POWER PLANT SYSTEM ENGINEERING

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Module 2

Lec 11: Steam Generator

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering, module number 2 that is Vapor Power Systems part 3. So, in this lecture, we are going to focus on the important component of a steam power systems that is steam generator and mainly we will talk about fossil fuel type steam generator for which the energy is supplied through fossil fuel. When this energy is supplied to the fuel, the water receives heat from the fuel and that happens in a component what we call as water tube boilers. Many a times in modern steam power systems, we call it as a steam drum.

So, we will try to focus on these two main important segments. Then we will also discuss, how water is circulated in the boiler. That means in a steam generator, continuously we are supplying water, at the same time we are generating superheated steam. Sometimes the water is at saturated state, sometimes the water is also in the superheated state. So, to analyze this, we need to see how water circulation takes place. So, mainly because one is at gas phase, other is in the liquid phase. So, the density difference that occurs between gas phase and liquid phase has an advantage that makes the circulation of water in the boiler.

Another category of water boiler is the Once-through boiler. When you supply heat to the water, the traditional way of going to superheated steam is through the liquid to gas phase and through latent heat of heat addition and subsequently we go to the superheated state. So, basically we deal with the property diagram of pure substance for water that considers the dome. Now, in a once-through boiler what happens- if you want to bypass the saturation regions, then liquid phase can be converted to gas phase.

In other words, we can take water to steam directly and such a boiler is known as once-through boiler that means, without going through the latent heat phase, we can go from water to gas phase directly. So, this is the overall discussion for today. So, if you look at our previous analysis, where you studied- how a steam power system looks like. Basically it has main three segments M, N, O and P. M stands for the supply of energy to the working fluid. Our working fluid is water and the supply of energy we can have it through fossil fuel, nuclear, solar, and geothermal, so, many resources of energy we can use. So, our main focal point of few lectures from now, will be on steam generators and mainly we will be talking about the M part. In our previous lectures, we covered turbines, we also covered condensers and subsequently in other phases, we will also cover the cooling towers. And additionally if you look specifically for the Rankine cycles, the heat addition phase starts from point 4 and ends at the point 1'.

So heat addition phase starts from 4, 4 –a is in the liquid phase. So, it is a constant pressure line. So, at constant pressure we keep on adding heat till we get the saturation point. Then from a-1 is the latent heat of heat addition that means, liquid water gets to saturated vapor and from 1- 1' it is the superheated region, where we find the superheated steam.

So, essentially speaking from 4 -1', entire heat addition takes place into as $\dot{Q}_{in}$. So, that is all the boiler does. But this heat addition phase in reality happens from liquid state to superheated state. So, this is essentially integral of various components and all these components are part of this domain that is steam generator. So, whatever I have explained so far, if you can recall them they are like this. So, in power stations that operates mainly fossil fuel and nuclear fuel, the steam generators is the integral part because their main aim is to produce the steam at a desired rate by burning the fuel in its furnace.

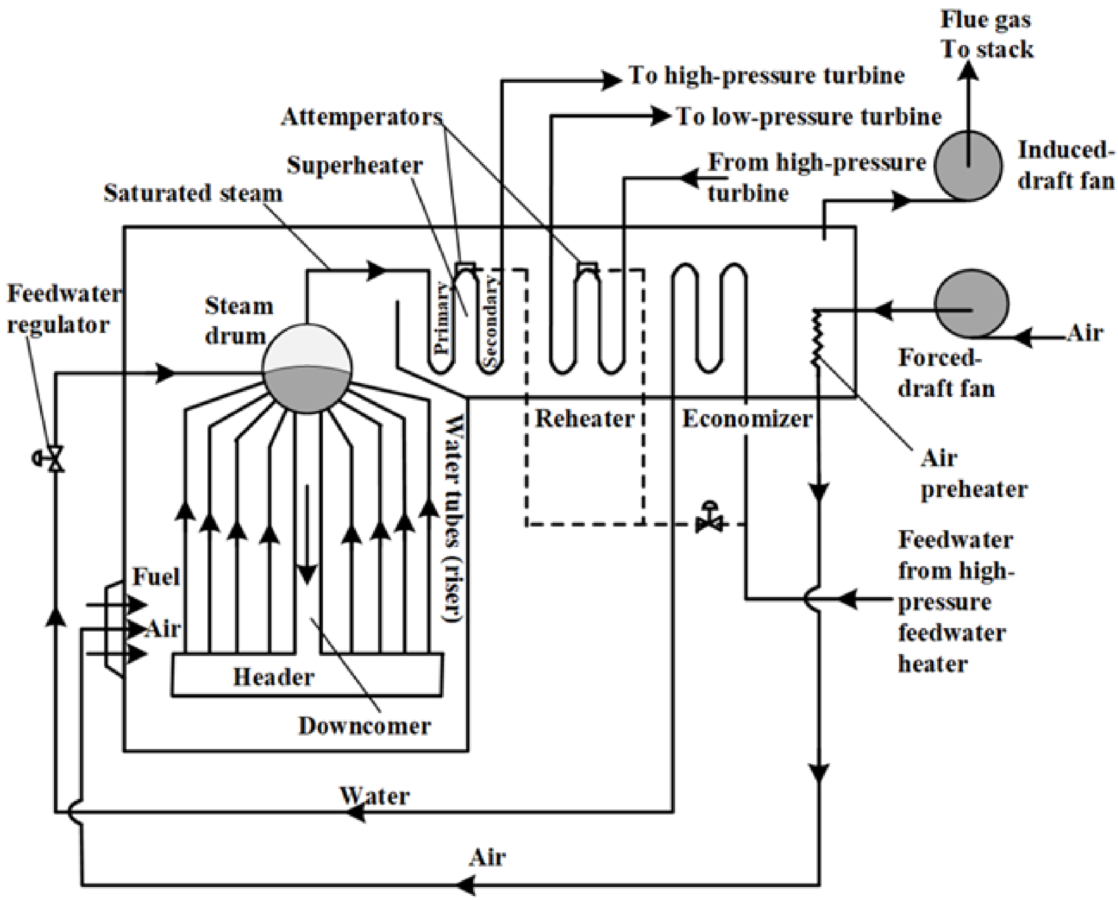
And steam generator represent greater source of energy for the power plants and they invariably use Rankine cycle. Now, for most of the modern power plants, when they are used as a steam generator, they operate close to 240 bar which is mainly for superheated steam and 70 bar for saturated steam. And if you look at the wide range of operations that is from liquid to superheated regions steam generator involves the complex combinations of the components and they are mainly heat exchangers. They are known as economizer, boiler, superheater, reheater and air preheater.

So, we will try to see how they are organized in a particular steam generator unit. Apart from this there are auxiliary units like pulverizers, burners, fans, ash handling equipment and so on. Another important significant difference is that we have been using is the boiler. So, essentially boiler is the word that is used in the Rankine cycle when we are handling saturated steam. That means, when we are just going from a-1, whatever heat that gets added that is latent heat of vaporization for the water and that part of the steam generator component is regarded as a boiler. But for a more precise or wide range of operations, we use the word called as steam drum. So, we will look at the steam drum very closely in the subsequent slides.

So, let us talk about the steam generator that are used in the modern steam power systems. I have mentioned that the steam drum is the most generic word. So, if you look at the steam drum, it is like a cylindrical structure of certain diameter and length and this steam generator has lot of tubes, they are called as a riser or down comer. Actually the steam drum collects the water, I mean it is a kind of a water reservoir for the plant. So, when this water gets stored in the drum then the buoyancy is taken as advantage that means, water gets circulated or comes down through some pipes which we call as a down comer. And when it interacts with a header which connects this water with the fuel air systems. So, basically heat is added through this process. So, when this heat is added, steam gets generated and this steam passes through another set of water tubes and we call them as risers. So, there may be number of down comers and number of tubes which are used for risers. So, why you say riser because when the density of steam comes down, it goes up and finally, when the steam is again stored in the steam drum for subsequent transmission to next unit. So, basically the steam drum supplies saturated steam.

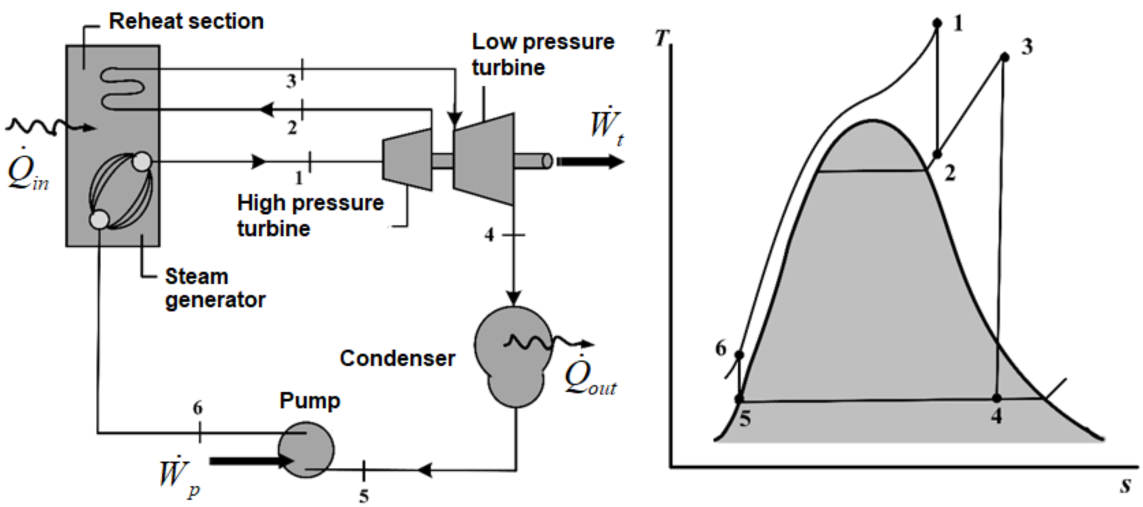
Now, to get superheated steam, we have super heaters which are another unit of entire water steam generating systems. We have super heaters and some cases we want the steam to be reheated, I mean by reheating of the steam is that after it comes from the high pressure turbine it again passes through the low pressure turbine. So, some reheating segment we used to do. So, there is a reheater. These are the major two units that are operated when we are operating beyond the saturated dome. Now, economizer is another unit which essentially specifies that economically how you are using the exhaust energy and how you are going to use them for initial preheating purposes.

So, economizer does some of this initial preheating stuff. Again we also require the air to be preheated. So, that preheating concept also integrated with what we call as air preheaters. So, basically wherever heat addition or heating is required for different parts of the power plants, that essentially is integrated with this steam generator and ultimately entire energy comes from the fuel air combustion. And here the fuel is mainly fossil fuel. So, this is about the overall concept of this steam generator which is replicated in this diagram.



Important Components of a Modern Steam Generator

So, now coming back to the classifications, there are three main segments of classifications. One is the utility steam generator, second category is industrial steam generator and third one is marine steam generator. Out of these three, if you look at marine steam generator, they are mainly used for giving necessary powers to ships for marine applications and that mainly use the fuel oil as a main source of heat, but again that is localized with respect to marine systems. Other is industrial steam generator, normally it is also kind of a power plant systems which is integrated with various auxiliary units like waste heat systems which is again can be integrated with some gas turbine systems. So, they are like intermediate units that operates relatively at low pressure. But one important thing is that the utility steam generator is mainly used for thermal power systems and they use two types of units, one is subcritical unit & other is supercritical unit.



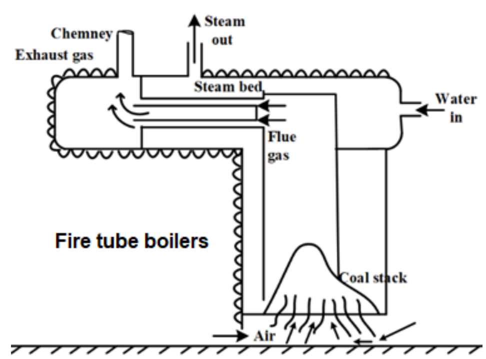
Now in a subcritical unit, we use a water tube drum type steam generator which I have explained earlier. So, in the subcritical unit what happens, if you look at this particular figure that means, we are operating the steam that means, if you want to go from point 6-1, there are two paths, one is we have to cross this dome and go up. That means, initially liquid water gets heat and converted from liquid to saturated liquid, then saturated liquid to saturated vapor, then saturated vapor to superheated region. So, essentially to reach point 1, our main path is covering this dome. That is what we call as subcritical unit which uses water tube drum type generator.

Now other type of generator- suppose you want to bypass this dome then we can reach from point 6 to 1 directly without entering into the dome. That is possible, if you operate your boiler at a pressure which is much above this critical point. So, in this dome there is one peak point which is called as a critical point for water and one should operate the boiler or generator at a pressure which is above this critical point and we call this type as a supercritical boiler or generator. And we call this as a once through boiler. Now the supercritical unit boiler operate at about 240 bar, just higher than the critical pressures while the subcritical units operate either in the range of 130 -180 bar and for which the maximum temperature falls in the range of 550- 600 ℃. Now while operating these units, we try to get the power in the range of 125 -1300 MW, for which the steam consumption is about 125 -1250 kg/s. And for all these things, we are using the energy from the coal to produce this power. So, these are the rough numbers, typically a steam generator operates at.

Now we will move on to component wise details. Regarding industrial steam generator I have already mentioned that they operate with various segments of energy resources either from coal, oil, natural gas, municipal waste, process waste, byproducts. So, it is a combination of the all of them. So, that is the reason this is called as industrial steam generator. So, they have flexibility of operating with multiple energy resources. Since they have to operate with multiple energy resources, pressure range is relatively less and typically around 100 to 105 bar with a steam capacity of 125 kg/s.

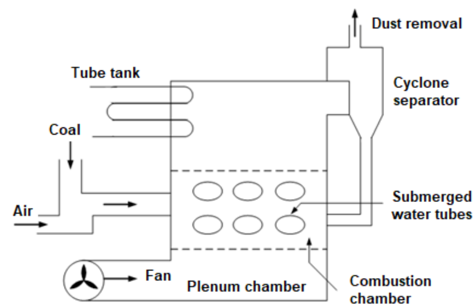
The last category, which is a low unit, is marine steam generators. They use main energy resources as oil and produce superheated steam at around 60 - 65 bar at temperature of 540℃. So, these are the overall summary of the steam generates that are normally operated.

Now, we will move on to mainly the fossil fuel type generators and they are essentially divided into the following components; fire tube boiler, water tube boiler, natural circulation boiler, controlled circulation boiler, once through boiler, subcritical and supercritical type boiler. Broadly they can be categorized into two types; one is water tube type, other is once through type. And these two can either be natural circulations type or they can be controlled way of circulation. They can be also subcritical, but once through boiler has to be supercritical. But the fire tube boiler is a very old concept. Initially when the concept of steam addition process started, they started with the fire tube boiler. So, this is the overall summary.



Now, we will start one by one to give some introduction about the type of fossil fuel generator and first category is the fire tube boilers. So, this concept was started in18th century. As its name is fire tube, so we used to create some kind of fire in a tube. So, that is why it is fire tube. So, there is a lot of coal stack. When you burn this coal, it will generate a flue gas that passes through a tube and this tube is integrated with a shell in which water comes in and water goes out. So, through this process water enters and we get the steam out and exhaust of the flue gas goes out through a chimney.

Here main important concern is that we are not able to effectively utilize this fuel properly because there are many waste, we cannot control. And second main limitation for this boiler is that it can produce the steam only up to 18 bar with an efficiency of 70%. So, people started thinking of the subsequent innovations against this fire tube boilers and new designs come up. So, that new design means instead of using the coal directly, the concept of fluidized bed boiler came into picture. This fluidized bed boiler is schematically shown here. So, instead of directly using the coal, you try to make the fuel in the powder form and try to use them properly.



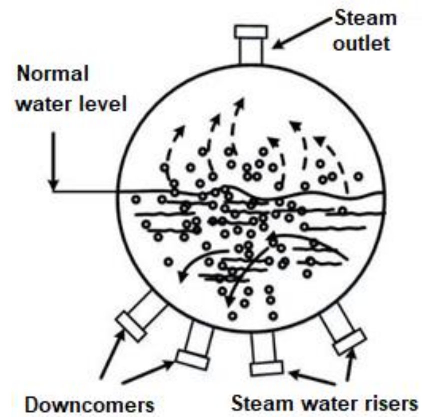
Fluidized bed boiler

So, basically from the plenum chamber you introduce the coal in a pulverized form into the combustion chamber and in this combustion chamber there are submerged water tubes and they get heat from these things. So, that means, one side coal and air mixture come in and get heated and subsequently the water goes out. And the exhaust product that means, whatever left out, which is called as a flue gas enters through the cyclone separator. So, this is how it operates, but through this process, it is observed that as compared to the conventional ones, here the volumetric heat release increases about 10 to 15 times. So, that way we can say, the surface heat transfer rate also becomes higher from the conventional boiler.

The next category of steam generator fall under the category of water tube boilers. In fact, this water tube boilers or other way called as a steam generator are eventually same, but they have different components like integration of economizers, boilers, super heater, re-heater and air- preheater. So, all these things are integrated in a sequence manner so that a single entity, normally called as a steam generator supplies the necessary quantity. So, water from high pressure feed water heater at 230℃ to 260 ℃ is received by an economizer and leaves as saturated or two phase of low quality then enters the steam drum at midpoint. From a close view of these, we can see in the same figure that the water enters into the steam drum from the economizer component and steam drum is basically a reservoir for water. To get saturated steam, one way is that we have to take out of the water from the drum through the down comer, header is the meeting point between the heat source and this incoming water through the down comer. When heat is being received the steam gets generated, since its density is low, it rises through riser and from riser we get saturated steam at this exit of the steam drum which is subsequently used for the super heater.

So, essentially we are coming from this path and if some reheating is required then we have a reheater unit. Reheating unit means, once you have reached superheated steam and then first expansion takes place in the turbine then you are reheating from 2-3. So, that reheating is done by re-heater. And again it is also a part of the complete component of steam generator. To operate the steam we also require forced-draft fans. Forced-draft fan is mainly required because we require very high steam rate, then mixing has to take place and we also expect a temperature of close to 1650℃.

Again the combusted gas has to leave. So, once the combustion process is over, exhaust from the steam has to leave from the fuel stack and that leaving takes place at around 320℃. So, that is the reason we also require the induced draft fans that draws away unwanted flue gases which has to be drawn away from the system and then they have to get out of the stack and moreover it has to go to the higher atmosphere or higher altitude, at a relatively higher height. So, that is the reason we require an induced draft fan.



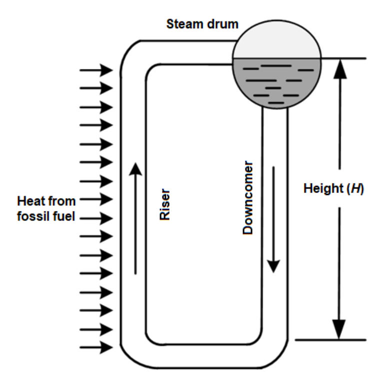
And of course, another thing is that the water exit temperature of the flue gases about 150℃ and you require exit temperature more than 100℃, just to make sure that we are exiting only the steam means there is no component of water that remains in the entire unit as due to condensation it may lead to corrosion of the surface. Second thing is that when you go for higher temperature, the density of flue gas becomes lower. So, that they can go relatively to a larger height through this high plume. So, this is made through complete dispersion in the atmosphere. So, these are some constraints that needs to be attended while designing this water tube boiler.

In next segment, we are going to talk about one particular component of this water steam generator that is steam drum. When you talk about steam drum, we say that it gives only saturated steam, but how does it happen? What are the different other complicacies that arises here? So, if you look this steam drum closely, in this particular figure which says that the drum essentially contains water and the saturated steam which is a mixture of this. We expect that only saturated steam goes out through the steam outlet and only water goes through the down comers and after receiving the heat from the fuel air, the steam has to rise and when it rises, it also submerges in this water and finally, goes as the saturated steam. So, that means, we need to separate the saturated steam from the water. So, this is the first task that the steam drum does.

Typically the steam drum is a cylindrical configuration of a length of 30m and diameter of 5m and a typical power plant must have at least 30 outlet nozzles and many more down comers and risers. And the entry for water into the steam drum comes from the economizer unit. That means, the entry comes from the economizer unit. So, economizer is located somewhere here.

Then one of the important work that steam drum has to do is to separate the steam from the water. So, there are three classical mechanisms, one is gravity separation, second one is mechanical separation, third one is centrifugal separation. So, first category is most conveniently used that is the gravity separation that means, it basically operates on the concept of density difference of steam and water. So, taking the advantage of gravity separations, we can see that when the water velocity is low, then we can use this concept more easily and naturally without any interference of water droplets, we can separate the steam and water. So, it is more economical for low stream quality and low pressure requirement.

Now when you go for relatively higher pressure, we expect the formation of this formation of water bubbles



Natural water circulation loop in steam drum limits the steam production rate at the outlet. Since water bubbles also creates the choking of the steam outlet, so these water doubles has to be separated. So, that mechanical arrangements like baffles, screens are made to separates these out and that is relatively at higher pressure.

Now for very high pressures, nearing to critical pressures that means, particularly when you are using one through boiler, we expect that the steam production has to be continuous and at higher rate because we are operating at very high pressures and to do that we have to forcibly allow this saturated steam to get out of the steam drum. For that we have incorporated the centrifugal separators and finally, screens are also used in the drum exit for the final drying operation action.

So, this is all about how the steam drum operates in different mechanisms. Now we will again talk about very specific components, like in the steam drum we have used the word riser and down comers. Down comer is for water to come out from the steam drum, riser is for a steam that goes up into the steam drum. So, if you take one particular segment as represented in this figure, we have a steam drum, through the down comer, the water comes in and the height of this thing is h and through this down comer subsequently water gets heat from the fossil fuel and again it rises and enters into the steam drum.

So, this process is called as a natural circulation process. Now we need to understand, in a conventional natural circulation process what is the mechanism, means how this density variations will help us in circulating water. So, this is a very well standard concept that is mostly used in the power plants. Other two mechanism like centrifugal separators or centrifugal devices or mechanical devices- baffle, screens, will not be covered in this section in a deep manner. So, we will only talk about the natural circulation of water in a steam drum through the riser and down comer arrangement. So, essentially the density difference is the driving force. We will try to find out what is the pressure requirement or what is pumping power requirement that essentially depends on the pressure rise through this riser. To calculate this, we have considered that there are possible ways of water circulations which are normally favoured for subcritical range of 160 bar. And at the critical pressure above 221 bar, density drops drastically. So, that means, at the critical point of water, the difference in the density of water or steam is almost nil or negligible. So, that's why, at very high pressure, the difference between the steam and water density decreases rapidly. Although this is an advantage part, there also is a disadvantage part that natural circulation may not be a feasible option when you go for very high pressure operations. However, let us see assume that we are going for a natural circulation based water circulation, through natural or buoyancy dependent water circulation. So, for that reason the critical parameter here is that when water comes through down comer, its thermodynamic state is pure liquid and when it enters to the riser, heat gets added into this water and it becomes steam. So, essentially when the slug of mass is moving through risers, not all of the water become steam immediately.

So, basically whatever slug of mass is within the riser, it is a mixture of water and steam. So, this is a two phase system. So, when it is a two phase system obviously, there is a density difference. Now, we need to find out what is the average steam density of the mixtures. Now, to find this average steam density of the mixture we introduce the term which is called as a void fraction which is α. Then we also talk about the average density of the mixture in the riser and also average mixture density distributions which is based on the amount of density with respect to liquid phase and density with respect to gas phase and α separates out between these two where, α is nothing, but the void fractions. So, below is a mathematical way of representation. I am not going deep into details.

Driving pressure caused by natural circulation, $\Delta p_d = (\rho_{dc} - \bar{\rho}_r) g H$

Average density of steam-water mixture in the riser, $\bar{\rho}_r = (1 - \alpha)\rho_f + \alpha \rho_g$

$$\bar{\rho}_r = \frac{\int_0^H \rho_m(z)\, dz}{H};$$

Average mixture density distribution, $\rho_m = (1 - \alpha)\rho_f + \alpha \rho_g$

A most standard way of expression, which you can directly take from the books which is well established expression for what we call as $\bar{\rho}_r$, which is nothing, but average density of steam water mixture in the riser. You can use this particular expressions is a derived expression which is mostly used in the steam power plant

$$\bar{\rho}_r = \rho_f - \left(\frac{\rho_f - \rho_g}{1-\psi}\right)\left\{1 - \left[\frac{1}{\alpha_e(1-\psi)} - 1\right] \ln\left[\frac{1}{1-\alpha_e(1-\psi)}\right]\right\}$$

H:Height of the drum-water level above header

g:Acceleration due to gravity

α_e:Void fraction at the exit of riser

z:Axial distance from the bottom of the riser

ρ_{dc}:Density of water in the down comer(nearly saturated at system pressure)

ρ_f&ρ_g:Densities of saturated liquid and saturated vapour, respectively

So, using this we can find out what is the driving pressure that is caused by the natural circulations. Of course, there are other parameters that are involved, one is the void fractions which is defined as the ratio of volume of the vapor to the volume of steam water mixture. Dryness factor is also important which is referred as ratio of the mass of dry vapor of the steam to the combined mass of the steam and liquid in the mixture. Now for a two phase system, we also define a parameter which is called as slip ratio. Since it is a two phase systems, we say that, maybe vapor move at a faster rate. So, how much faster, that typical value depends on the path length of the riser that is h and it is mainly in the range of 1 to 2, but we cannot go beyond 10. So, 1 to 2 is a reasonable number for water circulation in the boiler.

Void fraction, $\alpha = \dfrac{1}{1+\left(\frac{1-x}{x}\right)\psi}$; Drynessfraction, $x = \dfrac{1}{1+\left(\frac{1-\alpha}{\alpha}\right)\left(\frac{1}{\psi}\right)}$

$\psi = \dfrac{\rho_g}{\rho_f}S; S = \dfrac{\bar{V}_{s,g}}{\bar{V}_{s,f}}$ (Slip ratio of two-phase mixture)

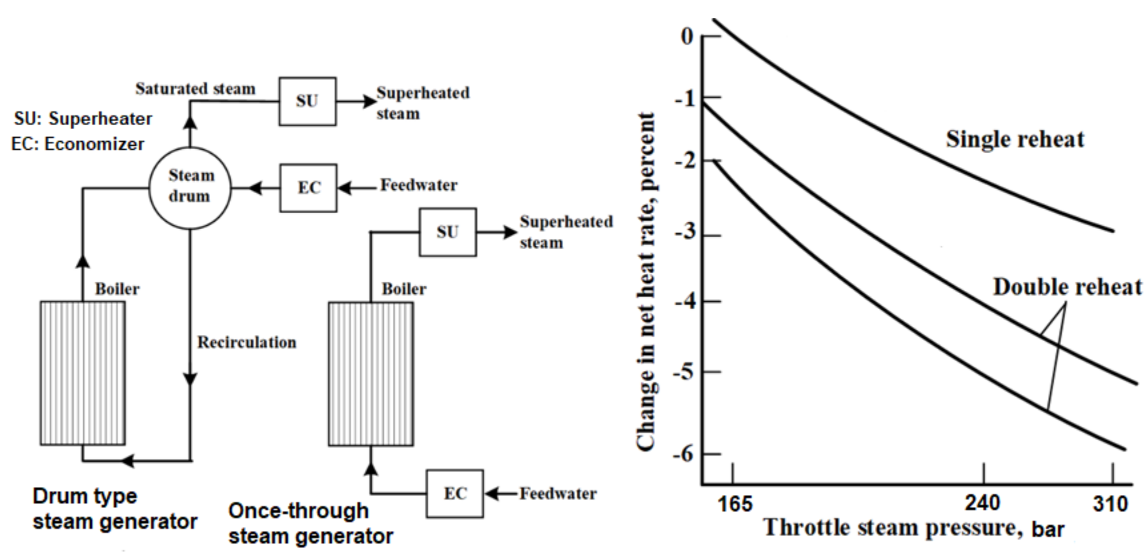
S: A non-dimensional number greater than1(upto10)

(S approaches 1at high pressures where liquid and vapour densities approach each other)

$\bar{V}_{s,f}$&$\bar{V}_{s,g}$:Average velocity of liquid and vapour phase at any cross-section of riser

ρ_f&ρ_g:Densities of saturated liquid and saturated vapour, respectively

Next part I have already mentioned several times that is, once through boiler. So, once through boiler takes care of operation of the steam boiler at a condition which is above the critical pressure 22.1 MPa So, while operating at this pressure, it is possible to bring water to steam directly, bypassing its critical point. So, let's compare the advantages of once through boiler and the conventional drum type boiler, which are shown in the figure. You can see the drum type steam generator has component like super heater, economizer or riser, down comer. So, all these components are integral part of this. But when you see once through boiler from the economizer to super heater, the water goes directly to steam. So, essentially for this to operate, we have to go for the pressure which is above 22MPa for water. Although it is very lucrative option; lucrative option means, we are actually bypassing many important components like down comer, riser & avoiding the heating part of liquid to vapor, which is transition state. So, all these things when we are bypassing, this this becomes an added advantage.



But another significant way in terms of economics is to look at the throttle steam pressure and change in the heat rate. So, basically heat rate is defined as the amount of energy which is added to by heat transfer to a cycle to produce one unit of work output. If you look at this part then interestingly we can observe most important concept that this heat rate comes down. That means if you see from this particular graph, throttle steam pressure vs. heat rate. If you are increasing the throttle steam pressure then heat rate comes down that means, the rate of heat addition in a once through boiler as compared to conventional boiler is less. So, when the heat rate is less that means, with low quantity of fossil fuels we can produce at higher steam. So, this is the advantage that economically once through boilers is chosen for many applications. Of course, for this once through boiler we must have operating range of 138 - 276 bar. And it has a flexibility of choosing the steam flow from very low to very high i.e., from 4 - 1250 kg per second. So, that is the unanimous choice that once through boiler has many more advantage over the conventional water based boiler. And of course, once through boiler is most unanimous choice when you mainly go for nuclear or any geothermal power plant system because of its uniqueness that we can directly go from water to steam by bypassing the critical point. So, this is all about the overall steam generator and its applications and before you end this lecture let us solve some numerical problems based on our discussion so far.

Q1. A steam generator burns fuel oil with 20% excess air. The flue gas pressure leaving the air preheater is 3.1 bar. Determine the minimum stack temperature required to avoid condensation.

So, the problem statement goes like this we have a steam generator, it burns a fuel oil with 20% excess air. The flue gas pressures leaving the air preheater is 3.1 bar and we need to find out what is the minimum stack requirement to avoid the condensation. So, first thing is that let us understand that where is this air preheater is located. So, air preheater is somewhere here and this air preheater is used to take heat from the flue gas which is going as 3.1 bar. Now, the flue gas is essentially the products of combustion. So, main important requirement is that we must keep this stack temperature to a point for which there will not be any condensation. And why the condensation? Because the products of combustion mainly consist of water component H_2O. Now, let us see how you go about it. So, first thing is that let us see that what is your fuel.

$$Fuel\ oil(Fossil\ fuel) \rightarrow C_{12}H_{26} + Air \rightarrow Flue\ gas(H_2)$$

So, fuel in this case is the fuel oil. So, fuel oil which is typically a fossil fuel, for which the chemical formula is assumed to be $C_{12}H_{26}$. For this, it takes along with air and gives flue gas and this flue gas mainly contains water. And this flue gas is leaving at 3.1 bar and we need to find out that at this pressure the water should not condensate. For condensation of water, we also need to find out what is the partial pressure of this water vapor. To solve these problems first thing that you have to find out is stoichiometric combustion equation.

$$C_xH_y + a(O_2 + 3.72\ N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76\ a(N_2)$$

Here air contents oxygen plus 3.72 times nitrogen. So, basically if you take 1 mole of oxygen there has to be 3.72 moles of nitrogen.

Here, $a = x + \frac{y}{4}$

In our case, $x = 12; y = 26$

$\Rightarrow a = 18.5$

Now, the combustion equation will look like

$$C_{12}H_{26} + 18.5\ O_2 + 69.56\ N_2 \rightarrow 12\ CO_2 + 13\ H_2O + 69.56\ N_2$$

This is the stoichiometric combinations, but what happens it actually burns with 20% excess air. That means, in the term 18.5 O_2 18.5 has to be increased by 20%, $18.5 \times 0.2 = 3.7$.

Now, combustion equation will be

20% excess air,

$$C_{12}H_{26} + 22.2O_2 + 83.473\ N_2 \rightarrow 12CO_2 + 13H_2O + 3.72O_2 + 83.473\ N_2$$

Now, once you got this balanced equation then we will be finding out what is the mole fraction of water.

Mole fraction of H_2O, $Y_{H_2O} = \frac{13}{12 + 13 + 3.7 + 83.473} = 0.116$

You require to calculate mole fraction of water because correspondingly we need to find out partial pressure of H_2O.

Partial pressure of H_2O,

$$p_{H_2O} = Y_{H_2O} \times p_{tot} = 0.116 \times 3.1 \,;\, p_{tot} = 3.1 \text{ data given}$$

$\Rightarrow p_{H_2O} = 0.3596$ bar

So, that means, the saturation pressure will be 3.96 bar, but our question is asked for temperature.
So, we refer steam table that is saturated pressure table.

$T_{H_2O} = 72$°C

So, this is your answer, we say that the minimum stack temperature should be 72°C to avoid condensation. And essentially this is the requirement that condensation should not happen as it will lead to corrosion effect.

Q2. A down comer-riser system (height 12 m) receives uniform heat and saturated water. The exit quality of the steam is 50% and the system operates at 172 bar. Calculate the driving pressure for the system.

So, the next important problem is about the natural circulation in the water tube boiler. I have mentioned several times that we are going to calculate the driving pressure Δp_d, which is the density difference between the down comer and riser. The riser contains mixture of steam and water. So, we need to find out the average density distribution through this expression.

Driving pressure caused by natural circulation, $\Delta p_d = (\rho_{dc} - \bar{\rho}_r)gH$

Average density of steam-water mixture in the riser,

$$\bar{\rho}_r = \rho_f - \left(\frac{\rho_f - \rho_g}{1-\psi}\right)\left\{1 - \left[\frac{1}{\alpha_e(1-\psi)} - 1\right]\ln\left[\frac{1}{1-\alpha_e(1-\psi)}\right]\right\}$$

And in this expressions we are using the terms like α, which is the void fractions, ψ, another fixed term that is the ratio of specific volumes. We also know this exit quality. So, for the solutions, we must understand the key notations that we have to calculate individually.

$H = 12m$

$x_e = 50\% = 0.5$

$p = 172$ bar

Now, here it is operating in liquid plus vapor mixture. So, from the steam table, you refer saturated vapor conditions, which will give you two important parameters at 172 bar.

$Steam\ Table\ (Sat.Vap.) \rightarrow 172$ bar,

$v_f = 0.00177\ m^3/kg;\ \ \rho_f = {}^1/_{v_f} = 565\ kg/m^3$

$v_g = 0.00836\ m^3/kg;\ \ \rho_g = {}^1/_{v_g} = 119.6\ kg/m^3$

Void fraction, $\alpha_e = \dfrac{1}{1 + \left(\frac{1-x_e}{x_e}\right)\psi}$

$\psi = \left(\dfrac{v_f}{v_g}\right)S$; where S = slip ratio

I mentioned, the steam in this riser is a mixture of liquid vapor mixtures. So, vapor travels at a faster rate. That means, we say that for this the slip ratio, $S = 1.2$ $\psi = 0.254$

Now, $\alpha_e = 0.8$

Now when you have all this number then we can find out, $\bar{\rho}_r$ that is average density of steam water mixture in the risers.

$$\bar{\rho}_r = \rho_f - \left(\frac{\rho_f - \rho_g}{1-\psi}\right)\left\{1 - \left[\frac{1}{\alpha_e(1-\psi)} - 1\right] \ln\left[\frac{1}{1-\alpha_e(1-\psi)}\right]\right\}$$

$$\Rightarrow \ \bar{\rho}_r = 331 \ kg/m^3$$

Now, $\Delta p_d = \ (\rho_{dc} - \bar{\rho}_r)gH$

Down comer density is mainly liquid, so it is assumed that, $\rho_{dc} = \rho_f$ =565.

$$\Delta p_d = (565 - 331) \times 9.81 \times 12 = 27546 \frac{\mathrm{N}}{\mathrm{m}^2} \approx 0.275 \mathrm{bar}$$

So, driving pressure for this system through this circulation is about 0.275 bar. That means, we need to give some additional device that can create this pressure, so that the steam can rise in the riser. So, this is all for the discussion today. Thank you for your attention.