POWER PLANT SYSTEM ENGINEERING

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Module 4

Lec 10: Energy Storage-III

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering module number 4, Hydro and Renewable Energy Power Generation Systems. So, in this module lecture number 10, we are going to discuss about the Energy Storage schemes part 3. And in this lecture, we will try to emphasize the following energy storage mechanisms. First is flywheel storage system, then battery storage systems, magnetic storage systems, chemical reaction storage systems, and finally, we will think about this hydrogen energy storage because this energy storage system is the driving mechanism for the next future generation power mode, as hydrogen is treated as a clean fuel and it satisfies all the needs of zero carbon emissions. Now, out of these storage systems, the first three that is flywheel, battery and magnetic, they fall under direct electrical energy storage system. And chemical reaction storage falls under a mode which is called as thermal storage mechanism. Hydrogen generation storage is an additional topic which have been introduced and we call it as a clean fuel and it has the potential for power generation in future.

So, to start this energy storage topic, first thing I need to emphasize that we require the energy storage mechanism to cater the need of peak demand. Every power plant system must have some mechanisms to store the excess energy. And that excess energy has to be catered during the peak load demands. Hence, energy storage is inevitable and mostly for renewable power systems, it is a must. Now, to look for the cyclic variations, hourly, monthly or yearly, you need to tap the energy from the base plant and that has to be stored in a particular mechanism and that energy has to be disposed of at the time of need. So, that is what we call as a necessity for energy storage.

So, the complete flow diagram tells that we have primary heat source, method of storage is electrical and thermal. And in our previous lectures, we emphasized about the electrical storage, mainly electromechanical systems stored by pumped hydro or compressed air storage systems. And we also discussed about the thermal energy storage by sensible heat, latent heat. And in this lecture, we will talk about some of the fundamental aspects of auxiliary energy resources which is mainly flywheel, then we have the storage batteries and thirdly chemical reaction systems. We will not go deep into this because this is not the part of this complete course. However, I will try to emphasize the basic principle and working operations for all this type of storage systems.

Now, first thing we will see is a flywheel energy storage system. We all know that flywheel is a large mass and stores the kinetic energy and that kinetic energy is typically converted to an electrical motor generator set to discharge its energy. So, what we normally do is that during charging mode or off peak period, the flywheel is supposed to be attached to a motor generator set. So, which means that during charging phase that is off peak period, the motor adds energy to the flywheel and that energy is stored in the form of kinetic energy. And for generation mode, the flywheel rotor delivers this kinetic energy to the generator during the peak demand period.

Now, if you want to know how much energy stored in a flywheel, then there is a very simple expressions for kinetic energy.

$$\text{Kinetic energy} = \frac{1}{2}mv^2; v = \text{Rotational speed} \times \text{Linear length}$$

So, here v stands as a rotational speed multiplied by its linear length. So, normally the flywheels are circular in diameter. So, length travelled for each revolution is $2\pi Rn$, n stands as revolutions per second.

$$\text{Energy stored in a flywheel}, E = \frac{1}{2}m(2\pi Rn)^2 = 2\pi^2 mR^2n^2$$

m: Mass of the flywheel; R:Radius of gyration

This radius of gyration is normally kept large. Of course, if you look at this expression, energy can be maximized by increasing the radius of gyration or increasing the mass. So, the very fundamental features of storing energy in the form of flywheel is that you add large mass as well as large size. So, when you say large size, the energy stored would be proportional to R^2 that means, huge amount of energy can be stored if your radius of gyration is large.

Now coming back to revolution of speed, it is n^2. So, for flywheels normally at the time of discharge of energy from the flywheel, kinetic energy is transferred back to the generator set which means that there is always a fluctuation of speed because the demand and the speeds are correlated. So, during the peak demand, when there is a fluctuation of speeds that has to be restricted. So, for that things what we can say is that we can rewrite this expressions as

Energy absorbed/released by fly wheel between speed of rotations, ΔE

$$= 2\pi^2 mR^2(n_2^2 - n_1^2)$$

So, this is the final expression for speed fluctuation, but normally we do not have much control about the fluctuation in the demands. So, what we can do is that whatever may be the fluctuation, we can ensure that we are delivering the energy with least fluctuation with respect to speed. To counter this we define a term called as coefficient of speed fluctuation.

Coefficient of speed fluctuation, $k = \dfrac{n_2 - n_1}{n} = \dfrac{2(n_2 - n_1)}{n_1 + n_2}; n = \dfrac{n_1 + n_2}{2}; \Delta E$

$$= 4\pi^2 k_s mR^2 n^2$$

n:Revolutions per second; k_s:Speed coefficient (0.005 to 0.2)

Now, from this expression we can now get back this particular expression for ΔE as a function of *n* which is the average speed that means, flywheel running at average speed with a parameter called as coefficient of fluctuation k_s.And this k_s tells about whether we are providing a steady energy or there is a fluctuation in the speed.

So, for that reasons this $k_s$value is kept between 0.005 & 0.2, which means that this parameter defines the closeness of speed regulations. For fine speed regulations $k_s =$

0.005 & for coarse speed fluctuation, that means fluctuation can go as high as 20% that is 0.2 for this thing. So, that is the control limit we can have for k_s. So, the choice is with our hand what type of k_s we are going to regulate. Now, to minimize this k_s or speed fluctuations what we expect is that mass and radius of gyration of the flywheel must be high to have a very close speed regulation.

So, now let's come back to the flywheel design criteria. So, when a rotating flywheel is at high speed, it is always subjected to a stress level and this stress level gives you a lot about the critical design considerations. So, there are two parameters that is used for considering these design criteria. First one is theoretical maximum specific energy which means energy observed per unit mass of the flywheel that is characterized in terms of mass of the flywheel. Other thing is characterized in the form of volume or size of the flywheel that is maximum volumetric specific energy that is energy observed per unit volume. Then again we try to correlate this specific energy with respect to material properties. So, here we can say that maximum specific energy is dependent on stress to density ratio.

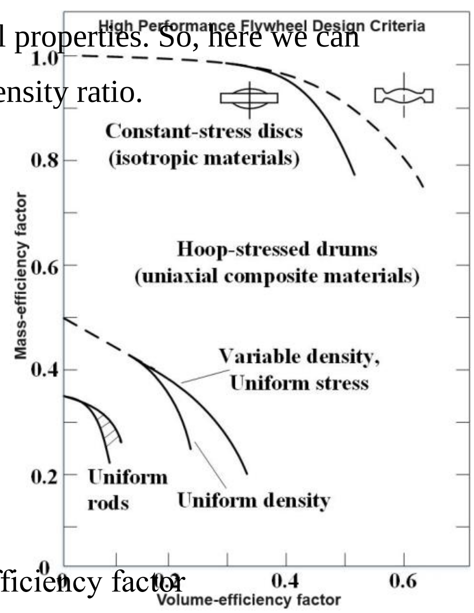
Maximum specific energy, $\left(\frac{E}{m}\right)_{max} = C_1 k_m \left(\frac{\sigma}{\rho}\right)$;

C_1 is a constant; ρ: Density m: Mass of the flywheel

Maximum volumetric specific energy, $\left(\frac{E}{V}\right)_{max}$

$= C_2 k_v \sigma$; C_2 is a constant; σ: Allowable stress

$k_v = \frac{k_m}{\rho}$; k_m:Mass efficiency factor(0.5 to 1); k_v:Volume efficiency factor

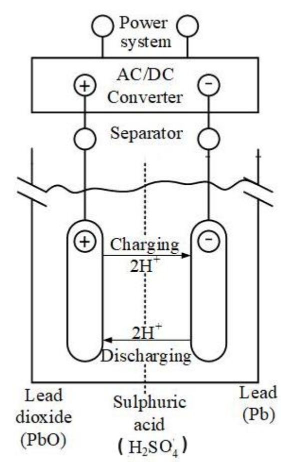


So, here there are two important parameters that are mass efficiency factor and volume efficiency factor and these two factors regulate the maximum specific energy. Now how to regulate or how to control this k_m & k_v? So, for that reason we need to think about whether the flywheel is designed in a continuous isotropic material or anisotropic material or it is designed based on considering variety of constituents with their mass fractions or volume fractions to make it light. Based on these things k_m & k_v are chosen. So, the plot here that talks about the mass efficiency factor k_m and volume efficiency factor k_v. So, it has been plotted for various types of materials. First is constant stress type or isotropic materials, here we can see that they have a constant type of property, mass and volume fraction are closely related, but at some point of volume efficiency factor, the mass efficiency factor drops down. Another category called as uniaxial composite materials, for which the mass and volume efficiency factor falls in the range of 0.6. Third category is variable density materials, which have good mass efficiency factor, but less volume efficiency factor. And uniform rods they are also least preferred. So, basically speaking that we have to choose k_m & k_v in such a way that we can maximize the specific energy either in terms of its volume or in terms of its mass. Hence, the design criteria for flywheel is as follows, the materials for the energy storage flywheel must have high strength to density ratio, high resistance to cyclic crack growth because this cyclic word is a very common in flywheel because it is continuously charging and discharging. Then it should have high strength density to cost ratio. So, these factors decide what type of material to be used.

A typical materials are alloy steel, fiber reinforced plastics, Kevlar epoxy. So, such kind of materials are there. In addition to that the flywheel energy storage also incurs losses in terms of windage, bearing, eddy current and so on. Now, let me give a conceptual idea that what is the kind of energy storage we are looking at, if you want to go for a flywheel energy storage systems. If you think of 10000 kWh of energy to be delivered, which needs to be stored in a flywheel rotor and we should rotate at 1250 rpm which is typically the speed at which the IC engines normally operate, then the flywheel rotor can be prepared with anisotropic composite materials for which the mass requirement will be 3.3×10^5 kg and the size can be like inner, outer diameter & height of 4.3 m, 6.2 m and 3 m. So, these are just some tentative numbers that talks about the typical size of storage unit we require. So, there is no point in going for low energy storage by investing for large cost or using large size of the material.

So, next type of energy storage system, which is a direct form, is called as electric battery. In our day to day life we all come across various type of batteries and a typical battery is lead acid battery. This is a very common in our day to day life, but in a large scale, a direct method of energy storage in terms of lead acid battery can be considered. So, lead acid battery is a direct current battery which are conventionally used in the motor vehicles. Even all vehicles has this type of battery. So, typically it contains 6 number of voltaic cells and they are connected in series for a 12 volt capacity. And the typical circuit diagram of a lead acid battery is shown here. Here we have one unit and the working principle is an electro chemical reaction. Here we have an anode and a cathode. In the anode we have lead in solid form and in the cathode we have lead oxide which is solid and they are kept in an aqueous solutions of H_2SO_4 or sulphuric acid and this side we have lead and this side we have lead oxide.

Now, what happens during the design phase we say that we need to have an anode which is considered with a spongy grey lead and a cathode which is formed from the lead oxides and both of them are immersed in a water solution of sulphuric acid in a separate compartment. Then what happens during charging and discharging is that the lead in the anode oxidizes to ion immediately then it precipitates as lead sulphate. So, lead oxidizes to ions and during the charging phase, the lead oxidized to form ions in the anode and in the cathode the lead oxide takes this ion to get back to the $PbSO_4$ and again forms as aqueous solutions. So, through this process we get some free electrons in the anode and that is the driving force for the current flow in the circuit. Now, during the discharge phase both anode and cathode sections are slowly covered with lead sulphate that replaces lead in the anode and lead oxide in the cathode.



Lead-acid Battery Storage

Electrochemical reaction: Anode: $Pb(s) + SO_4^{2-}(aq) \rightarrow PbSO_4(s) + 2e^-$

Cathode: $PbO_2(s) + 4H^+(aq) + SO_4^{2-}(aq) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(aq)$

discharging $\rightleftarrows$ charging; s: Solid & aq: Aqueous conditions

So, through this process, we can see is that the concentration of sulphuric acid will drop which means it is an indication that we are entering into a partially discharge cell. Now, in the charging mode the battery can be restored to the original conditions by reversing the direction of current in the electron flow. So, both cathode and anode are taken into account simultaneously to ensure that we are doing charging and discharging in a cyclic process. Since it is a cyclic process, we expect that with time the performance will drop down. So, the lead acid battery deteriorates its performance typically after 2000 cycles due to irreversible physical changes in the electrodes.

However, since it is an electrical based storage system, we can expect that turnaround efficiency that is charging and discharging efficiency for this kind of storage systems falls in the range of 70-80%. So, this is typically comparable with pumped hydro and compressed air storage systems. However, we do not consider this particular application in a large scale. So, here I have emphasized only one type of battery storage that will lead acid battery, but there are possibilities that for a large scale utility application, we can have sodium-sulphur, zinc chloride battery, lithium chloride, lithium telluride batteries. All these things can be considered. High energy, low mass, long cycle life should be the characteristics of battery storage for high energy utility requirement.

We will now move on to next type of energy storage systems which is the direct energy. And that concept is called as magnetic energy storage. Magnetic energy storage is based on the principle called as superconductivity. The basic definition goes as follows which means that dependence of electrical resistance of metals at cryogenic temperatures means, we are talking about in the order of 90 K, is observed by the phenomena called as superconductivity. That means, we are looking at the resistance of materials at cryogenic temperatures. This particular property called as superconductivity that means, some of the materials have inherent characteristics that they lose resistance when they are kept at cryogenic temperature close to 90 K or less.

Hence we call this superconductivity as the set of physical properties which are observed in certain materials for which the electrical resistance vanishes. When the electrical resistance vanishes side by side the magnetic fields becomes predominant and they are expelled from the materials. So, that means, at cryogenic temperature, those metals behave as magnets. So, this is the basic principle of superconductivity. However, all materials do not exhibit superconductivity, only some materials can exhibit.

The temperature below which the metal become superconductive is called as transition or critical temperature. Any material exhibiting this property is called as a superconductor for which the resistance drops to 0 below its critical temperature. So, this concept gives rise to the fact that we can store magnetic energy by using superconducting materials. Initially the superconductive magnetic storage was considered for pulsed energy storage. Wherever there is a pulse energy requirement that means instantly there is large energy requirement, then we can give that energy for a while. But if you want to store it for a large time duration then we require some kind of charging and discharging circuit. So, in a pulse energy storage, the charging and discharging times are very short. But for long duration, we require some kind of designs in which we can store magnetic energy by using superconducting materials. Hence the concept of this superconductivity for certain materials is found to be suitable for large scale energy storage utility systems.

So, the principle states that energy can be stored in the magnetic field associated with the coil which are made out of superconducting materials. When the temperature of the coil is maintained below its critical temperature and once the coil is charged, the current will not decay which means resistance drops to 0. Current does not fall down means the material behaves as if it does not offer any resistance to the current flow. Then it can store this magnetic energy because at that condition, the metal becomes magnet. So, we call this magnetic energy which can be stored indefinitely and this stored energy can be released back to the network by discharging the coil.

Now, I will give you some basic principle for understanding for magnetic energy storage with little bit of mathematical background. So, we call this as a simple functional relation where we need to bring a few electrical terms. First thing is the inductance of a coil which is a function of its dimension and it is characterized for a coil with a conductor of rectangular cross section. So, basically we are looking at a electrical conductor with dimensions a and b and this is positioned with reference to some axis at a distance R and we are going to see for this kind of geometrical configurations, if it behaves as a superconductor then how we can define its magnetic energy storage capacity. So, energy stored in a superconducting coil can be simply expressed as the following equation. Now, for this kind of geometry and there are some mathematical treatment which was done and finally, for a superconducting situations the electrical energy stored in the conductor can be expressed by this functional relations.

Energy stored in a superconducting coil, $E = \frac{1}{2}LI^2 = \frac{1}{4}\pi^{\frac{-5}{3}}f(\xi,\delta)\xi^{\frac{-2}{3}}V^{\frac{5}{3}}j^2$

Inductance of a coil, $L = f(\xi,\delta)RN^2$; Currentdensity, $j = \frac{NI}{ab}$; $\delta = \frac{a}{b}$

a & b:Width and depth of conductor; R:Mean radius of coil; L: Inductance; I: Current;

$f(\xi,\delta)$:Form function; N:Number of turns of coil

Now, let us understand each terms here. So, $f(\xi,\delta)$, we call this as a form function, which is basically geometrical part of this coil. And ξ is another kind of geometrical function which is defined in the following expression.

Volume of conductor in one coil turn, $V = \frac{8\pi R^3}{\xi^2}$; $\xi = \frac{2R}{\sqrt{ab}}$

However, a lot of work has been carried out in this manner and people tried to find out for a given coil how much maximum in magnetic energy we can store. So, it was found that a coil which gives maximum value of volume to inductance, called as a Brookes coil stores maximum magnetic energy. And using that Brooks coil concept, the energy stored for a Brooks coil, called as a reference point that is the maximum energy & it is expressed as

Maximum magnetic energy stored(Brookes coil), $E_B = 3.028 \times 10^{-8}V^{\frac{5}{3}}j^2$

So, this Brooks coil is made as standard. Now, for any other coil if you want to find out how much magnetic energy you can store then we refer that with respect to Brooks coil and find out a fraction called as energy fraction.

Energy fraction for any cylindrical superconducting coil, $F = \frac{E}{E_B}$

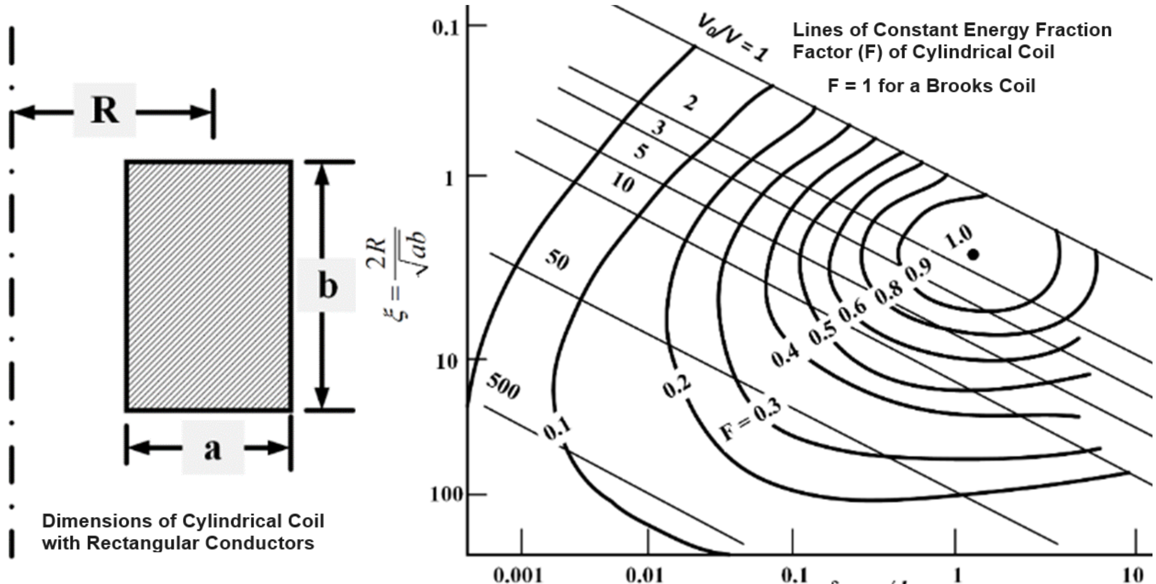
But it is very difficult to achieve this Brooks coil concept. So, it is normally energy stored for any conventionally available coil. Then another characteristics part for magnetic energy storage we require as we have aspect ratio involved, is the volume of material per unit energy stored.

Volume of material per unit energy stored, $\frac{V}{E} = \frac{V}{FE_B} = \frac{0.33 \times 10^8}{FV^{\frac{2}{3}}j^2}$

So, this expression gives the actual utility for magnetic energy storage concept. What it tells is that the volume of material per energy stored is a function of current density and the volume of the material. And when volume of the material becomes larger, the cost will be larger. So, a counter or balancing approach is taken care as we cannot always have a Brooks coil. Brooks coil gives the maximum energy storage and it has some unique dimension of the cross section of the material.

Brookes coil, $\frac{L}{V} \rightarrow$ maximum; $a = b$ & $R = 1.5b$; $\delta = 1$; $\xi = 3$; $F = 1(E = E_B)$

So, for that reasons we take this parameter V / E as the characteristics parameter for magnetic energy storage and try to see the physical significance that is the possible way for a magnetic storage coil or superconducting coil to be designed. So, this particular plot talks about the aspect ratio of the coil which is $\delta = {}^{a}/_{b}$ to $\xi = {}^{2R}/_{\sqrt{ab}}$, which is another geometrical parameter.



Magnetic Energy Storage in a Cylindrical Coil

And when it is plotted we start with the factor called as form factor. So, as you proceed further your storing capacity drop because *F* becomes smaller and smaller. If you are going towards Brookes coil for which *F* becomes 1, we are storing maximum energy. For storing maximum energy we need to have $V_o/V = 1$. So, the volume becomes high, and the cost factor also goes up. Hence a magnetic storage need a very large structural mass to contain the maximum stored energy, but if you store maximum energy this gives a high value of radial outward force for the solenoid. That coil now becomes a solenoid or magnet and it gives a very large radial outward force. So, to counteract that always Brookes coil is not preferred.

So, that is the idea that the design of a magnetic storage systems require the knowledge of important factor that is volume of the material per energy stored, which demonstrates the economy scale of the coil. The cost of the coil is proportional to its volume and the cost of energy stored is inversely proportional to volume and the current density. Hence the main mechanical problem which is associated for a magnetic storage is the requirement of very large structural mass to contain the magnetic field energy. But when you talk about high magnetic energy it gives large outward force for the solenoid. So, a balancing approach is made in which we can have choice of mass of the material and the amount of energy requirement.

Now for a typical proposed magnetic storage systems there are some silent features. So, if you are looking for magnet energy storage of 5500 MWh, we require some kind of supercritical fluid which would make this conductor to be a superconductor and this material has to be prepared with a special type of things which exhibits the characteristics feature of superconductivity and typically it is an alloy of aluminum, Niobium and Titanium. We require a low aspect ratio cylindrical structure which means typically it can have inner diameter of 1570 m, 5 m thickness, 16 m long & this is of course, too high for the energy storage of 5500 MWh. And we also need the solenoid which must have at least 112 turns that carries 765000 A current and this number is very large. Because of this high current we expect a magnetic tensile load close to in the range of 3.3×10^{10} N to 3.1×10^{11}N and radial pressure of 4 bar. Which means of course, it is good that it will have a very good turnaround efficiency during charging and discharging. Hence the choice of magnetic storage decides the type of material. When you choose this kind of material, we also have to make a judgment that what current density we are handling. And when we look for this current, we have to see that stability range for the current should be within the acceptable limit.

The next important segment of storing in energy is the chemical reaction storage and this is a kind of a thermal energy storage and we all know that a chemical reaction is characterized by endothermic or exothermic reaction. Endothermic reaction means energy absorbing, &exothermic reaction means energy releasing. So, these two characteristics behavior of a chemical reaction can be thought of charging and discharging process of energy. So, if by some mechanisms you can initiate this reactions and continuously the reaction becomes reversible then we can utilize this energy as storage mechanism. So, this concept we call this as a chemical reaction storage.

A reversible chemical process is used to store the thermal energy during an endothermic reaction. The energy is released during exothermic reactions. The heat of reactions, which is nothing, but the higher heating value which includes the condensation of water, is used in the process that is interpreted as energy stored during a chemical reactions. So, this is something similar to an alternative way which is thought of either in the absence of latent heat or sensible heat in energy storage medium. Now, this exothermic reaction which occurs in presence of a catalyst, is called as methanation and endothermic reaction is referred as reformation.

Why we are talking about methanation? Because we are considering a very familiar reaction, particularly applicable for nuclear reactor thermal energy storage systems which says that a reversible reaction in which carbon monoxide reacts with hydrogen to form methane and water. So, here two important catch is there one is process of methane formation, other is process of hydrogen generation and these reaction is reversible. When the reaction is reversible we can think that energy released during this process and energy absorbed can be interpreted. So, that is the way with respect to this reaction we call this as a methanation and reformation. So, reformation is a process by which low grade or low molecular weight hydrocarbon is catalytically reformed to high grade or high molecular weight hydrocarbon. So, this process is also referred as the production of hydrogen from methane and steam, in presence of nickel catalyst. Methanation is the production of methane from the mixture of carbon monoxide and hydrogen.

Now, to explain this let us try to understand this particular figure which talks about schematic flow diagram of a power plant using a chemical storage system, where we consider this chemical reaction as

Chemical reaction: $CO + 3H_2 \rightleftarrows CH_4 + H_2O \mp 250.3 \left(\frac{\text{kJ}}{\text{g.mole}}\right)$

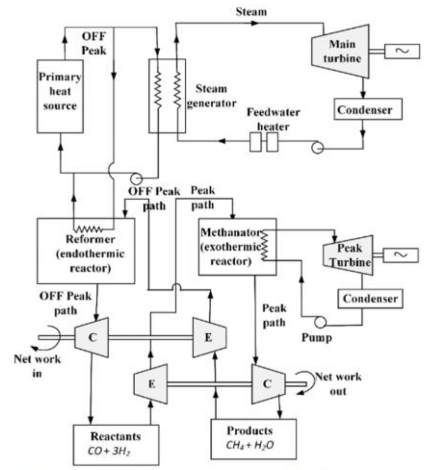
Methanator (exothermic reactor): $CO + 3H_2 \rightarrow CH_4 + H_2O - 250.3 \left(\frac{\text{kJ}}{\text{g.mole}}\right)$

Reformer(endothermic reactor): $CH_4 + H_2O \rightarrow CO + 3H_2 + 250.3 \left(\frac{\text{kJ}}{\text{g.mole}}\right)$

(Endothermic reforming of methane is also referred as production of hydrogen)

And reaction is reversible and through this reaction energy released or energy observed is close to $250.3\,{}^{\text{kJ}}/_{\text{g. mole}}$. And typically the power plant that operates using this chemical reactions is similar to a conventional main power plant.

So, if you take this particular part which is the primary plant and that operates at base load, we are just tapping some of the energy or heat from this primary heat circuit and form two reactor, one is reformer which is an endothermic reactor and other is methanator which is exothermic reactor. And for reformer which is an endothermic reactor, it takes out CH_4 and H_2O and for methanator, it takes CO and H_2. And this process keeps on happening for charging and discharging phase. Now, how it operates? Of course, both the reactors has to be operated at different pressures because your charging and discharging conditions are different. Normally the reformer operates at low pressure to maximize the rate of endothermic reaction. In the lean period certain quantity of heat from the primary heat source is diverted to this endothermic reactor, which is stored at ambient pressure and high pressure of 70 bar. During high demand period, the reactants are fed to a methanator, which is an exothermic reactor, where heat is generated to run the peak turbines.



Chemical reaction : $CO + 3H_2 \rightleftarrows CH_4 + H_2O \mp 250.3$ (kJ/g.mole)
Methanator (exothermic reactor): $CO + 3H_2 \rightarrow CH_4 + H_2O - 250.3$ (kJ/g.mole)
Reformer (endothermic reactor): $CH_4 + H_2O \rightarrow CO + 3H_2 + 250.3$ (kJ/g.mole)
(Endothermic reforming of methane is also referred as prduction of hydrogen)

Schematic Flow Diagram of a Powerplant with a Chemical Storage System

So, there are two turbines one is primary turbine other is peak turbine. So, the peak turbine operates with this fluid. And again the reactants are converted back to products which is stored in a separate vessel for later use in the reformer. And typically we are considering a storage pressure close to 70 bar and this storage units reactors can be kept either above ground in a large steel tank or it can be an underground cavern. And for this case of chemical reaction, we can expect the turnaround efficiency of 85% to 90%.

Reversible Chemical Reactions for Energy Storage

Chemical Reactions	Temperature Range (K)	Heat of reaction at 298 K (kJ/g.mole)
$CO + 3H_2 \rightleftarrows CH_4 + H_2O$	700 – 1200	250.3
$2CO + 2H_2 \rightleftarrows CH_4 + CO_2$	700 – 1200	247.4
$C_6H_6 + 3H_2 \rightleftarrows C_6H_{12}$	500 – 750	207.2
$C_7H_8 + 3H_2 \rightleftarrows C_7H_{14}$	450 – 700	213.5
$C_{10}H_8 + 5H_2 \rightleftarrows C_{10}H_{18}$	450 – 700	314
$C_2H_4 + HCl \rightleftarrows C_2H_5Cl$	420 – 770	56.1

So, this particular diagram gives the schematic of a chemical reaction storage. However, there are other possible reversible chemical reactions one can think of, for energy storage. Here we have only discussed about CO and H_2 give CH_4 and H_2O. Other combination is also possible CO & H_2 can give also CH_4 and CO_2, but at different pressure and temperature conditions. And here we can say that storing capacity falls in the range of 700-1200 K and heat of reaction we can expect at room temperature of 298 K as in the range of 250 $^{kJ}/_{g.mole}$. Apart from this there are other chemical energy storage situations, but those have lesser value of energy release.

The last segment of our energy storage section is hydrogen energy storage. Although it does not fall in our conventional loop of primary energy resources or thermal energy storage, but nowadays energy storage through hydrogen has received the attention around the globe because hydrogen is treated as an ultimate clean fuel and it is an energy storage medium and it can lead to zero carbon emission. These advantage have given the concept of hydrogen economy in terms of its storage and cheap transmission for a long distance.

The standard process of hydrogen formations can come from a very fundamental process that is electrolysis of water. By using electrolysis of water, we can get high quality energy that can be combusted back to water again without any pollution. However, production of hydrogen can happen by any of these following methods, which are thermal decomposition of water with thermochemical cycle, catalytic steam reforming of natural gas, industrial photosynthesis, ultraviolet radiation, partial oxidation of heavy oils and some reactions which we have already covered in chemical reaction storage, which is $CO + H_2 \rightarrow CH_4 + H_2O$. We can also think of a water gas reaction when you deal with the coal as a fossil fuel for the power plants, where we can see that carbon can mix with water to form CO and H_2, this is another way. Electrical decomposition of water through electrolysis which is a very standard method where 2 H_2O at cathode gives you H_2 + 2 OH and at anode we can get back the hydrogen.

Now the main drawback of this hydrogen is its extreme flammability because hydrogen gas is considered as a highly flammable gas which means 4% mole fraction in air is still flammable at room temperature. And it has also associated problems of storing under pressure. Hydrogen is very difficult to store. Hence liquefaction for hydrogen storage is a simple solution, but again it consumes lot of energy.

So, people have evolved various mechanism to find different routes to store hydrogen. One such things which already I have mentioned, is in the form of methane. One can think that CO and H_2 can give CH_4 and H_2O, & this process gives about energy release of 200 kJ and for reaction of carbon with hydrogen gives 73 kJ. So, one way is that through methane route we can store hydrogen. Other is through ammonia. And there is a standard process called as Haber process where nitrogen reacts with hydrogen to form ammonia. So, through this process we can have 90 kJ of energy.

So, basically speaking all these reactions talks about the various mechanisms for how we can store hydrogen not in its purest form but in the other forms. One way is methane, other is ammonia. Through this process the advantages we get are higher energy density, easy liquefaction process and safe storage. So, hence hydrogen is considered as primary fuel for peak power generation.

Apart from this storing mechanisms like in a compressed gas form, liquefied form or chemical compound, there are other possible method in the form of metal hydrides. Nowadays this is receiving a very good catch. Why we look for metal hydride based storage systems? Because first point is the cost of liquefaction is high and bulk storage of hydrogen as a compressed gas requires large size underground caverns which is similar to a natural gas. Hydrogen in chemical compound like methane or ammonia is more commendable to energy storage. Liquid hydrogen has mass energy density three times higher than any other fuel, but it requires cryogenic temperature & is highly inflammable, but this process of storing is a very costly affair. But the storing liquid hydrogen is very much attractive for thrust generation in heavy surface transports and aircraft, mainly rocket engines use liquid hydrogen as a fuel. The principal disadvantage high pressure hydrogen storage system is that it is highly explosive and require large storage space.

So, every method has its own advantage and disadvantage, but another choice that people think of is the concept of metal hydrides. This is another alternative or viable option. So, how this metal hydrides works? The primary aim is to select a hydride which can be thermally decomposed in a reversible manner so that hydrogen may be withdrawn or entered into the system. The choice of metal hydrides has many desired features, like they have high hydrogen content per unit mass of the metal, low dissociation pressures at moderate temperatures, constant dissociation pressure during decomposition, safe exposure to atmosphere and low cost. When hydrides are used as hydrogen stores in heat engine, the waste heat again can be returned to hydrides and act as a thermal storage device. So, hydrides has additional advantage that is waste heat thermal energy storage.

So, considering this typical advantage of metal hydride based storage systems, I am trying to emphasize how it works and what is its viability. Typically we say that when hydrogen reacts with a metal it forms a hydride and heat. So, we say charging means it is heat release and discharging means heat addition.

For example, $FeTiH_{1.7} \rightarrow FeTiH_{0.1}$ (1856 kJ/kg). If you take this material, $FeTiH_{1.7}$ & when it becomes another compound $FeTiH_{0.1}$ it releases 1856 kJ/kg.

$Mg_2NiH_4 \rightarrow Mg_2NiH_{0.3}$ (4036 kJ/kg). Other kind of material is in terms of magnesium. Magnesium through this process hydride systems we can expect 4036 kJ/kg of energy.

$MgH_2 \rightarrow MgH_{0.005}$ (9198 kJ/kg). Third choice is magnesium hydrogen, it can give 9198 kJ/kg of energy.

So, what I am trying to say is that choice of metal hydrides in titanium, magnesium and iron has a definite scope as a metal hydride based storage systems. So, you can typically compare a conventional liquid fuel which is nothing, but your fossil fuel with respect to hydrogen and hydrogen can be stored either in the gas form or liquid form or metal hydride form. We can say it is a relative comparison. Mass energy density for conventional fuel is 44000 kJ/kg whereas, for hydrogen it is 140,000 kJ/kg. Similarly of course, volume density will be less for hydrogen that is 1700MJ/m^3. And for conventional fuel volume energy density is high. Now if you talk in terms of liquid and metal hydrides, they are also equally compatible, but when you talk about metal hydrides, their volume energy densities are relatively high. So, that is the catch, when you store energy we have to store in terms of its volume part. So, this is how we can say that hydrogen is one economic or viable energy options as a clean and renewable fuel and which is catching the attention across the globe, mainly because it has a cheap transmission energy over long distance. So, conceptual thoughts one can have is that from a large scale power station if we want to extract hydrogen energy, there are possibilities that we can think of storage underground, we can store in terms of liquid, then through this transmission process, we can fed it to power station, we can use as industrial fuel, we can have synthetic chemicals, we can also explore as the domestic fuels. So, this particular cheap transmissions of energy gives you attention for hydrogen for next generation systems. So, with this I complete entire module. So, after completing the entire module I will now try to revisit what we have explained in our intro lectures.

The entire course has been constituted in four modules. Module 1 review of concept of basic thermodynamics, where I have emphasized about the basic requirement to understand this course for various concepts which are covered in this course. And in the module 2, we cover the complete module considering about 50% of our lecture components. Third module is on gas turbines and combined power systems, where I try to emphasize about gas turbine as power generation, gas turbines as thrust generation and combined power systems and to some extents I have given some brief introduction about aircraft propulsion systems. And other important module that is the last module, which is on hydro and renewable energy generation systems and we can say this complete process involves energy conversion, we have thermal energy, electrical energy and mechanical energy. And variety of other resources which we have covered in our module is hydro and wind. We have covered geothermal energy to some extent we have covered chemical fuels. We also covered most of the case of thermal energy from the coal combustions then we have latent heat energy storage and sensible heat storage. Through the electrical case, we have battery storage, magnetic storage and in mechanical form of energy we have considered about the flywheel storage, hydro and wind, so much things we have covered. But what we have not covered is solar and nuclear. However, these two courses are very vast and I mean in future we may think of developing similar courses on solar and nuclear. However, these courses are very specific in nature and of course, in these two cases many resource materials are already available. So, with these notes I conclude my lectures and I hope great success to all of you in the final exam. Thank you for your attention and thank you for your time that you have spent & devoted in understanding these lectures. Thank you for your attention.