 2\left(\frac{p}{\sigma}\right)\left(\frac{\rho_s c_s}{\rho_f c_f}\right) \ \& \ \left(\frac{p}{\sigma}\right) \sim 0.03; \left(\frac{\rho_s c_s}{\rho_f c_f}\right) \sim 1;$$

p: Storage pressure; σ Wall stress c & ρ: Specific heat and density respectively;

ρc:Volumetric heat capacities. D, L & t:Diameter, height and thickness of the cylinder, respectively

Subscripts s & f:solid and fluid.

So, it is a cylindrical steel container with dimension D, L & t. So, two things can be quantified here one is store capacity for material solid material ρ_s & $c_s$that is density and specific heat of solid and store capacity of the steam ρ_f & c_f that is density and specific heat of fluid. And this is of same order that means, they should have same capacity.

Other thing is that if you talk about storage pressure and this storage pressure has to be withstand by this wall. So, for that we call this as a wall stress which is σ and this ratio $\left(\frac{p}{\sigma}\right) \sim 0.03$ which means we should choose that kind of material. So, steel is the best choice. Considering these 2 energy ratio E_d/E_s, this number turns out to be so less that there is a minimal dissipation of energy which is from the stored steam. So, only possibility that energy can come out from the system is through convection.

So, for that things we say that convective heat loss from the water to the environment is a major contributor for the thermal turnaround efficiency. So, we will try to find out thermal turnaround efficiency for this kind of pressurized-water sensible energy storage system.

And for which this particular model can be analyzed as a lumped heat capacity model. In this lumped heat capacity model, the parameters involved are density of the fluid, temperature, volume, surface has area A and outside temperature T_∞ and heat that tries to come out is q by convection. So, there are 2 parameters that are involved; the thermal resistance for fluid and for solid. And to justify this we would introduce a parameter which is called as Biot number.

Biot Number, $B_i \ll 1; B_i = \frac{hL}{k}$

h: convective heat transfer coefficient for fluid; k: thermal conductivity of the solid

So, what it says is that in a lumped capacity model, we imagine such a system that initially we have a stored temperature at T_1 and suddenly when it sees this ambient temperature, it tries to come down. So, through this process assuming that if the system is completely insulated, we say there is no heat loss. But if there is a heat loss through convection, so system can start from initial temperature to final temperature. So, final temperature becomes T_2. But what we require is that the steam accumulator should have some capacity so that it should store the steam for certain time. So, we introduce one more parameter what is called as storage time θ_s and corresponding temperature is called as T_s. So, the relation between T_1, T_s, T_2 & θ_s can be formulated based on this lumped capacity model and we can assume this Biot number to be much much lesser than one.

So, any heat transfer book we will talk about the expressions of temperature distribution at any time instant. So, considering this one can have this equations. So, here there is an exponential decay from initial temperature T_1 to final temperature T_2. So, this exponential decay contains a term τ and this is called as time constant which is defined as the ratio of heat capacity to heat flow resistance.

Temperature distribution (T)at any time instant(θ), $\frac{T(\theta) - T_1}{T_\infty - T_1} = 1 - e^{-\left(\frac{\theta}{\tau}\right)}$

So, for this we can have this heat capacity in terms of fluid that is $\frac{\pi}{4}D^2L\rho_f c_f$, & $\frac{\pi}{4}D^2L$ is volume of the cylindrical tank and also heat flow resistance is can be defined as a function of overall heat transfer coefficient U. So, putting this we can define this time constant.

$$\text{Time constant}, \tau = \frac{\text{Heat capacity}}{\text{Heat flow resistance}} = \frac{\frac{\pi}{4}D^2L\rho_f c_f}{\pi DLU} = \frac{D\rho_f c_f}{4U}; \frac{T_s - T_1}{T_\infty - T_1} = 1 - e^{-\left(\frac{\theta_s}{\tau}\right)}$$

c_f & ρ_f:Specific heat and density of fluid, respectively; $\rho_f c_f$:Volumetric heat capacity

U: Overall heat transfer coefficient between water and outside environment

D & L:Diameter and height of the cylinder, respectively

T_1:Initial temperature of liquid during fully charged condition

T_s:Temperature of liquid at storage period(θ_s)

T_∞:Enviornmental temperature; T_2:Final temperature at θ_2; h:Enthalpy of liquid

Now we are going to talk about thermal turnaround efficiency. So, basically we have initial & final temperature T_1 & T_2. During this the enthalpy difference should be $h_1 - h_2$, but we are actually looking at the storage time θ_s for which enthalpy can drops from h_s to h_2. So, from this enthalpy can be expressed in terms of temperature and this temperature and finally the value of T_s can be found out from the above equations. Putting this we find out a thermal turnaround efficiency term as a function of initial temperature, final temperature and free stream temperature. And below stated equation is actually our expressions for thermal turnaround efficiency for a pressurized water sensible storage system and this will help us to find out for how long we can store this pressurized steam in this accumulator.

$$\text{Thermal turnaround efficiency}, \eta_{ta} = \frac{h_s - h_2}{h_1 - h_2} = \frac{T_s - T_2}{T_1 - T_2} \Rightarrow \eta_{ta}$$

$$= 1 - \left(\frac{T_1 - T_\infty}{T_1 - T_2}\right)\left[1 - e^{-\left(\frac{\theta}{\tau}\right)}\right]$$

Now, from this we can get some inferences that thermal turnaround efficiency is a strong function of ratio of storage period and time constant. So, higher value of time constant will result higher thermal turnaround efficiency.

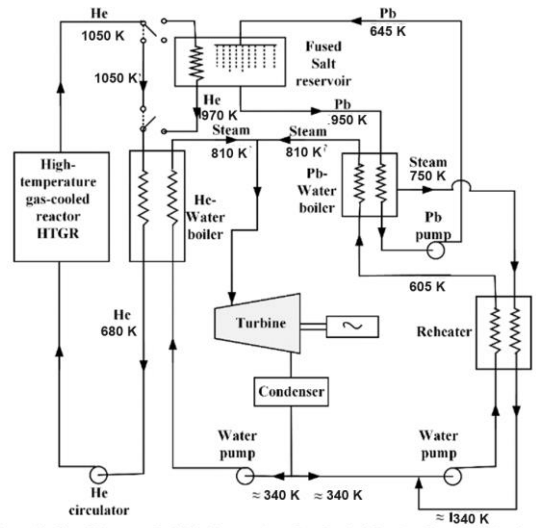
So, main intention during design of steam accumulator is that we should choose higher value of time constant, but then to choose this higher value of time constant we can say that the overall heat transfer coefficient should be minimum. So, that overall heat transfer coefficient is a complete function of the thermal resistance that occurs for variety mode of heat transfer like conduction as well as convection and also depends on the volumetric heat capacity. So, this is the reason that we need to have overall heat transfer coefficient as low as possible. Since we cannot have any control over time constant because it is a complete function of so many parameters, but we can have control over the choice of fluid and choice of overall heat transfer coefficient. For that reason one can think of keeping the accumulator above ground or underground. So, this is the idea that can be explored for choice of accumulators.

Now, next thing we are going to move is the latent heat based energy storage systems. So, when you say sensible heat storage, there basically the temperature difference plays a role, but when you talk about latent heat, here we say that there is no change in the temperature. We can think of some phase change materials that continuously get vaporized and continuously also get condensed. So, through this process we can store quite substantial amount of energy. And it in fact, here also we talk about storage density which is equal to product of latent heat of vaporization with density of the storage materials.

Moreover, these latent heat based storage systems are more efficient than that of a conventional sensible heat type of storage systems which involve single phase materials because the heat storage occurs at single phase only. And we have a wide choice of materials with different fusion and evaporation temperatures. So, this will allow that we can have wide range of operating temperature and pressure range. And it also have the ability to generate high temperature of steam at the peaking turbine. But only drawback is this choice of materials with their fusion and evaporation temperature. This has to be judiciously chosen for a reliable operation. And of course, for large scale power plants, it is not considered as a viable option, but it can do some kind of justice if the cost factor is considered.

So, why it is so? Let us try to understand here. So, typically this is a flow diagram for a latent heat storage in which we have a high temperature gas cooled reactor and this reactor supplies necessary steam for running this base turbine. So, this is what we call as base load. For base load operation, this is a conventionally Rankine cycle based operation. The turbine operates for base loads. But what extra feature which is added here is a fused salt reservoir which is nothing, but your latent heat based storage unit.

And this salt absorbs necessary working fluid which is called as a secondary fluid and here the secondary fluid is your Pb that runs in the circuit of this fused salt reservoir and this main plant unit. So, when we take out some steam to this circuit and maybe take out some heat to add energy to this fused slot and also side by side the energy from this helium circuit can also be added here. So, thereby the fused salt gets necessary heat and that energy gets stored here. Now, during the discharge period, this energy can be released to cater the need for the peak heating hours. So, here the main plant although operates in mode of water as a primary working fluid, but other circuits involved the materials like helium coolant, here we require lead for this fused slot operations. And this what is this fused slot I will come back later.



Schematic Flow Diagram of a High Temperature Gas Cooled Reactor Powerplant using Latent Heat Energy Storage

So, the choice of this fused slot with their combination is very vital for efficiency of this plant. So, that is the reason, although this plant is not typically considered as a better option, but at the time of requirement this can be considered as a possible solution. So, the efficiency of this latent storage systems mainly depends on the type of fusion salt requirement we have. So, for that reason, here we have mentioned some of this requirement of the storage materials. For the storage materials for latent heat storage must possess a proper transition temperatures, high latent heat, good thermal conductivity, stability for cyclic phase change operation, the working fluid should be non-toxic and also low cost.

However, all these things cannot be achieved by any particular materials. So, no material meets this requirement. Especially we need to explore some fluoride salt which has to be designed. So, one such possible choice is called as Eutectic salt. It is a combination of 70% sodium fluoride and 30% iron fluoride. It has a fusion temperature of 680℃. So, that means, they can be stored till that temperature. Now, when stored at this temperature, they have a possibility of storage density to provide 1500 MJ/m^3. And of course, other materials like zinc chloride will have storage fusion temperature of 370℃, and can give a storage density of 400 MJ/m^3. And for a typical unit which I shown in that circuit which is called as eutectic salt that is operating with helium coolant at 48 bar, one can explore that storage capacity can be of 7200 MWh and charge discharge rate can be 600 MW. So, it means, 7200 MWh of energy you store, but during charging and discharging rate, it can operate at 600 MW power. And through this process one can think of getting 200 MW power for about 12 hours. And if you want to achieve this with that thermal conceptual circuit, we require a Eutectic salt of 42000 tons, storage vessels will have diameter 36 m and height 30 m. So, it has to be contained in a ice wall stress type of storage materials typically steel. And this cyclic efficiency or thermal turnaround efficiency would be close to 90%. So, this is just a kind of a conceptual design or idea for a latent heat based storage systems. Anyway it is a conceptual design, but it can be considered as one kind of storage unit. Even not today maybe in future this particular storage unit can also be explored for a large scale power plant systems.

Q1. A powerplant is designed for 1000 MW for its base load operation. It is integrated with a pressurized-water sensible storage system for which the thermal energy of 4000 MWh has to be stored daily. The accumulators (4m diameter) are well-insulated and have overall heat transfer coefficient of 5 $kJ/h.m^2$-K. The maximum and minimum storage pressures are, 20 bar & 2 bar, while the storage time is 15 hr. Take specific heat of water under storage condition as 4.35 kJ/kg.K and the peaking efficiency is 25%. Calculate, thermal turnaround efficiency, total volume of accumulator, minimum energy release and cost of storage if the unit volume cost of accumulator is Rs. 25000/-.

So, with our discussion today we will try to solve a numerical problems in which we talk about a pressurized water based sensible storage system in which heat losses are quantified mainly by convection. And the entire idea of this heat loss is modeled through a lumped heat capacity model. The necessary theory for this lumped heat capacity model I have mentioned in this lecture. So, I will be using only those end results to give the glimpses or the idea that how this pressurized water based storage system works. So, essentially it is a nothing, but a steam storage. And operation is quite similar because it works on the simple principle of Rankine cycle. So, the solution of this problem starts with the fact that we have the steam accumulator unit. This steam accumulator unit has certain parameter and the steam has to be stored at 20 bar and 2 bar pressures and for this using steam table we can find out saturated values.

$$\text{Saturated condition at 20 bar } \rightarrow T_1 = 212.37℃; h_{f1} = 908.5\,\frac{\text{kJ}}{\text{kg}}; v_{f1} = 0.0011766\,\frac{\text{m}^3}{\text{kg}}$$

$$\text{Similarly at 2 bar } \rightarrow T_2 = 120.23℃; h_{f2} = 504.8\,\frac{\text{kJ}}{\text{kg}}; v_{f2} = 0.0010605\,\frac{\text{m}^3}{\text{kg}}$$

Now, since we know this volume, we can find out as average density because we need to find out the time constant for which we require average density of steam which is stored.

$$\text{Average density}, \rho = \frac{\rho_1 + \rho_2}{2} = \frac{1}{2}\left(\frac{1}{v_{f1}} + \frac{1}{v_{f2}}\right) = 896.43\,\frac{\text{kg}}{\text{m}^3}$$

$$\text{Then time constant}, \tau = \frac{D\rho_f c_f}{4U};\ \text{Data given for water } c_f = 4.35\,\frac{\text{kJ}}{\text{kg.K}}$$

$$\text{Overall heat transfer coefficient}, U = 5\ \frac{\text{kJ}}{\text{hr.m}^2\text{.K}}; \text{Diameter}, D = 4\text{ m}$$

$$\text{Time constant}, \tau = 781\text{ hr}$$

So, the first expression that we need to find out is the thermal turnaround efficiency.

Thermal turnaround efficiency, $\eta_{ta} = 1 - \left(\frac{T_1 - T_\infty}{T_1 - T_2}\right)\left[1 - e^{-\left(\frac{\theta}{\tau}\right)}\right]$

So, the value of T_1 & T_2 is known to us.

$T_\infty = \text{Ambient condition} = 20°\text{C};\ \text{Storage time}, \theta_s = 15\ \text{hr}$

$\text{Putting these values, Turnaround efficiency}, \eta_{ta} = 0.96 = 96\%$

Next question is what is the total volume? So, to find this total volume we require the information from the peaking turbine.

$\text{Peaking efficiency}, \eta_p = 25\%; \text{Storage capacity(Power)} = 4000\ \text{MWh}; \eta_t = 0.96$

$$\text{Stored Energy}, P_s = \frac{4000 \times 3600 \times 1000}{0.25 \times 0.96} = 6 \times 10^{10}\ \text{kJ}$$

$$\text{Mass of water}, m = \frac{P_s}{h_{f1} - h_{f2}} = \frac{6 \times 10^{10}}{908.5 - 504.8} = 1.5 \times 10^8\ \text{kg}$$

Once we know this mass then volume can be found out.

$$\text{Volume}, V = m.\left(v_{f1}\right)_{20\text{bar}} = 1.5 \times 10^8 \times 0.0011766 = 174840\ \text{m}^3$$

So, this is the volume of steam. So, accumulator should have the minimum size that is of this range. Then next part is minimum energy release.

$$\text{Minimum energy release}, E_{min} = E_{stored} - E_{ambient} = m\left(h_f\right)_{20\text{bar}} - m(h_\infty)_{ambient}$$

$\text{At } 20°\text{C, Free steam enthalpy}, h_\infty = 293\text{KJ}$

$\Rightarrow E_{min} = 1.5 \times 10^8(908.5 - 293) = 9.2 \times 10^{10}\ \text{kJ}$

That means, the steam can give a minimum energy which can be released from this is 9.2×10^{10} kJ.

And last part is to calculate cost of the accumulator. So, it is given that unit volume cost is Rs. 25000/-. Total volume is 174840 m^3. So, cost of accumulator or we can say minimum cost for the accumulator would be

$C_{min} = 25000 \times 174840 = 4371$ lakhs ≈ 4.371 crore

So, we can say that it is a huge initial cost of investment. However, you can see the amount of energy that can be released from this and we can talk about power requirement of 4000 MWh. So, why these numbers are important? Because energy storage is justified only when we are storing it at very high conditions as the infrastructure requirement is huge and involvement cost is also high. So, then only the choice of a power plant with an integration with energy storage systems will be justified. So, this is all about today's lecture. Thank you for your attention.