POWER PLANT SYSTEM ENGINEERING

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Module 2

Lec 17: Feed Water Heaters

Dear learners, Greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering Module 2, Vapor Power System Part 3. In this lecture, our main intention is to study feed water heaters. So, here the learning components would be as follows. First one is the condenser and feed water systems which we discussed in our last class. Then we will revisit the regenerative cycles which were studied in the beginning of this module. Why we go for this regenerative cycle? Because this regenerative cycle uses closed and open feed water concepts. So, we will try to see thermodynamic viewpoints, some of the design aspects of closed and open type of feed water heaters. Then towards the last segment, we will discussed about boiler treatment concepts. So, let us start with this concept of condenser and feed water systems.

We discussed this concept in our previous lectures, where in a condensate feed water systems, the condenser plays a dominant role. And during this condensation process, the steam from the turbine exhaust loses heats and condense to liquid water. So, this is the role of condenser, but at the same time the story does not stop here, rather we also require feed water systems that can supply the required quantity of water at a pressure which is desired at the boiler end. In fact, either you look at condenser or feed water system directly which is supplied from the atmospheric reservoirs, all these things come under the single entity and we call this as a feed water system.

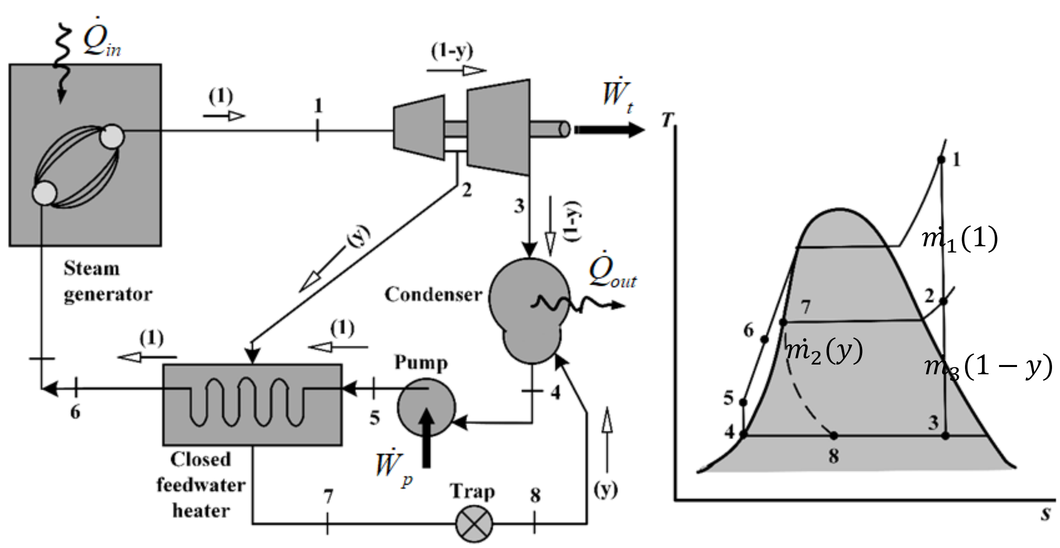
And moreover, the feed water is normally supplied at an elevated temperature to reduce the boiler load. This is another kind of requirement that we need for this power plant system. All these needs has to be addressed by these thermodynamic concepts which we discussed earlier that is through regenerative cycles. So, let us see how this regenerative cycle concept helps us in deciding the role of the feed water heater system. To keep the brief concepts, the combined analysis of condenser and feed water heaters is called condensate feed water systems and the plant heat rejection system also deals with circulating water treated separately through cooling water and that cooling water is supplied from the cooling tower, which is also part of this feed water system. But the role of condenser is only to condense the exhaust steam from the turbine and to recover high quality feed water to be reused in the cycles.

So, considering all these things, let us see how this modified Rankine cycle can help us. So, in our earlier discussions in modified Rankine cycle, it was emphasized that the necessity of the regenerative feed water heaters is required for improving the cycle performance. And the role of these feed water heaters is to rise the temperature of the water before it enters to the steam drum or steam generator. And by doing so, they raise the temperature up to 200 - 250℃. And when you rise this temperature to this end then obviously, the boiler load also will come down. So, essentially these feed water heaters are kind of a heat exchangers which is either a closed type or open type.

Closed type means, the streams are not allowed to mix while exchanging the heat, but in an open type or direct contact type or deaerating type heaters, the streams are allowed to mix and when they mix obviously, they will come back to a single temperature and pressure. So, that is maybe, you can say a drawback for an open type or direct contact type feed water heaters. Now, let us revisit the modified Rankine cycle and one of the concept was a regenerative cycle. So, the concept of regenerative cycle is that, if you look at this thermal circuit of a modified Rankine cycle, we have a steam generator and there are two stages of turbines then we have condenser pump and additionally we have a unit called as closed feed water heater. This means, essentially requirement is that, at the exit of the condenser, the thermodynamic state of this is at saturated liquid state that is state 4 and this has to be pumped to the generator pressure means that liquid has to be pumped.

But essentially when you want to pump it, we also need the temperature of this water to be increased so as to reduce the boiler load and to achieve this, normally you tap some of the steam from one of the turbine ends. One is high pressure or the other is low pressure turbine. So, you tap some of the steam from the HP turbine and then that heat used to heat up the water. So, essentially we do this dual load and through this heating process, the steam will get condensed and that will be trapped again in the liquid mode and then again goes back to condenser. So, this is the concept of tapping the water or steam from some end of turbine and reusing heat for heating the water. And you can say this particular thermal circuit is for a regenerative feed water systems which involves closed feed water heater.

Closed feed water heater means, it is a kind of a shell and tube heat exchanger, where the temperature of the steam is dropped because it exchanges heat with the water, which is at the outlet of the pump and this heated water again goes to the steam generated at its



desired pressures. And here main intention is that both the steam that is the steam that is tapped from the turbine and the water that enters from the pump they do not mix. So, that is the thing why you call this as a close type feed water system. So, here the concept, which you have already discussed so far, goes like, if you say 1 unit of steam enters into the first stage of turbine that is HP turbine at state 2 and we take y unit of steam and rest

1- y unit of the steam expands in the turbine and then that condenses in the condenser. So, liquid water enters into the pump then this y unit of steam heats the 1- y unit of water, so, that we again get back 1 unit of steam at the state 6.

So, through this process, we can do the mass balance and energy balance for the closed feed water system. Now, for the closed type feed water system, we can write the mass balance equations as stated below. $\dot{m}_1$ Which is entering from the state 1 is diverted by two parts. One goes as $\dot{m}_3$ and other goes $\dot{m}_2$. So,

Mass balance :$\dot{m}_2 + \dot{m}_3 = \dot{m}_1 \Rightarrow \frac{\dot{m}_3}{\dot{m}_1} = 1 - y \;\&\; y = \frac{\dot{m}_2}{\dot{m}_1}$

Now, for this 1 unit of steam, we can write the energy rate balance as stated below.

Energy rate balance:$y(h_2 - h_7) + (h_5 - h_6) = 0 \Rightarrow y = \frac{h_6 - h_5}{h_2 - h_7}$

This is this energy balance is done for the feed water. Thereby, we can get back the fraction of the steam which is extracted.

Then obviously, we can get back the turbine work that is in the first stage of turbine, we get $(h_1 - h_2)$ and in the second stage turbine we get $(h_2 - h_3)$, but the steam flow rate is$(1 - y)$

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

And similarly for the single pump present here we get,

Pump work:$\frac{\dot{W}_p}{\dot{m}_1} = (h_5 - h_4)$

Energy added to working fluid:$\frac{\dot{Q}_{in}}{\dot{m}_1} = (h_1 - h_6)$

And obviously, when you see the heat added for the working fluid it will be $(h_1 - h_6)$. Since it is already at elevated temperature so, essentially the temperature has already gone to state 6. So somewhere at point 6 heat will be added and this temperature from h_5 to h_6 is attained by the feed water system.

Energy rejected by heat transfer to cooling water: $\frac{\dot{Q}_{out}}{\dot{m}_1} = (h_3 - h_4) - y(h_3 - h_8)$

So, these things were discussed in the regenerative cycle.

There is another concept in the same regenerative cycle study that is open feed water concept. So, in our last analysis in the closed water systems, the two streams that is tapped steam from the turbine and the water from the pump they are not allowed to mix. But an open feed water system is a direct contact type heat exchanger, in which streams at different temperatures mix to form an intermediate temperatures. So, this mixing is done in this open feed water unit. And obviously, when there is a mixing, you can see that the y unit of steam which is at state 2 is at a different pressure and (1- y) unit of liquid water at the exit of the pump is also a different pressure and temperatures, and when they mix, the combined system has a thermodynamic state at 6 where the pressure and temperatures are not same at which they entered. So, we require another pump because we require the same the water to be pumped. Although its temperature has increased, but the pressure again drops, so we require a second pump which can push this water to boiler pressure or steam generator pressure. So, that is the reason we require two pumps in an open feed water regenerative cycle.

So, rest of the concept remains same and if you do this analysis for an open type feed water system for a regenerative cycle, similar study we can make that is mass balance and energy balance equations for open type of feed water. Only difference is that if you look at the circuit, for open feed water the y units of steam at enthalpy state 2 enters and again another entry comes from h_5 state that is from pump end which is (1- y) unit at state 5. But what is leaving is $-h_6$ that is $y + (1 - y) = 1$ unit. So, from this we can get back the fraction of steam which is extracted at state 2.

Mass balance: $\dot{m}_2 + \dot{m}_3 = \dot{m}_1 \Rightarrow \frac{\dot{m}_3}{\dot{m}_1} = 1 - y \,\&\, y = \frac{\dot{m}_2}{\dot{m}_1}$

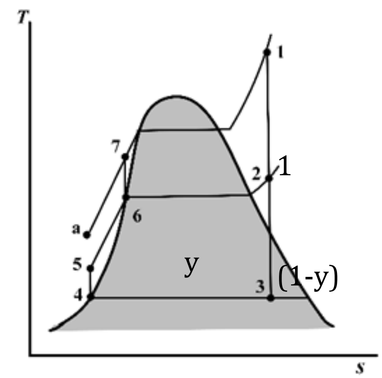
Energy rate balance: $yh_2 + (1-y)h_5 - h_6 = 0 \Rightarrow y = \dfrac{h_6 - h_5}{h_2 - h_5}$

And in this analysis also, we can calculate the turbine work.

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

Similarly there are two pumps one at W_{p1} and W_{p2}. So, for first pump 1, we have (1-y) unit of water and $(h_5 - h_4)$ for its enthalpy and for second pump it goes from h_6 to h_7 that is only for 1 unit of working fluid.

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

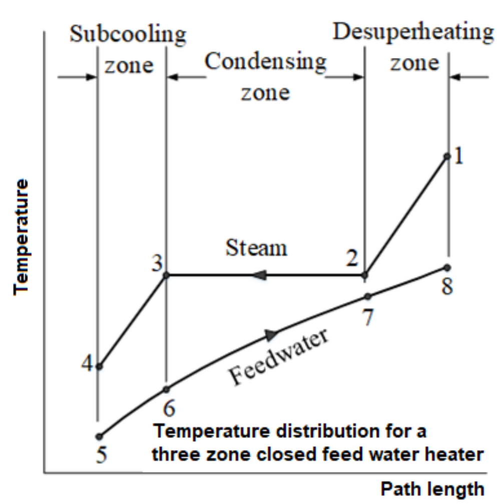


If you look at this particular diagram, the picture becomes clear. So, in an open feed water, you take 1 unit, (1- y) unit further expands & this y unit goes to state 6 and then it is pumped to state 7 and again (1- y) unit goes in the condenser line. So, in the first pump, it goes to state 5 then it mixes with state 6 and finally, again becomes 1 unit and it goes to 7. So, thereby pressure as well as temperature is increased in a regenerative cycle with open feed water heater arrangement. So, this is all about the thermodynamic aspects.

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

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

Now, further we need to know essentially for a closed and open feed waters, what are the typical arrangements normally we do. We all know that these closed feed water heaters they are nothing, but kind of a shell and tube type heat exchanger. So, shell is considered for steam which is tapped from the turbine and tube is considered for the water that enters from the pump end and within this feed water heater there is an exchange of heat.



Temperature distribution for a three zone closed feed water heater

Now, we need to know through this exchange process, what happens?

If you look at this particular diagram, ideally the steam that comes from the state 2, which is kind of a superheated region, its temperature drops first. So, as the temperature drops, we say it is a de-superheating zone. So, in the first process the temperature drops. Now, when it reaches to this saturated point that means when it is at saturated vapor at state 2 then steam starts condensing in this closed feed water system. So, when it condenses, it releases latent heat of vaporization and then it reaches to saturated liquid. So, saturated liquid means which is tapped from the state 7 and then there is a sub cooling zone. The second part is called as a condensing zone and third is sub cooling zone. And in the sub cooling zone further drop in temperature takes place from 3 - 4.

So, basically speaking the steam follows a reverse path, what is normally done in a reheater or boiler unit. And through this process, the feed water temperature sequentially increased from 5, 6, 7 and 8. So, this concept is similar to condenser, but its role is completely different from the condenser. Here the role of the feed water system is to supply necessary heat for the steam from the water to reach the boiler pressure.

Then there are some words that we use, that is shell side steam is called blade steam. And suppose when you trap the steam from the low pressure turbine, it is at 40 bar and if you take trap from the high pressure turbine, it may go around 80 bar. So, in other words, we can say that feed water system should have capability to operate at this high pressure range. So, that is the reason normally close type of feed water system is preferred because they can handle such a large pressure drops. Then this heater has some units, we call it as a deep separating zone, where the steam is cooled to saturation temperature & then it is followed by a condensing zone where latent heat of vaporization is removed and finally, steam is condensed to saturation temperature. Then there is a word that is used like heater drain. So in the condensing zone, which is somewhere between 2 to 3, the steam releases the latent heat of vaporization. So, this liquid which is formed is called as heater drain for all types of feed water heaters. Similarly there is a sub cooling zone or drain cooling zone in which steam is cooled below the saturation temperature.

So, in general the close type of feed water systems be of three zone type, two zone type or a single zone type, depending on the nature of heat release. So, depending on the condition of steam at state 2, one can imagine or design the feed water either as a three zone type or two zone type or in fact, it can be a single zone type. For example, for sub cooling zone you may have different arrangement that means, we can design the feed water only for condensing zone and in most of the cases it is preferred to use this condensing zone type feed water unit. And the orientation and location should be at par, either it can be vertical or horizontal positions depending on the availability of the pressure line. That means, whether the feed water has to be operated in connection with high pressure turbine or low pressure turbine, it depends on the location and space availability for the power plant system unit.

Now, let us see some of the heat transfer concepts. So, we all know that while designing this feed water, we also need to calculate the heat load. A general expression of heat load can be represented as follows.

Heat load, $Q = UA_0(\Delta T_m) \Rightarrow A_0 = \dfrac{Q}{U(\Delta T_m)}; A_m = \dfrac{(A_o - A_i)}{\ln\left(\frac{A_o}{A_i}\right)} \approx \dfrac{A_o + A_i}{2}$

If it is only operating in the condensing zone, LMTD expressions becomes follows this expression; this one aspect.

Logarithmic mean temperature difference, $\Delta T_m = \dfrac{(\Delta T_i - \Delta T_e)}{\ln\left(\frac{\Delta T_i}{\Delta T_e}\right)} = \dfrac{(T_3 - T_6) - (T_2 - T_7)}{\ln\left(\frac{\{T_3 - T_6\}}{\{T_2 - T_7\}}\right)}$

Second aspect is that how to consider the overall heat transfer coefficients. This overall heat transfer coefficient takes care about the convective heat transfer coefficients at the outer surface, convective heat transfer coefficient at the inner surface and then considers the thermal conduction within the thickness of the tube. So, overall heat transfer coefficients can be calculated.

Overall heat transfer coefficient, $U = \frac{1}{\left(\frac{1}{h_o}\right) + \left(\frac{\{tA_o\}}{\{kA_m\}}\right) + \left(\frac{A_o}{\{h_i A_i\}}\right)}$

A_i&A_o:Inner and outer surface area of the tube per unit length

A_m:Logarithmic mean area of tube per unit length

k:Thermal conductivity of tube material; t:Thickness of tubes

h_i:Heat transfer coefficient of fluid(water)inside the tube

h_o:Heat transfer coefficient of fluid outside the tube

And the area can be outer area or many a times we can assume the mean area or logarithmic area or you can write closely as average area of outer and inner surface. So, this way, approximations can be made for area. So, through this way, we can go for area calculations, LMTD calculations and overall heat transfer calculation separately and that can be used by these equations to find the heat load.

And of course, there are drop in pressure for the feed water systems. However, there is no standard calculations for this pressure drop rather some of the experimental evidence talks about some empirical relations where the pressure drop is measured in terms of psi which involves average temperature at in °F , inside tube diameter in inch, number of passes and length. This is just some glimpses that how pressure drops in a closed feed water systems can be calculated.

Total pressure drop in tube side $\Delta p(\text{psi}) = \frac{F_1 F_2 (L + 5.5 d_i) N}{d_i^{1.24}}$

F_1:Factor depending upon water velocity at 60^0F

F_1:Factor depending upon average water temperature $(T_{av} = T_s - \Delta T_m)$in^{0}F

d_i:Inside diameter of the tube(in) N:Number of passes L:Length of tubes in one pass

Then moving further, another concept which drops in is this open type of feed water and here main constraints, what we have discussed so far is that open feed water systems allows both the steam and water to be mixed together. But then problem arises that the steam may be a high quality steam, but the water may have lot of impurities. So, when they mix together there are gas formations, there may be possibility of oxygen concentrations, there could be possibility of non-condensable gases. This is a very common problem, when we mix multiple streams together in a direct contact type or deaerating heaters. And again there is possibility of air leakage into the system. And it is not possible to avoid these non-condensable gases. So, that is the reasons we must limit these oxygen concentration to some value because it gives many unwanted behavior such as corrosion in these tubes, reduced overall heat transfer coefficient. So, considering this there is a limit to keep oxygen concentration in the range of $0.005 cm^3/L$. Of course, the open feed water may be of spray type, tray type or combination of spray and tray type, but we are not going deep into this details.

This is all about feed water systems. Now, let us think some concepts about the boiler treatment. What does this mean by boiler treatment? Many a times what happens over the period of time in a steam power unit, when the boiler or steam generator operates continuously, we require some kind of overhauling means removing corroded surfaces, replacing many components. So, that is reason we require some kind of boiler treatment or overhauling. And since it is a continuous operation i.e., steam power system is a continuous 24x7/ throughout the year operation, so it is normally very difficult to completely shut down the systems. So, while operating them we must treat the water quality. This is the concept, we call as a boiler treatment. Since we are dealing with water and there is a presence of oxygen in the steam or water system hence, there is a possibility of corrosion. So, to avoid corrosion, we require some kind of chemical treatment that is what we call as a boiler treatment. This is one aspect.

Second aspect is when the boiler runs continuously or power plant run continuously, there is a standard loss of water up to 1.5 to 2%. That means, in cycle by cycle when it operates, every time there is a loss about 2%. So, that make up water has to come from some other sources. We call this as a boiler makeup.

So, this entire thing is called as boiler treatment. So, this boiler treatment involves the water makeup system. For the water makeup system, we require a pretreatment which means removal of chlorine from the contents of raw water. Other is demineralization which is the process that removes dissolved salts by ion exchange. Second part is we also require high quality of steam that means, in the thermal circuit we must reduce the non-condensable gases. So, at the end, the boiler makeup produces high quality makeup water, but still there are impurities in the churning of water at various components. And for example, one part at the boiler end and again at the condensate polishing. Then we also use some kind of condensate polishing where the condensate is allowed to pass through demineralization vessels, which contains both cation and anion resins. They capture all kind of dissolved solvents solids and act as a filter for the impurities and suspended solids. So, this is one way that we say boiler blow down lines periodically removes the portion of water from the steam drum where the concentration is high due to steam flashing and this blow down is then further cooled and treated for reuse. So, some of the steam is trapped additionally during the boiler blow down process.

Another kind of treatment normally we use that is the evaporators. So, evaporator is another kind of concept that we normally use for a boiler makeup and it uses flash type distilling units and there are possibility of using single effect and multi effect evaporators. What normally is done in this evaporator is that for the makeup water, we keep the pretreated water at state w in a shell and half of this shell is completely filled with the pretreated water. Now, inside this we put this evaporators and the entry line for the evaporator is the motive steam. Motive steam is nothing, but the steam which is trapped from the various ends of the turbine. So, they are basically high quality steams. Basically the pretreated water gets treated through this motive steam and only high quality vapors at v goes to the plant again. So, essentially some of the steam gets trapped from the turbine which is a very high quality steam and it takes all kind of impurities from the pretreated water and it supplies only vapor to the plant and thereby the condensate leaves the plant for again for the treatment. So, this is what we call as a single effect type evaporator.

Now, another concept is a double effect type of evaporator. In a double evaporator type plant system, the exit from this single evaporator unit goes to the second stage evaporating unit that is another stage. This another stage also does the same thing and finally, the plant receives at v_2 instead of 'v'. And this is called vapor to the plant. So, the idea of using this is that to get quality water or quality vapor for the plant systems and why do we do this because we need to pretreat this raw water. How do you retreat this water, by this motive steam which is trapped from the turbine net. So, in a single evaporator system unit, preheated raw water is introduced at point 'w' steam from the plant known as motive steam is introduced at point 'm' that goes through the steam chest and subsequently discharge as a condensate at point 'c' at relatively low pressure. The preheated water boils and pure saturated vapor is extracted as a makeup water to the plant at point v and this as I mentioned we need to have that entire unit that is the evaporator unit should be submerged in this water which is contained in this sell.

We also define the heat head by virtue of which the heat load is defined. So, heat head is nothing, but the difference between the saturation temperature of the motive steam and the raw water temperature and corresponding to this temperature difference, we can calculate the heat load. And there are considerations that heat head below freezing temperature is not effective & above 35 ℃ also it is not effective. So, effective zone of heat head is 2-14℃. Since we are dealing with tubes, we require the determination of overall heat transfer coefficient for the evaporator which is essentially the function of the motive steam saturation temperature and heat load.

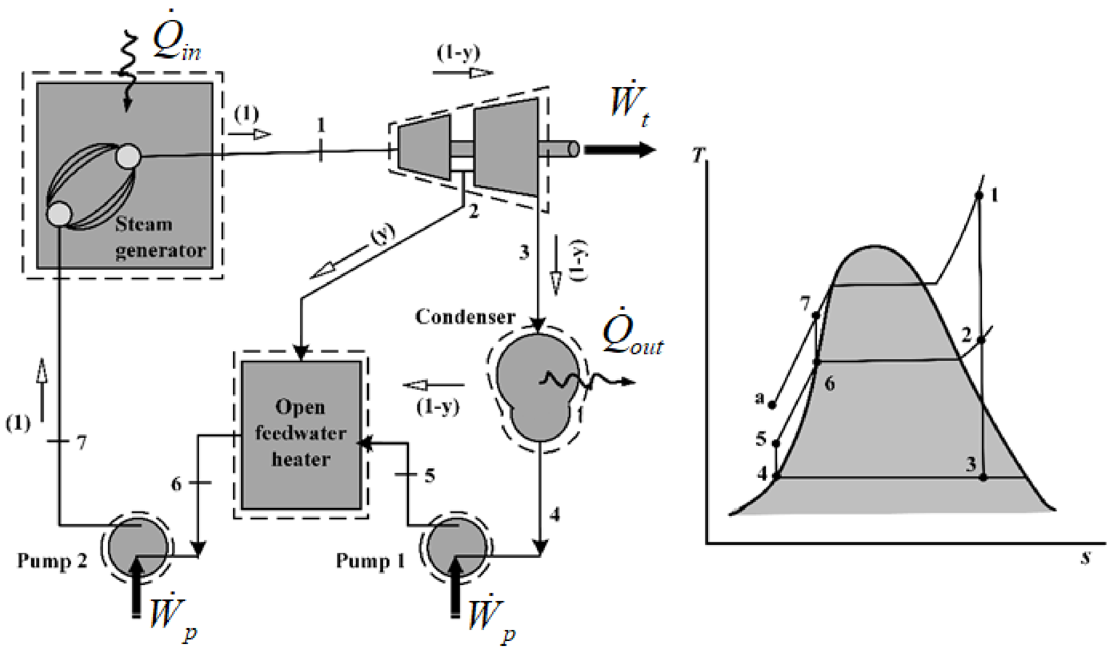
One more important point I need to emphasize is that for one unit of motive stream, the single effect evaporator produce 0.8 units of vapors while double effect and triple effect evaporator produce 1.52 and 2 units of vapors. But when you go for the double effect evaporator, it adds complexity and capital cost. Although we get the vapor quantity almost two times in a triple effect evaporator, but the capital cost and complexity of the system is increased.

So, this is all about the condenser and feed water systems and we will try to solve one particular problems which was done for a regenerative cycle concept. Of course, just to see the importance of a feed water system in a thermal power systems.

Q1. Consider a regenerative cycle with one open feed water heater as shown in the figure. Steam enters the turbine at 8 MPa & 480°C and expands to 0.7 MPa, where some of the steam is extracted towards an open feed water heater. Saturated liquid leaves the heater at 0.7 MPa. The remaining steam further expands in the second-stage condenser to the condenser pressure of 0.008 MPa. The isentropic efficiencies of each turbine & pump is 85%. Determine, (a) thermal efficiency of the cycle; (b) mass flow rate of steam entering the first stage of the turbine for net power output of 90 MW.

Let us consider a regenerative cycle. For this problem, I urge the learners to revisit the modified Rankine cycle that includes regenerative cycle to understand this regenerative cycle and we also expect the learners to be familiar with the use of steam tables to solve these problems. I have explained this thermal circuit of regenerative cycle many times and I will try to link this particular problem with this thermal circuit. So, the problem statement goes like this, here the most emphasis is not for the regenerative cycle rather it is to do the thermodynamic analysis for the open feed water systems.

To give this more emphasis, let us see this regenerative cycle and what the problem statement says is that the steam enters the turbine at 8 MPa and 480℃. So the State-1 is at 8MPa & 480℃And it expands to a pressure of 0.7MPa. So the state 2 is at 0.7 MPa. And in this situation the sum of the steam extracted is y unit by this feed water heater unit. The saturated liquid leaves the heater at 0.7 MPa that means, here we say saturated liquid is at state 6 and that pressure is 0.7 MPa.



If you see in this particular thermal circuit line, they are at same pressure. The remaining steam further expands in this second stage turbine. So, we have taken y. So, 1-y unit enters into the next turbine. Here this will be low pressure turbine & first one would be high pressure turbine. So, 1- y units again expands in the second stage turbine and they further expands in the condenser. So, at state 3, it enters into the condenser and goes at state 4 and from 4 – 5, there is a first stage pump and then 5- 6 is an open feed water system and at state 6 both 1- y and y unit of merge & give 1 unit again and also we have mentioned the isentropic efficiencies. So, thereby we may revise this diagram something like this and add state 2s & 3s. So, all these data is given.

So, the first step is to calculate all enthalpies at each state point. For that, we require steam table. Now, for this steam table, data we know already is

$\text{State} - 1; \quad p_1 = 8\text{MPa}, T_1 = 480°\text{C},$

$\text{State} - 2\ \&\ 6; \ \ p_2 = 0.7\text{MPa},$

$\text{State} - 3\ \&\ 4\ ; \ p_3 = 0.008\text{MPa}$

And some of them are saturated liquid state and some will be in the saturated vapor state. So, accordingly we have this turbine efficiency as 85% and pump efficiency is also 85%.

$\eta_t = 85\%\ ;\ \eta_p = 85\%$

So, considering this data and from our previous discussions, from the steam table, one can find out coordinates of these enthalpies. So, I am just writing down the end values which is extracted from the steam table. And whatever enthalpies we require, only those numbers I am writing.

$$h_1 = 3348.4 \frac{\text{kJ}}{\text{kg}};\ h_2 = 2832.8 \frac{\text{kJ}}{\text{kg}}$$

$$h_3 (\text{can be calculated from turbine efficiency}) = 2249.3\ \frac{\text{kJ}}{\text{kg}}$$

$$h_4 = h_f \text{ at } 0.008 \text{ MPa} = 173.88\ \frac{\text{kJ}}{\text{kg}}$$

$$h_5 = h_4 + v_4(p_5 - p_4) = 174.6\ \frac{\text{kJ}}{\text{kg}}$$

$$h_6 = h_f \text{ at } 0.7 \text{ MPa} = 697.22 \frac{\text{kJ}}{\text{kg}}$$

$$h_7 = h_6 + v_6(p_7 - p_6) = 705.3\ \frac{\text{kJ}}{\text{kg}}$$

So, through this process we know all these enthalpies at all state points.

Then let us try to find out the analysis for open feed water. For open feed water we write these expressions

$$y(h_2) + (1 - y)h_5 = h_6$$

$$\Rightarrow y = \frac{h_6 - h_5}{h_2 - h_5} = \frac{697.22 - 174.6}{2832.8 - 174.6} = 0.196$$

a) So, once you know y then rest of the problem is very simple. First is working calculation for thermal efficiency.

$$\eta_t = \frac{\left(\frac{\dot{W}_t}{\dot{m}_1}\right) - \left(\frac{\dot{W}_p}{\dot{m}_1}\right)}{\frac{\dot{Q}_{in}}{\dot{m}_1}};\ \dot{m}_1 = \text{mass flow rate of steam at state 1}$$

Work output per unit mass flow rate of steam for pump,

$$\frac{\dot{W}_p}{\dot{m}_1} = (h_7 - h_6) + (1 - y)(h_5 - h_4) = 8.7 \frac{\text{kJ}}{\text{kg}}$$

Work output per unit mass flow rate of steam for turbine,

$$\frac{\dot{W}_t}{\dot{m}_1} = (h_1 - h_2) + (1 - y)(h_2 - h_3) = 984.4 \frac{\text{kJ}}{\text{kg}}$$

Heat addition, $\frac{\dot{Q}_{in}}{\dot{m}_1} = (h_1 - h_7) = 2643.1 \frac{\text{kJ}}{\text{kg}}$

So, noting all these numbers we write thermal efficiency for the plant

$$\eta_t = \frac{984.4 - 8.7}{2643.1} = 0.37 \approx 37\%$$

That means, through this regenerative cycle with open feed water systems, we can see that, thermal efficiency from this will be higher as compared to conventional cycle. So, this is the efficiency range for a regenerative type cycle.

b) Second part of these things we need to calculate mass flow rate. So, mass flow rate means we require the output power.

$\dot{W}_{cycle} = \dot{W}_p - \dot{W}_t = 90$ MW; This value was calculated per unit mass flow rate.

So, this means mass flow rate of steam entering to the first stage of turbine, $\dot{m}_1$

$$\dot{m}_1 = \frac{90 \times 3600 \times 1000}{984.4 - 8.7} = 3.3 \times 10^5 \frac{\text{kg}}{\text{hr}}$$

So, this problem emphasize the role of an open feed water in improving the thermal efficiency of a Rankine cycle which involves regenerative concept. With this I conclude. Thank you for your attention.