POWER PLANT SYSTEM ENGINEERING

Lec 5: Modified Rankine Cycle

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course, Power Plant System Engineering module 2 that is Vapour Power System part 1. So, in this lecture we are going to cover the following topics. So, in our previous lecture we covered about the Rankine cycle. Here we will see that how performance enhancement can be done for a Rankine cycles. Under this segment we have three important cycles for vapour power systems.

One is super heat cycle, other is reheat cycle, third one is regenerative cycles. More elaborate mathematical modeling and thermodynamic analysis will be covered in this lectures. So, let us see first thing is that why there is a necessity for enhancing the performance of a Rankine cycle. So, first of all when you dealt with an ideal Rankine cycle, we say that saturated steam at state 1 expands in the turbine.

So during this expansion process we land off at the exit of the turbine, the steam quality to be not par with respect to operating requirement for the turbine. In general turbine blades are then designed to operate the steam in vapour state, but if the quantity of water vapours or quality of the steam is not adequate then it it normally erodes the turbine blades. For that reasons, the turbine blade degrades. Now, when it degrades, to overcome this problem what we thought of is that steam quality is retainedat least 90 percent in the turbine exit. So, if you want to retain the steam quality of the turbine exit that is state 2 or $2''$ then we must push the inlet state to somewhere in this domain.

That means, 1 should be pushed off to the superheated region. And when we say it is a superheated region; so, thereby what advantage we get is that after expansion, the quality of the steam always remains in the vapour regions. That is one aspect, second aspect that when you do the super heating, we are actually going for the mean temperature of heat additions for the fluid. Through this process you have the higher work output because another important aspect is that when you go to the superheated regions, due to the divergence of the constant pressure line, this difference that is Δh becomes progressively higher if you handle the steam in the superheated regions. And here two things that gets ensured through the super heating, one is higher expansion workin the turbine, second is quality of the steam becomes at least more than 90 percent.

The other method of increasing the thermal efficiency of vapour plant is providing a regenerative feed water heating or regenerations. So, this thermal circuit diagram we will revisit subsequently, but here through this regeneration, what we essentially do is that the if you consider the ideal cycle that is 1-2-3-4-a-1 and another you can say $1' - 2' - 3 - 4 - a - 1'$. In any of the cases what we actually do in the regenerative system is during the expansion process you take some fluid out and suppose during this expansion process from 1-2, 1 unit of fluid is entering and you tap y amount of fluid or steam through another process. So, that is what we call as a feed water heating systems and rest of the things we expand in the turbines. So, through that process what actually goes into the boiler is that a thermodynamic states which is 4a which is in between the state 4 and state a.

So, through this regenerative methods we are actually increasing the mean temperature of heat additions. In fact, this is more logical in many of the senses because most of the times we have exhaust steams coming out various locations in the power plant and those exhaust streams can be tapped to do this kind of heating systems. So, this particular method we call as feed water heating systems or regenerations. It can be an open system or it can be a closed water feed water heater. Then let us first see the important modification that you do in the Rankine cycle which is super heat cycle.

We already mentioned that quality of the steam at the turbine exit should be at least 90 percent. How we need to do the super heating arrangement is like this, in a conventional cycle which is 1-2-3-4-a-1, it operates at a state when the steam is at saturated vapor. Now, through this super heating process what it says is that once we reach the state during the heating process in the boiler that is from 4 to 1, heat is added till we reach the state 1, but in a super heating systems we say that keep adding heat to the steam and so that we reach the region which is called as a superheated region or if you say this is liquid plus vapor, this is pure liquid and this is only vapor regions and we call this as a superheated vapor. So, through this process once you do this, now at the state 1 we expand the steam in the turbine so that we land of the exit condition of the turbine as 2' and obviously, quality of 2' is greater than quality of 2. So, $x_{2'} > x_2$.

So, through this process we solve the problems of not getting eroded of the steam turbine blades. Now, coming back to the boiler sides so, the essential or extra arrangement that you do is that we need to have a another unit called as a super heating unit and the boiler and super heating unit combinedly is called as steam generator. So, we look into the steam generator in more details in the subsequent modules, for the time being we just have to understand the steam generator term nothing but includes boiler and super heating systems that supplies necessary heat to the working fluid. So, from subsequent onwards we will now see that only superheated cycle can give a better thermal efficiency. The another part is a reheat cycle.

So, ideally speaking reheat cycle and super heat cycle they run in parallel because normally we take the advantage of this reheat because in the reheat systems first you need the expansion process in the turbine is done in two or more phases. So, first phase is called as high pressure turbine, second phase is called as low pressure turbines. So, let us understand how we achieve this. So, once the steam from the boiler at state 1; state 1 stands at this super heated region at temperature T_1, it enters to the high pressure turbine unit. Now after the expansion in the high pressure unit, so state goes to 1 to 2.

So, the thermodynamic process of expansion or isentropic expansion from 1 to 2 takes place in a high pressure turbine, at point 2 the steam is again reheated. So, instead of expanding further it is reheated and when it is reheated it goes to the state 3 and this reheating systems happens again in same boiler unit. However, while doing this reheating we necessarily do not go to the state point 1, somewhere less than that. So$T_3 < T_1$. Now the steam at state 3 enters to the low pressure turbine unit and it expands.

So, there are work output happens in $h_1 - h_2$, the first part and second part is $h_3 - h_4$. So, these two additionally enhances the work output. So, this is the advantage what we get in a reheating process. So, ideally speaking then the system goes to 4 to 5 in a condensing unit, 5 to 6 in the pump and again from 6 to 1 it goes in a boiler. So, this is all about the reheat cycle. Now, there is another concept of called as supercritical reheat cycles. So, what we understand the supercritical system is that for every working fluid or pure substance it has the thermodynamic diagrams like PV diagram, TS diagram; for example, for steam if you draw the state of the working fluid in a TS diagrams, we have liquid regions we have liquid plus vapor regions then we have vapor regions. Now while operating the reheat cycle, we really do not go beyond this saturated dome. So, classical process of going to this is that the state of the system goes within this liquid vapor regions and that happens in a constant pressure line. Now what the supercritical system tells is that you increase the pressure such a way that we cross this critical point. So, that the liquid directly goes to the steams without crossing this liquid vapor regions. That means, in this boiler arrangement or our steam generator unit is equipped in a such a way that we create a pressures and such that liquid water goes directly to the steam and that means, in that case we have to operate the pressure at which it is above the critical pressures. Now for water, this critical pressure is 22.1 Megapascal. In other words it means that you retain the pressure in the steam generator which is about 22 MPa or above, through this, from 6 to 1 we can directly reach in a cycle which is called as supercritical cycles and essentially the cycle does not cross the liquid vapor regions, but although there are infrastructure difficulties, but they are higher efficient than the conventional reheat cycles.

And for a supercritical cycles we need to have a combustion process which can be achieved through pulverized coal or coal powder and specialized steam generators. Now just to give you some brief idea that what advantage we get using a supercritical reheat cycle is that if you use a conventional steam reheat cycle, then maximum efficiency we can achieve is 40 percent with all types of augmentations, but when you think about a supercritical power plants. So, we need to expect that steam generator should operate at more than 22 mega Pascal or above. Now a close thermodynamic analysis reveals that a supercritical power plant which operates at 30 MPa and 600 degree centigrades if you can design this, then we can achieve efficiency up to 47 percent. Now ultra supercritical power plant they again go beyond such pressures like they operate somewhere are about 35 mega Pascal and 700 degree centigrades for that we can achieve efficiency up to 50 percent.

So, except the installation difficulties supercritical power plants have more advantages as compared to the conventional power plants operating through a reheat cycle. Then we will move on to regenerative cycles. So, we have understood superheat cycle, reheat cycle then we will move to regenerative cycles. Let us try to understand this reheat cycle. So, before that we have said that we require superheating for the steam to expand in a turbine. So, if you take this as an advantage then what we can say that during a continuous expansion process in the turbine that is from 1 to 3, we think of tapping some amount of water or some amount of mixture through some process and that is essentially achieved through a open feed water systems. What you typically do is that, the turbine stage is designed in 2 folds one is stage 1 and second is stage 2, we may think of high pressure stage and stage 2 is a low pressure stage. During this expansion process that means, when the steam enters into the turbine at state 1, after certain expansion that is at state point 2 somewhere here, we tap y quantity of mass or steam. Suppose we have 1 unit of steam which is entering, at state 2 we tap y quantity of steam and allow the rest 1-y quantity to expand in the next stage turbine and in this condenser process also that is from 3 to 4, 1-y unit gets condensed. So, it reaches at state point 4, then from 4 there is a feed water pump that takes this 1-y quantity of saturated liquid at state 4 to state 5 and then you allow it to enter into a open feed water systems and when you allow to enter to the feed water systems, there it meets y unit of steam.

So, thereby additional heating we get from this steam and again the combined working fluid that is y unit of steam which is entering along this line and 1-y unit of condensed water it mixes with y unit of steam and the combined system enters into the boiler at state 7. So, through this process what happens is that your $\frac{\dot{Q}_{in}}{\dot{m}} \rightarrow h_1 - h_7$. So, in that process what happens your additional load from the boiler is reduced. So, when additional heat load is reduced. So, we have enhanced thermal efficiency of the plant.

So, had this process been done without reheating then from 5 to 1, the boiler load would have been bringing the state from 5 to 1. Now it becomes from only 7 to 1. So, through this process your heat addition into the boiler is reduced. So, this is the advantage that we get in an open feed water systems. So, in practice the operating conditions are such that reduction in heat addition is more than the offsets with respect to decrease in the work output and there is a enhancement in the thermal efficiency.

So, we will see a brief look into the cycle analysis. here our attention is focused to the mass balance equations that happens when you tap this heat in the turbines. So, we say that at state 1, 1 kg of steam which enters and at 2 we take out y unit or y kg of steam and rest of the steams 1-y, it is allowed to expand in the second state turbine. Then subsequently 1-y goes into the condensing unit and ultimately at state 6 both the fluids mixes and this goes to the state 7. If you can do this mass and energy balance we can write it for this mass balance that is $\dot{m}_2 + \dot{m}_3 = \dot{m}_1$. So, state 3 is somewhere here, state 2 is this and so $\frac{\dot{m}_3}{\dot{m}_1} = 1 - y \& y = \frac{\dot{m}_2}{\dot{m}_1}$.

So, through this we can find out actually how much y we are going to get. Now, if you can take a close look of this feed water systems, this energy rate balance we can frame and through this process, we can find out what is the value of y. $yh_2 + (1 - y)h_5 - h_6 = 0 \Rightarrow y = \frac{h_6 - h_5}{h_2 - h_5}$. Then subsequently in the same procedure we can get turbine work, pump work, Q in, Q out.

$$\text{Turbine work:} \frac{\dot{W}_t}{\dot{m}_1} = (h_1 - h_2) + (1 - y)(h_2 - h_3)$$

$$\text{Pump work:} \frac{\dot{W}_p}{\dot{m}_1} = (h_7 - h_6) + (1 - y)(h_5 - h_4)$$

$$\text{Energy added to working fluid:} \frac{\dot{Q}_{in}}{\dot{m}_1} = (h_1 - h_7)$$

$$\text{Energy rejected by heat transfer to cooling water:} \frac{\dot{Q}_{out}}{\dot{m}_1} = (1 - y)(h_3 - h_4)$$

Now, if you look at this open water feed water system, actually there are two pumps that is pump 1, pump 2 and pump 1 stands for condensing 1-y unit of steam and whereas, pump 2 stands for pumping entire unit of the mass that enters at state 6 and it takes from this pressure at 6 to the boiler pressure. So, here in an closed feed water systems the main intention was that steam is not allowed to mix.

So, what it means is that the y unit of steam that comes at state 2 and it does not mix with the condensate that comes at state 5. That means we are only tapping the heat of the steam not the mass which gets mixed. So, there is no mixing is allowed in this closed feed water systems. So, thermodynamically if you look at this diagram we start with state 1, at state 2 we take out y unit of steam remaining 1-y unit expands in the low pressure turbine. Now when you are at state 3, at state 3 we condensate this 1-y unit through this condensate line.

Then what happens to the rest y, at state 7 that means after the this y unit of steam enters the saturated liquid we use a trap system. So, that only traps the vapour. So, thereby the condensate or liquid state comes at somewhere in the state 8. So, entire fluid mix at 8 and then again it goes to the state 4 and the state 4 is nothing, but in the condensing unit and then entire process is repeated and the we get the state 5 as the exit of the closed feed water systems. And then from 5 to 6 and 6 to 1 is the heat addition process.

So, additionally what advantage we get here, there is no extra additional pump. So, only one pump which is actually used in the conventional power plant that is sufficient to run this type of system. So, this is all about3 important cycles reheat, superheat and regenerative cycles. So, some of the advantage of this reheat cycle I can say is that reheats gives additional benefit of getting more power output and improving the quality of the steam. And again regenerative cycle reduces the heat load in the steam generator and thereby cycle efficiency gets improved.

Some of the power plants can operate in both modes like reheat and regenerative modes to get enhancement in both power output and efficiency. And with respect to the closed feed water systems, there are some advantage which says is that there is no extra pumping requirement. So, with this I completed this part now at the end of this lecture we will try to solve a numerical problems. So, this numerical problem is based on a Rankine cycle that operates with reheat and superheat. Reheat and superheat I mean the we have to draw the thermodynamic cycles which means that we are operating the steam in the superheated regions and at the same time we need to take the advantage of reheat.

So, the problem is that the steam enters the first stage of turbine at 8 MPa and 480 degree centigrades it expands to 0.7 MPa. So, let me redraw the thermodynamic cycle. So, in a T-S diagram we first define the states. So, we have the first pressure line which is the highest pressure line which is 8 MPa, second one is second pressure line where reheating is done 0.7 MPa and third one is condenser pressure line that is 0.008 MPa. So, we are at state 1, that state 1 is 8 MPa, 480 degree centigrades. Then after expanding to 0.7 MPa, it is reheated to 440 degree centigrades. So, that means, we are somewhere at state 3, which is 440 degree centigrades and state 1 is 480 degree centigrade. The net power output of the cycle is 90 MW. So, we get 90 MW as power output from the cycles. The each turbines operate with 88 percent efficiency.

So, turbine efficiency is 88 percent. So, this makes us aware that the state 2 has to take into account of the isentropic efficiency for the turbine. So, for that reason this is irreversible process. So, state 2 will be somewhere here and had it been the isentropic process corresponding point would have been 2s. Similarly, state 3 isentropic process and 4 would be an irreversible process and 3-4s is isentropic process and 3-4 is irreversible process. So, point 4 is located. Then from 4 – 1, it goes into the condenser and it reaches to state 5. Then at 5, there is a pump that takes the saturated liquid to a boiler pressure and then from 6 to 1 it goes through this manner. So, this is your heat addition process Q in, W_{T1} & W_{T2} is power recovery process and heat rejection process we say Qout and this is Wp. So, we have to individually calculate all these numbers. So, this problem is nothing but we have to revisit the steam table and once you draw this cycle diagrams, it is possible to note down all the thermodynamic states from the steam table.

$$State - 1@8MPa, 480°C: h_1 = 3348.4\frac{kJ}{kg}, s_1 = \frac{6.66kJ}{kg-K}$$

$$State2\ \&\ 2s\ @0.7\ MPa, T_3 = 440°C: s_f = 1.992 \frac{kJ}{kg-K}; s_g = 6.708\ \frac{kJ}{kg-K}; h_f = 697.22 \frac{kJ}{kg}; h_{fg} = 2066.3\ kJ/kg$$

$$As\ s_1 = s_{2s} \rightarrow x_{2s} = \frac{s_{2s} - s_f}{s_g - s_f} = 0.9895$$

$$h_{2s} = h_f + x_{2s}h_{fg} = 2741.8 \frac{kJ}{kg}$$

$$\eta_t = \frac{h_2 - h_1}{h_{2s} - h_1} = 0.88 \rightarrow h_2 = 2814.6 \frac{kJ}{kg}$$

$$State - 3@0.7MPa, 440°C\ (Superheated): h_3 = 3353.3 \frac{kJ}{kg}, s_3 = \frac{7.757\ kJ}{kg-K}$$

$$State4\ \&\ 4s\ @0.008\ MPa: s_f = 0.5926 \frac{kJ}{kg-K}; s_g = 8.2287\ \frac{kJ}{kg-K}; h_f = 173.88 \frac{kJ}{kg}; h_{fg} = 2403.1\ kJ/kg$$

$As\ s_3 = s_{4s} \rightarrow x_{4s} = \frac{s_{4s}-s_f}{s_g-s_f} = 0.9392$ (which clearly says that the exit rate is more than 90 percent, this advantage we get through this reheat and superheat)

$$h_{4s} = h_f + x_{4s}h_{fg} = 2428.5 \frac{kJ}{kg}$$

$$\eta_t = \frac{h_3 - h_4}{h_3 - h_{4s}} = 0.88 \rightarrow h_4 = 2539.5 \frac{kJ}{kg}$$

So, we are left with 5 and 6 conditions and that is nothing but for the pump. And you have to find out the saturated liquid state for the pump which is operating at 0.008 mega Pascal from condenser pressure to the boiler pressure of 8 mega Pascal. To do that we need to revisit data for saturated liquid at 0.008 mega Pascal.

$$Sat. Liquid\ at\ 0.008MPa: h_5 = 173.88 \frac{kJ}{kg}; v_5 = 1.0084 \times 10^{-3} \frac{m^3}{kg}$$

$$h_6 = h_5 + v_5(p_6 - p_1) = 173.88 + 1.0084 \times 10^{-3}(0.008 - 8) \times 10^6 = 181.94\ kJ/kg$$

So, we have till this point of time we have all the data for all the thermodynamic states, then we have to relook into the part by part analysis. First one is thermal efficiency, mass flow rate of steam, heat transfer into the working fluid into the boiler and condenser.

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{t1} + \dot{W}_{t2} - \dot{W}_{p}}{\dot{Q}_{in}} = \frac{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)} = \frac{1339.6}{3705.2} = 36.15\%$$

Second part is mass flow rate of steam. So, for mass flow rate of steam we know that net power is 90 megawatt. So, $\dot{W}_{cycle} = \dot{m}W_{net} = 90 \times 10^3 \rightarrow \dot{m} = 67.2\frac{kg}{s} \approx 2.4 \times 10^5 \frac{kg}{hr}$. Now, heat transfer into the working fluid in the boiler.

$$\dot{Q}_{in} = \dot{m}(h_1 - h_6) + \dot{m}(h_3 - h_2) = 67.2 \times 3705.2 = 248986\frac{kJ}{s} \approx 249MW$$

$$\dot{Q}_{out} = \dot{m}(h_4 - h_5) = 67.2 \times (2539.5 - 173.88) = 158970\frac{kJ}{s} \approx 159MW$$

So, in summary we can make out is that we have supplied 249 megawatt of energy to produce the work of 90 megawatt and in this heat rejection process we have rejected 159 megawatt . So, this process leads to overall efficiency of about 36 percent. So, this is a realistic scenario for a steam power plant that operates with reheat and superheat mechanism. So, with this I conclude. Thank you for your attention .