POWER PLANT SYSTEM ENGINEERING

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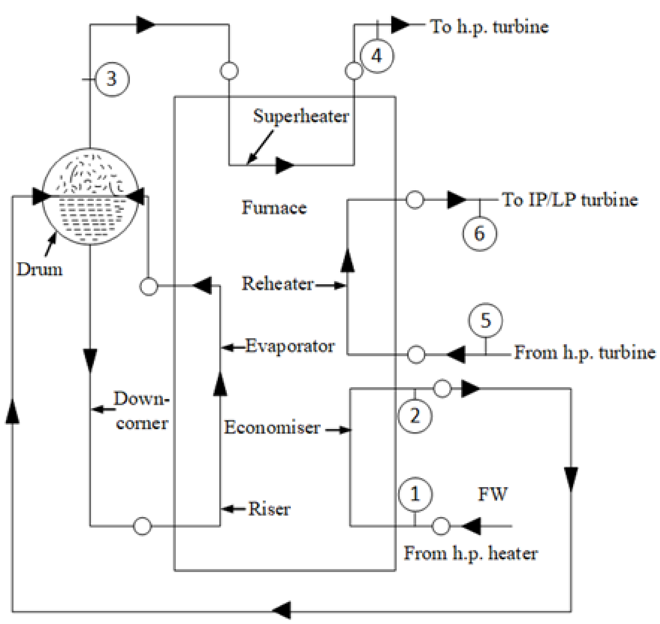
Module 2

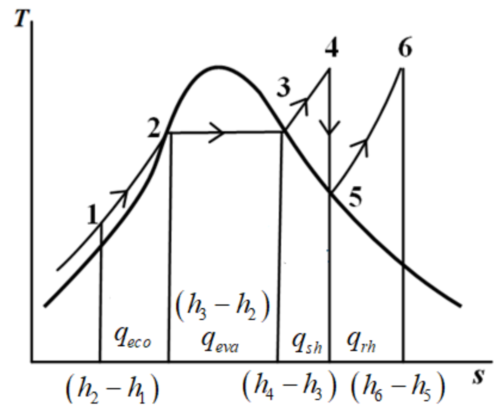
Lec 12: Water Tube Boiler (Part I)

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering Module 2, Vapor Power System Part 3. So, in this lecture our main focus would be to discuss about heat absorption concepts in water tube boilers. So, in our last lecture, we have exhaustively talked about different components of the water tube boiler. Now, in this lecture we are going to summarize different components such as super heater, attemperator, reheater and economizer. So, these four components are nothing, but a heat exchanger unit and they have been interpreted in different forms.

We will see how under what circumstances or what are the different criteria or what are the different forms in the subsequent part. So, let us revisit what we discussed in our last lecture that is water tube boiler. So, essentially a water tube boiler has important components like steam drum, super heater, re-heater, economizer, air pre-heater and of course, we have header, down comers and risers. So, the main aspects of our lecture today that we will be focusing on are three important parts- super heater, re-heater and economizer.



Of course, steam drum is also a part of it. So, in general the modern steam power systems or steam generators operate in the pressure range of 70 bar for saturated steam and pressure range of 240 bar for super-heated steam. The steam generator is nothing, but the integration of different components like furnace, economizers, boiler, super heaters, air reheater and air pre-heater. So, our main goal in this lecture is that we will be mainly focusing on the super heater part. Before you go for those super heater component, let us think about in a broad sense what do you mean by heat absorption in the water tube boilers.



So, basically our main job is to add heat to the working fluid, in this case it is water and heat addition takes place in a heat exchanger unit like economizer, which is located in this line. And the economizer is located at the first basic heat exchanger that supplies water to the steam drum. Down comer and riser circuit gives the saturated steam, super heater gives the super-heated steam and reheater uses the bypass from the turbine and reheats again in the same steam generator unit. So, essentially speaking the feed water from high pressure heater enters the economizer where it receives heat from the outgoing flue gases till saturated liquid stage then fed to the drum. Then saturated liquid falls through the down comer circuit into the bottom of the header and moves again through the riser circuit, where the water is partially boiled back in the drum and saturated steam goes out of the steam drum. Then from there it enters to the super-heated steam. Now from the super heater unit it is directly fed to the turbine. So, essentially speaking the role of super heater is to keep this dryness fraction to this maximum possible extent, so that there is no water content in the boiler.

Now, let us think about this water tube boiler in terms of thermodynamic diagrams. So, whatever we have discussed so far like, what happens in the economizer or a boiler-many a times this boiler in this unit is also called as an evaporator then super heater and reheater. So, if you look at this thermodynamic diagram i.e., T-s diagram, we see that point 1 refers to the liquid phase of water, point number 2 refers to the saturated liquid, point number 3 refers to the saturated vapor, point 4 is superheated vapor again point 5 is the saturated vapor and point 6 is the superheated vapor. It means that for each kg of steam, heat is absorbed in the economizer, which is in liquid phase, then in evaporator which is in liquid vapor phase as latent heat of vaporization and then in the super heater that is in gas phase. The multistage expansion in the low pressure turbine involves reheating of steam from saturated state to super heating state in a reheater.

So, the basic idea is that the reheater concept is also introduced in the steam generator unit of the water tube boiler. Now, if you want to calculate the heat absorption in a water tube boiler per kg of steam and since you know the state points 1, 2,3,4,5 and 6, so, using the steam table you can calculate these enthalpy values. These enthalpy values depends on the state point coordinates of 1, 2, 3, 4, 5 and 6. Now, once you know the enthalpies then you can calculate the heat load for component wise. And the total heat load is nothing, but the addition of all these four component loads.

Heat absorption in water-tube boiler per kg of steam formation:

$$q_{eco} = h_2 - h_1; q_{eva} = h_3 - h_1; q_{sh} = h_4 - h_3; q_{rh} = h_6 - h_5$$

Percentage share in components :

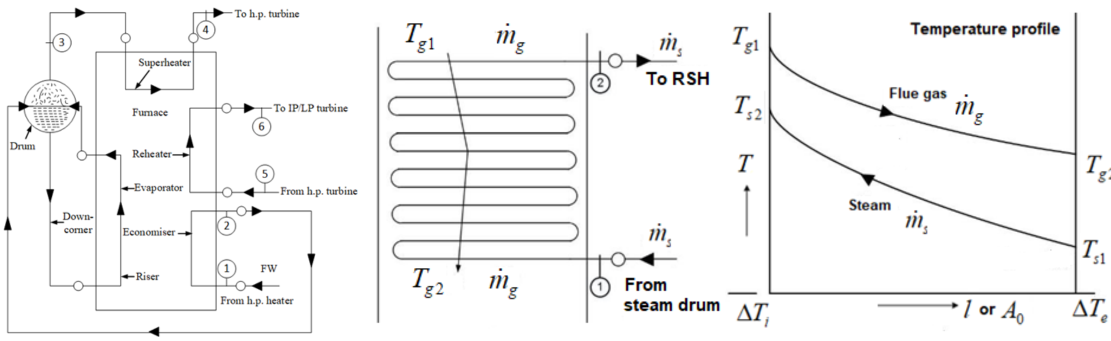
Economizer: $\left(\frac{q_{eco}}{q_{eco} + q_{eva} + q_{sh} + q_{rh}}\right) \times 100 = \frac{(h_2 - h_1)}{(h_4 - h_1) + (h_6 - h_5)} \times 100$

Evaporator: $\left(\frac{q_{eva}}{q_{eco} + q_{eva} + q_{sh} + q_{rh}}\right) \times 100 = \frac{(h_3 - h_2)}{(h_4 - h_1) + (h_6 - h_5)} \times 100$

Superheater: $\left(\frac{q_{sh}}{q_{eco} + q_{eva} + q_{sh} + q_{rh}}\right) \times 100 = \frac{(h_4 - h_3)}{(h_4 - h_1) + (h_6 - h_5)} \times 100$

Reheater: $\left(\frac{q_{rh}}{q_{eco} + q_{eva} + q_{sh} + q_{rh}}\right) \times 100 = \frac{(h_6 - h_5)}{(h_4 - h_1) + (h_6 - h_5)} \times 100$

And then we can find out the percentage share for economizer, for evaporator-many books also refer evaporator as boiler. This word evaporator is normally used in the refrigeration systems, where the evaporation of refrigerant takes place, and here again the boiler or evaporation concept remains same with a view that it is from steam and water unit. Then we can calculate the same for the super heater and the reheater. This percentage share can be calculated by knowing the enthalpy values.



Now, let us focus on the most important component of steam generating unit that is super heater. So, super heater is nothing, but a kind of a heat exchanger. So, once we get the saturated steam from the steam drum at state point 3, it enters to the super heater. So, schematically if you look at this figure, from the steam drum, the saturated steam enters at point 1 and super-heated steam leaves at point 2. So, these are called as super heater coils that means, when it passes through these super-heated tubes, it interacts with the flue gases, which is essentially at high temperature T_{g1}. And by taking heat from the flue gases, the temperature of the steam increases further. Thereby we also need to do the energy balance for the flue gases and the mass balance for the steam requirement.

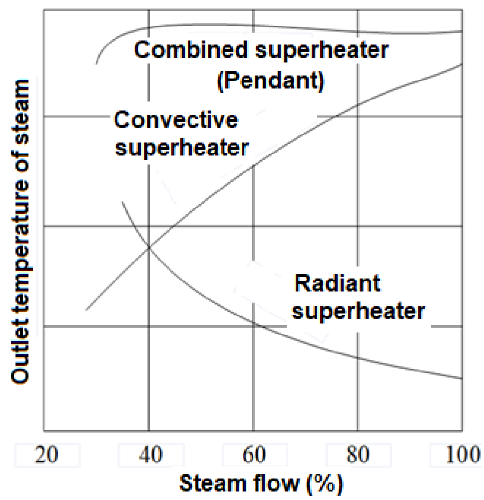
So, this particular problem can be viewed as a heat exchanger problem and this heat exchanger is nothing, but a counter flow heat exchanger. So, in this case we see that along this length or area if temperatures are plotted or temperature profiles are done for steam and flue gases, we can see that flue gases temperature falls down from T_{g1} to T_{g2}, whereas steam temperature increases from T_{s1} to T_{s2}. So, thereby we can model the super heater tube as a counter flow heat exchanger. Now, let us see the different types of arrangements, a super heater can have. They are of three types on basis of heat exchange method which can take place in pure convective mode or pure radiant mode.

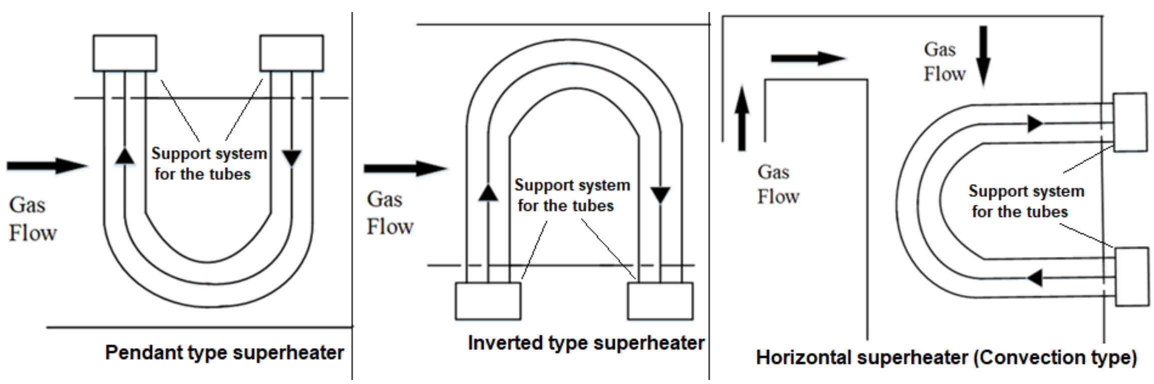
1) For pure convective mode, it is called as convective super heater (CSH).
2) For pure radiant mode, it is called as radiant super heater (RSH).

3) Pedant type super heater (PSH) means it is a combined version of convective and radiant mode.

So, in this T-s diagram, you can see that super heating units operates between state point 1 and 4, as saturated steam that enters at state 1 and superheated steam leaves at state 4. So, through this the heat addition takes place. So, basically for very high degrees of superheater, we have to go for radiant type and for less degree of superheated that means, if you want to stop this super heating somewhere at point 2 then convective super heater is sufficient, but in some cases we also require both type.

One important thing we must see that there is a characteristics that when the steam flow rate increases or the mass flow rate of the steam increases, the outlet temperature changes. If you are using the convective super heater, the outlet temperature characteristics curves is in an increasing trend. Whereas, in case of radiant super heater, with increase in the steam flow rate the outlet temperature drops. But this is essentially not the user requirement. The user wants a flat curve, like for the range of operation, let us say 40- 80 % of





steam flow rate, user needs to have a flat type of curve where the temperature remains to be flat. So, for that case the combined super heaters are most beneficial and they are called pedant type super heaters. So, that is the main advantage.

The configuration of a pedant type super heater is a like a vertical inverted tube and the gas flow direction is shown in picture. The mode of heat transfer is partially convective and partially radiative that means, initially it is convective and once it is superheated to some extent it is operated in a radiant mode. Whereas a purely horizontal type super heater mainly operates in a convection mode. So, this is how the configurations of super heaters are required for increasing the temperature of steam.

Now, repeating whatever I have explained, we can say that heat absorption techniques in the super heaters can be classified as convective, radiative or combined mode where heat is taken from gas to the steam. Convective modes are normally located in the convective zone of the furnace that means, the entire steam generating unit it is mainly closer or just ahead of the economizer. And this convective super heaters are normally referred as primary super heaters where the saturated steam from the drum is admitted. Now, after convective super heating the steam proceeds towards the radiant super heater which is placed in the radiant zone of the furnace. So, radiant zone means it is close to the wall of the furnace so as to absorb the heat only by radiation. Now, steam leaving from radiant super heater goes to de-superheater where highly pure water is sprayed to the steam at a desired quantity such that last stage of super heating in combined mode is normally done. So, this is called as pedant type super heaters. So, this spraying is again required for the controlling of steam and I will come back to this point at the later stage of this lectures, why the spraying of water is required in a pedant type super heaters. And normally this pedant type super heater is called as secondary super heaters. So, at the end of the super heating unit, the constant flow rate of steam should go at a fixed temperature. So, that is the essential requirement when the steam enters into the turbine.

Now, let us give more view to this convective super heating concept where heat transfer is mainly by convection and this is the simplest mode in which heat exchange can takes place. So, I have already mentioned the heat is taken from the flue gas thereby temperature of flue gas drops and steam temperature increases from T_{s1} to T_{s2}.

Now, coming back to heat exchange for this super heaters, one can model it as a heat exchanger model. First thing one can find out the convective super heating from this equations. The amount heat that is being added during the convections super heating from

1 to 2 is equal to the energy that is lost by the flue gases, that is $\dot{m}_g c_{pg}(T_{g1} - T_{g2})$, where c_{pg} is the specific heat of the flue gases, $\dot{m}_g$ that is mass flow rate of the flue gases & T_{g1}, T_{g2} are the temperatures at the inlet and the exit of the super heater.

Energy balance for convective super heating, $\dot{Q}_{CSH} = \dot{m}_g c_{pg}(T_{g1} - T_{g2}) = \dot{m}_s(h_2 - h_1)$

This one aspect. Now with respect to super heater unit this can be model as the below equation.

In terms of overall heat transfer coefficient, $\dot{Q}_{CSH} = U_0 A_0 (\Delta T)_{LMTD}$

So, LMTD is nothing, but the logarithmic mean temperature difference and that is we refer for a counter flow heat exchanger using this figure.

Logarithmic mean temperature difference, $\Delta T_{LMTD} = \dfrac{(\Delta T_i - \Delta T_e)}{\ln\left(\dfrac{\Delta T_i}{\Delta T_e}\right)}$

Overall heat transfer coefficient, $\dfrac{1}{U_0} = \dfrac{1}{h_i} + \dfrac{x_w}{K_w} + \dfrac{1}{h_0}$;

Now, U_0 is the overall heat transfer coefficient and this overall heat transfer coefficient is related to the convective heat transfer coefficient for outer wall and for inner wall and its thermal conductivity along the thickness. So, essentially these are nothing but the resistance offered for this heat exchange to happen.

So, U_0 can be found out by knowing this convective heat transfer coefficients for inlet surface and outer surface of the tube and the thermal conductivity along the thickness of the tube where the conduction takes place. So, basically if you can assume the thickness of the tube, its inner part and outer part, then you can find $h_{i,}$ which is inner convective heat transfer coefficients at the inner wall and h_o that is the convective heat transfer coefficient at the outer wall. And through the thickness of tube the conduction takes place. So, basically outside the tube, we have flue gases and we have steam inside the tube. So, heat transfer takes place from flue gases to steam. So, thereby you can model this as a convective mode at the outer surface, convective mode at the inner surface of the tube and then along this thickness it is a conduction mode of heat transfer.

Then the size of the tube that can be called as outer surface area of the tube, A_0 can be calculated as per the following equation.

Surface area, $A_0 = n\pi d_0 l$; Steam mass flow rate, $\dot{m}_s = \left(n\frac{\pi}{4}d_i^2\right)\left(\frac{V_s}{v_s}\right)$

d_0:Outer diameter of tube(50-75mm); l:Length of the tube

d_0:Inner diameter of tube; x_w:Thickness of tube; n:Number of tubes

h_i&h_0:Convective heat transfer coefficient for inner & outer surface

V_s:Steam velocity $\left(12\text{-}22\,\frac{\text{m}}{\text{s}}\right)$; V_g:Combustion gas velocity $\left(8\text{-}12\,\frac{\text{m}}{\text{s}}\right)$

v_s:Specific volume of steam at operating pressure & temperature

In counter-flow heat exchanger,temperature difference at inlet and exit:

$\Delta T_i = T_{g1} - T_{s2}$; $\Delta T_e = T_{g2} - T_{s1}$ (T_{s1}&T_{s2}corresponds to enthalpy of steamh_1&h_2)

So, most of the data will be given to us and accordingly we can use this equations to design the heat exchanger. To design the heat exchanger means you need to calculate the area requirement, outer diameter of the tube, number of tubes required and all these parameters.

Now, same philosophy can be extended for radiant superheater type. But for radiant superheater we have to use the following equation.

Energy balance for radiative super heating:

$$\dot{Q}_{RSH} = \sigma A_T F_{fw}\left(T_f^4 - T_w^4\right) = \dot{m}_s(h_3 - h_2)$$

Since, $T_f \ggg T_w \Rightarrow \dot{Q}_{RSH} \alpha T_f^4$

σ:Stefan-Boltzmann constant $\left(= 5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m^2.K^4}}\right)$

A_T:Total surface area of super heater exposed to the flame$(\mathrm{m^2})$

F_{fw}:View factor with respect to flame and wall

T_f&T_w:Absolute temperature for flame and wall, respectively

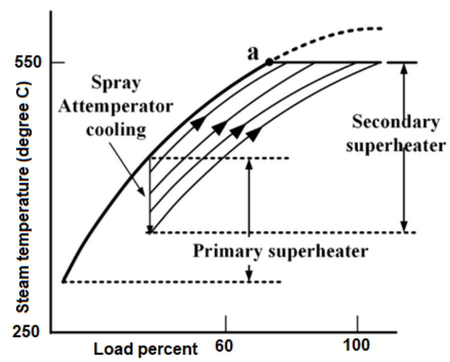
$T_w = T_{sat} + 50\mathrm{to}75^0\mathrm{C}$

So, this is the radiation heating and using these equations it can be correlated to what is the rise from the point 2 to 3 because 2 to 3 normally we use radiant superheater. And this radiant superheater means that the steam is allowed to have contact with the surface of the wall. That means, at the wall the radiation is most predominant. So, the steam is allowed to be exposed to the wall side. So, that is the reason the radiant super heaters are located in the radiant zone of the furnace that provides greater heat absorption by radiative mode of heat transfer. So, in other words for a higher degree of superheat we require the steam to be exposed to the high temperature with view of the combustion flames.

Then moving further, there is another limitation for radiant superheater, i.e., your velocity. To get the maximum benefit of radiation mode of heat transfer the steam velocity should not exceed 7.5 m/s with heat transfer coefficients as 3.14 $\mathrm{kW/m^2}$ and maximum heat flux of 116 $\mathrm{kW/m^2}$. And this flame temperature is almost independent of flow. But as the steam flow increases, the heat transfer per unit pass flow rate decreases. So, in the characteristics curve when you increase the steam flow rate the outlet temperature drops. So, this is the biggest disadvantage for a radiation mode of heat transfers.

So, basically a most appropriate choice is to use the combination mode that is convective and radiative mode of super heaters. And such super heaters are known as pedant type super heaters. So, in a pedant type superheater that means, normally it is in the region of 3 to 4 when you go for higher degrees of superheating we see that pedant super heaters they are like inverted u tubes are exposed to the gas flow. So, and if you see this thermodynamic diagram the flue gas temperature drops from T_{g1} to T_{g2}. But if you look at the steam side, from T_{st1} to T_{st2}, it is goes as a convective steam mode and here a counter flow type of steam enter, so that the curve is little deviated from the actual rise. So, basically speaking we are going to mix these two type of steams in such a way so as to require the flat curve. So, how you are going to do that I will come back in the subsequent slides.

So, that's what is normally done to control the temperature at the outlet of the super heaters. And we need to essentially get a flat curve that is flat steam outlet temperature which is insensitive to the load change. So, basically in pendant type super-heaters, we can say 3/4th heating is made as a counter flow, 1/4th heating is considered as a parallel flow. So, if you look at steam and gas point of view from this side it is a parallel flow from this side it is a counter flow.



And this is the most economical arrangement for safe operation of the thermal failure of the materials. And this is what I was emphasizing, how do you get this combined superheater, pendant type superheater in a flat curve. So, we call this as a process which as attemperation. So, in certain cases, the convective and radiant super heaters are arranged in series to yield a flat final curve over a wide range of temperatures. So, attemperation is a method of reduction of steam temperature, which is done by two methods, one is surface attemperator & the other is spray or direct contact type attemperator.

Now, the surface attemperator is nothing, but a shell and tube type of heat exchanger. So, conceptually from the steam drum, the saturated steam comes out and enter to this superheated zone. And the superheated zones are two types, primary and secondary. Primary is normally made as convective type and secondary is made as pendant types.

So, basically pendant type combines radiant and convective mode, which is partly counter flow and partly parallel flow. Now, if you look at this curve, in one case, in a convective superheating mode that is in the primary zone, the outlet temperature increases with increase in the steam flow rate, but in the radiant mode, outlet temperature drops. But to have this flat curve, we need to have the pendant type super-heaters. But then controlling the temperature becomes vital because these two have a very huge temperature difference. So, for that reason what we normally do that between primary and secondary super heater? There is a primary super heater that gives a steam temperature of this range and in secondary super heater, the final requirement let us say 550℃ need to be achieved. Now if you do not use this attemperator then the curve will keep on increasing after 550℃. That means, 550 is the point a, that is the landmark point. So, beyond that the temperature should not go, and with continuous increase of the load rate also, this should remain flat at this point. And for that reasons, we use the surface attemperator direct contact type attemperator to bring back this flat curve.

So we do this by a method called as spray attemperator cooling, where some collected water from the steam drum is being sprayed to keep this flat curve, so that unnecessarily the temperature will not rise rather it will lead to a flat curve. And the amount of this flatness we can control by controlling the water spraying mass into the main steam.

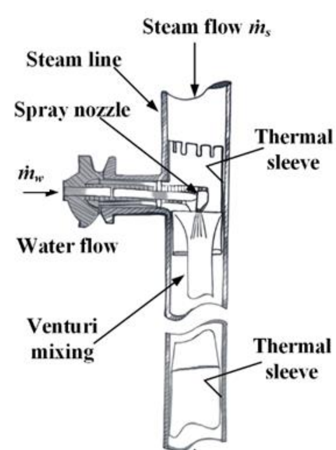
The surface attemperator is again a shell and tube heat exchanger that collects the steam from the pendant type of super heater and regulates the temperature for a flat curve. And this temperature is achieved by controlling the diverted steam. So, some portion of the steam from the primary or secondary super heater is diverted to shell and tube heat exchanger that contains boiler water in the shell. So, the steam gives up some heat to the water and then remixes with primary stream upon entering into the secondary heater.

So, basically between primary & secondary heating, we give a heat spray cooling so that the temperature of the entire unit does not go beyond the point a. Basically the attemperator can be of either type like surface or spray or direct contact type & they can be located before primary super heater/ in between primary and secondary super heater or after secondary super heater. So, these are the three locations this attemperator can be used.

So, the first choice means, it is used before primary super heater, means it can lead to the condensation of saturated steam on the boiler surface before it enters the condenser. In the last choice, it is used after super heater then the steam temperature exceeds the final desired value. So, the best way is that before it leaves the super heater entire temperature control has to be done in such a way that the curve relatively remains flat. So, this is what we say spray cooling type of attemperator.

Another way of doing the similar practice is through gas re-circulations. So, many a times, the gas recirculation is used in which gas from some point downstream of the economizer outlet is recirculated back to the furnace by a fan. So, by doing this we call this as a gas tempering. So, essentially this cooling can happen by a gas mode from the economizer unit and that process is called gas tempering.

Now, let us think about the most effective way of attemperation that is the second method, which is called as a spray or direct type attemperator, where we can reduce the steam temperature by spraying the low temperature water from the boiler or economizer exit in the line between primary and secondary super heaters. There is a steam flow that comes from the primary super heater and it enters to the secondary super heater that is $\dot{m}_s + \dot{m}_w$. And relatively this mass flow rate has to follow this flat curve which essentially means that we must regulate the quantity of water that needs to be sprayed and this arrangement is done through a spray nozzle. So, this spray nozzle arrangement configuration is a venturie type nozzles through which water is sprayed along this steam path. So, along the steam path when this steam comes and interacts with the water, its temperature drops. So, when the temperature drops the final value that is $\dot{m}_s + \dot{m}_w$ is the essential requirement of load. For that load the temperature is obtained as a relatively flat curve and typically the temperature requirement is about 550℃ after super heating unit. And depending on the requirement, we can control how much mass flow rate needs to be added. So, more or less this



Spray Attemperator for steam temperature control has been seen to be the most effective, most rapid and sensitive means of temperature control in a steam generator.

Then a simple energy balance equation can be applied. Referring to this figure, you can see steam flow rate is $\dot{m}_s$ and it enters at enthalpy let us say, h_{s1} and mass of the water that enters from the steam drum is $\dot{m_w}$ and at this pressure we can have the enthalpy value, h_w then the total mass that goes out is $\dot{m}_s + \dot{m_w}$, at an enthalpy h_{s1} . So, essentially speaking from this point to this point, there is drop in temperature and pressure remains same. So, to maintain same pressure at entry point relatively, we have similar pressures from this water inflow and the steam inflow.

So, if there is no involvement of work, heat and changes in the kinetic or potential energy, then you can simply frame the energy balance equation as the following equation.

Energy balance in a spray attemperator: $\dot{m}_s h_{s1} + \dot{m}_w h_w = (\dot{m}_s + \dot{m}_w) h_{s2}$

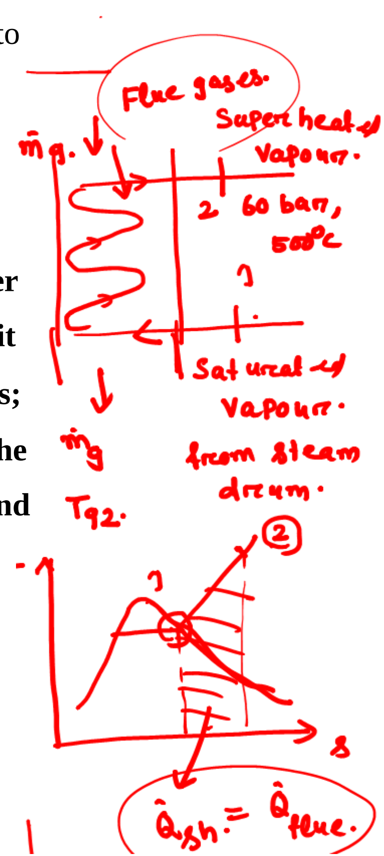
$\dot{m}_s$& $\dot{m}_w$:Mass flow rates of steam & water, respectively

h_s&h_w:Enthalpies of steam & water, respectively$S$

$ubscripts$ 1 & 2: Steam inlet and exit, respectively

So, this is the attemperation that is required for a super heating unit to generate a flat curve. So, with this viewpoint let us see some numerical problems that can be attempted in the topic of super heater, attemperator and of course, the heat loads on the water tube boiler.

Q1. In a modern steam generator units, it is desired to have superheater coils with internal diameter of 52 mm and thickness 5 mm. The exit condition of steam are as follows: 60 bar & 500°C; flow velocity 15 m/s; mass flow rate 75 kg/s. Due to material restrictions, the heat flux in the coil should not exceed 150 kW/m². Calculate the number of coils and length of each coil.



So, the first problem talks about a modern steam generator unit in which super heater coil has to be incorporated. Its dimensions are given like internal diameter 52 mm and thickness 5 mm exit condition of the steams are 60 bar and 500℃, flow velocity 15 m/s mass flow rate 75 kg/s. Due to material restrictions, the heat flux in the coil should not exceed 150 kW/m^2.

So, we have no information about the flue gas, we have only information about the super heater coil. So, basically this is the super heater coil, the saturated vapor enters from the steam drum and the steam exit conditions in the super heater coil is superheated vapor and that is state 2 at 60 bar, 500℃. And it enters through these tubes in a continuous manner and this side we have flue gases of $\dot{m}_g, T_{g1}$ and flue gases of $\dot{m}_g$ leaves at T_{g2}. That means, heat is taken from flue gases to the steam. And essentially speaking it is a convective type of super heating where we can draw this curve. We are at the point 1 steam requirement is at point 2. And this heat in a temperature entropy diagram this heat we called as $\dot{Q}_{sh}$, super-heated load and this $\dot{Q}_{sh}$ is to be supplied by $\dot{Q}_{flue}$.

Of course, no information required about the flue gases in these things. So, we do not need to bother about this flue gas as of now for this problem. We need to find out the heat load and from the heat load we need to find out the number of coils and length of the each coil. So, for the solution, you have to keep steam table intact. So, using the steam table, we can find out the following.

State-1: Saturated Vapor (60 bar)

$$h_1 = h_g = 2784.3 \text{ kJ/kg}$$

State-2: Super-heated vapor (60 bar, 500℃)

$$h_2 = 3422.2 \text{ kJ/kg}, v_2 = 0.05665 \text{ m}^3\text{/kg}$$

We also know the mass flow rate of the steam, $\dot{m}_s = 75$ kg/s

Then $\dot{Q}_{sh} = \dot{m}_s (h_2 - h_1) = 47842$ kW

But we see that due to material restriction, the heat flux on the coil should not exceed 150kW/m^2 that means kW per meter square. So, accordingly we must find out the area surface area of coil.

Surface area of coil: $A_0 = \dfrac{\dot{Q}_{sh}}{150\ \mathrm{kW/m^2}} = 319\ m^2$

Then we also require the mass flow rate.

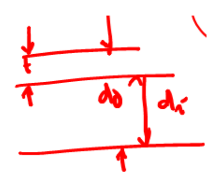
$$\dot{m}_s = \frac{A_2 V_2}{v_2} = 75\ \text{(data given)}$$

Now, $A_2 = n \times \dfrac{\pi}{4}(d_i^2), V_2 = 15\dfrac{m}{s}, d_i = 52\ \mathrm{mm} = 0.052\ \mathrm{m}$

We also know specific volume v_2. So, by putting all these value we can say

$$n \times \frac{\pi}{4}(d_i^2) = \frac{\dot{m}_s v_2}{V_2} \quad \Rightarrow n = 134$$

That means 134 number of turns in the coil is required for which heat flux should not exceed as 150kW/m^2.



Then, $A_0 = n \times \pi d_o l$

Here, outer diameter of tube, $d_o = d_i + 2t$

$\Rightarrow d_o = 52 + 5 + 5 = 62\mathrm{mm}$

Putting this in the equation, $A_0 = n \times \pi d_o l \ \Rightarrow l = \dfrac{A_0}{n\pi d_o} = \dfrac{319}{134 \times \pi \times 62} \approx 12\mathrm{m}$

So, basically, the number of coil is 134 & length of each coil is 12 m.

Q2. Steam enters a spray attemperator at 180 bar and 520°C. The spray water comes from a steam drum that operates at 190 bar. Calculate the mass of spray water to be added per unit mass of steam to reduce its temperature to 480°C.

Now next question is about the spray attemperator which regulates the flat curve for the superheated unit. If you refer this figure, we have secondary superheater and primary superheater. To regulate this flat curve we have a spray attemperator, for temperature control of the steam. So, basically speaking, steam, $\dot{m}_s$ enters the attemperator at 180 bar 520℃. And spray water,$\dot{m}_w$ comes from the drum at about 190 bar. So, more or less these two temperature are similar because they have to come out at same pressure of 180 bar but temperature has to drop down to 480℃.

So, to control this 480 ℃ we are adding water through this venturie type attemperator. Now using steam table,

Steam inlet, (180 bar, 520℃) ⇒ $h_{s1} = 3378$ kJ/kg

Steam outlet, (180 bar, 480℃) ⇒ $h_{s2} = 3203.2$ kJ/kg

Water inlet, (Saturated water at 190 bar) $h_f = h_w = 1776.5$ kJ/kg

Now we also know that per unit mass of the steam that means, $\dot{m}_s = 1\text{kg/s}$.

So, the working equation for energy balance

$$\dot{m}_s h_{s1} + \dot{m}_w h_w = (\dot{m}_s + \dot{m}_w) h_{s2}$$

$$\Rightarrow 3378 + \left(\frac{\dot{m}_w}{\dot{m}_s}\right)(1776.5) = \left(1 + \frac{\dot{m}_w}{\dot{m}_s}\right)(3203.2)$$

$$\Rightarrow \left(\frac{\dot{m}_w}{\dot{m}_s}\right) = \frac{174.8}{1426.7} = 0.122$$

$$\Rightarrow \dot{m}_w = 0.122 \text{ kg/s}$$

So, in other words we say mass of the spray water requirement per kg of steam is 0.122kg/s and this mass must be required to regulate the steam temperature to be maintained at 480℃.

Q3. It is desired to estimate heat loads of a modern steam generator for following operating conditions: Liquid water enters the economizer at 45°C; Saturated liquid enters the boiler at 8 MPa; Saturated vapor enters the superheater at 8 MPa and superheated steam leaves at 480°C; After expansion in high pressure turbine to 0.7 MPa, saturated liquid enters the reheating unit at superheated steam leaves at 440°C. Calculate total heat load per unit mass and percentage of each heat exchanger unit.

And last problem is a very simple problem which deals with heat absorption concept for a modern steam generator. So, the problem statement is that we need to estimate the heat load for modern steam generator that involves an economizer, a boiler or evaporator unit, a super heater and of course, a reheater unit. So, basically steam which is at liquid state enters into the generator unit in an economizer, it goes up to state point 2 which is the saturated liquid. Then at same pressure, the steam leaves at the evaporator or boiler at state point 3 and this heat transfer is mainly latent heat. And from 3 to 4, it is the super heater unit and after expansion process in the turbine the reheater unit dominates from 5 to 6 and it goes to state 6. So, basically we have the state point requirement and for each state point we need to calculate this enthalpy coordinates. Then we can calculate the heat load share.

So, for this again suggested to use steam table.

State-1: Liquid water, 45℃, $h_1 = 188.45$ kJ/kg

State-2: Saturated liquid, (8MPa), $h_2 = h_f = 1316.6$ kJ/kg

State-3: Saturated vapor, (8MPa), $h_3 = h_g = 2758$ kJ/kg

State-4: Super-heated vapor, (8MPa,480℃) $h_4 = 3348.4$ kJ/kg

State-5: Saturated vapor, (0.7MPa), $h_5 = 2763.5$ kJ/kg

State-6: Super-heated vapor, (0.7MPa, 440℃) $h_6 = 3353.3$ kJ/kg

Now, we have all the state point enthalpy values, we can find out heat load share for each component.

Economizer, $q_{ec} = h_2 - h_1 = 1128.15$ kJ/kg

Boiler/Evaporator, $\mathrm{q_{eva}} = h_3 - h_2 = 1441.5$ kJ/kg

Super-heater, $\mathrm{q_{sh}} = h_4 - h_3 = 590.4$ kJ/kg

Re-heater, $\mathrm{q_{rh}} = h_5 - h_4 = 589.9$ kJ/kg

So, adding these 4 we can find q_{tot}.

$q_{tot} = (h_4 - h_1) + (h_6 - h_5)$

$\Rightarrow q_{tot} = 3449.95$ kJ/kg

Now, we have all the state point values, so we can find out percentage share.

$$\%\ \text{Share for Economizer} = \frac{q_{ec}}{q} = \frac{1128.15}{3749.95} = 30\%$$

$$\%\ \text{Share for Evaporator} = \frac{q_{eva}}{q} = \frac{1441.5}{3749.95} = 38\%$$

$$\%\ \text{Share for Super} - \text{heater} = \frac{q_{sh}}{q} = \frac{590.4}{3749.95} = 16\%$$

$$\%\ \text{Share for Re} - \text{heater} = \frac{q_{rh}}{q} = \frac{589.9}{3749.95} = 16\%$$

So, basically speaking this is the heat load distributions across different components of a steam generator unit. So, with this I conclude this lecture for today. Thank you for your attention.