POWER PLANT SYSTEM ENGINEERING

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Module 2

Lec 13: Water Tube Boiler (Part II)

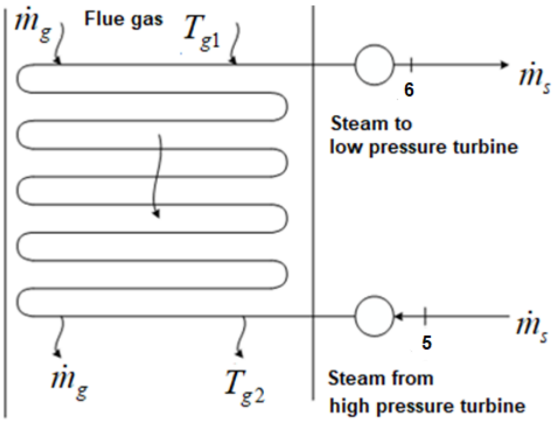
Dear learners greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering module 2 that is Vapor Power System part 3. So, in the last lecture we have covered the water tube boilers and modern steam generator systems and this modern steam generator systems mainly constitutes some important heat exchangers like super heaters, re-heaters, economizer and air pre heaters. Apart from that there are auxiliary units like fans and stacks. So, these things needs to be discussed. So, in our previous lectures we have mostly covered the important component that is super heater.

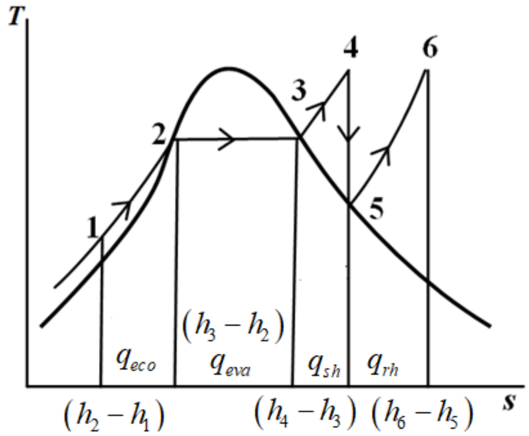
So, in this lectures we will follow our attention to the some other heat exchangers which are part of this modern steam generator systems. So, they are re heaters, economizers and air preheaters. So, let us give the brief introductions about water tube boilers that is nothing, but a modern high pressure steam generators. Normally, they operate at very high pressure, at 70 bar for saturated steam and 240 bar for superheated steam.

And this water tube boilers are nothing, but the integration of furnace, economizer, boiler, super heater, reheater and air preheaters. So, in other words we say that water tube boiler or steam generator is a complex combination of economizer, boiler, super heater, reheater and air preheater. So, if you look at this thermal circuit for a modern steam generator, we have a steam drum where saturated steam is generated and it goes to superheated unit which we discussed in our last class. So, in our lecture today, we will be mainly focusing on the important heat exchanger components that is reheater, second is economizers, and third is air preheaters. We will try to find out the need that arises for these components and why they are being used in these systems.

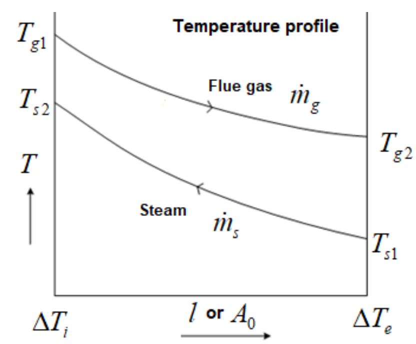
Apart from that we will also discuss about the thermodynamic analysis and heat transfer analysis for these heat exchanger components. Looking at this figure, which is a simplified circuit diagram where these heat exchanger units are placed. To begin with we have economizers, then we have steam drum which gives saturated steam, then we have super heater, then we have reheater unit. But all these heating applications, heating requirements are given in this steam generating unit. So, to summarize what we have is that feed water from high pressure heater enters the economizer where it receives heat from the outgoing flue gases till it becomes saturated liquid stage and then fed to the steam drum.

Then the saturated liquid falls through the down comer circuit into the bottom header and moves to the riser where the water is partially boiled back to the drum. And finally, the saturated steam from the drum goes to the super heater for further heat addition to the desired temperature. So, let us think about the reheaters. Now if you recall our thermodynamic diagram that is T-s diagram, the reheating part normally happens when the steam from its superheated state that is state 4 expands in the first stage turbine. After expansion to a lower pressure, then steam is further reheated to the point 6. So, essentially speaking, heat addition process from 4 to 5, 5 to 6 is done through a reheater heat exchanger unit. And in this reheater heat exchanger unit, we receive the steam from high pressure turbine and its mass flow rate is $\dot{m}_s$ and steam goes out at point 6 with mass flow rate $\dot{m}_s$.





And this heat addition takes place from this flue gas. Initially the flue gas temperature is T_{g1}, after heat this addition the temperature drops to T_{g2}. And the entire heat addition process is done through mass of this flue gas $\dot{m}_g$. So, our main topic of attention is to analyze this heat exchanger circuit. So, essentially if you compare the heat exchange part in a reheater & a super heater; in a super heater the mode of heat transfer can be convection or radiation, but here in reheater, since we are dealing with low temperatures as compared to super heating units, most of the heat transfer or prime mode of heat transfer is convection.



So, analysis of this heat exchanger has to be done through convection mode. So, in this figure, for this reheating unit, initial temperature of steam is T_{s1} and finally, steam gets reheated to T_{s2}. That means, Initial temperature T_{s1} is like T_5 and this point T_{s2} is like T_6. And this heat addition is given from the flue gas, so its temperature drops from T_{g1} to T_{g2}. It is a counter flow heat exchanger and temperature profile for this counter flow heat exchanger is given by this particular figure. So, what we have seen so far is that there are two temperature difference, one is ΔT_i & other is ΔT_e.

$$\Delta T_i = T_{g1} - T_{s2}; \Delta T_e = T_{g2} - T_{s1}; \Delta T_{LMTD} = \frac{(\Delta T_i - \Delta T_e)}{\ln\left(\frac{\Delta T_i}{\Delta T_e}\right)}$$

So, from this temperature differential, one can define logarithmic mean temperature difference (LMTD). Once you find the LMTD then we can link this heat transfer through the following expressions that involves overall heat transfer coefficients, outer surface area and ΔT_{LMTD}.

In terms of overall heat transfer coefficient, $\dot{Q}_{RH} = U_0 A_0 \Delta T_{LMTD}$

But this heat comes through convection. So, we can make a heat balance equation that says that the heat rejected by flue gas is added to the steam. For this T_5, the corresponding enthalpy is h_5 and for T_6, the corresponding enthalpy is h_6.

The rate of heat absorption in reheater, $\dot{Q}_{RH} = \dot{m}_g c_{pg}(T_{g1} - T_{g2}) = \dot{m}_s(h_6 - h_5)$

The heat transfer into the steam, $\dot{m}_s(h_6 - h_5)$ and the heat transfer that goes out from the flue gas is $\dot{m}_g c_{pg}(T_{g1} - T_{g2})$ as this is gas phase. Once you have this expressions then we can link these things to the outer surface area and the steam flow rate.

Surface area, $A_0 = n\pi d_0 l$; Steam 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_i: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; v_f:Specific volume of steam

So, knowing this we can solve this problem of counter flow heat exchanger unit and to get the desired parameters.

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

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

And normally we start with the calculation of heat requirement for this steam that is being supplied through the flue gas, then we this heat has to be linked to the geometrical aspects of the heat exchanger that mainly deals with the outer area of this tube. And this outer area will give you the number of tubes required & the length of the tube.

Then another mode of heat exchanger that is used in the steam generator unit is the economizers. So, if you can see this modern steam generator, economizer in the steam generator unit is mainly used to utilize the unwanted or exhaust gas from the flue gas. This means that the heat waste from the flue gas is being used in an economizer unit. The purpose of the economizer is to use the energy of the waste heat of the flue gas to preheat or to heat the liquid water to the saturated liquid which enters to the steam drum. So, the word economizer historically is used because the discharge of such high temperature gases would cause huge loss of exergy and efficiency of the plant. So, that is the reason it has been advisable that the waste gas available from the flue gas at around 350-500℃ should be utilized. And of course, it is being utilized in super heater and re heater other unit, it can also be utilized it in the economizers.

So, an economizer is a heat exchanger that rises the temperature of water leaving high pressure feed water heater to the saturation temperature corresponding to boiler pressure or entry to the steam drum . So, this is also an essential requirement for a modern steam generator unit. So, the analysis of the economizer is almost the same thing, what we have done for re heater and super heater unit with convection mode of heat transfer. Here also the mode of heat transfer is convection, but only difference is that here heat comes from the flue gas whose temperature drops from T_{g1} to T_{g2} and feed water temperature rises from feed water temperature to the saturated temperature. Only this difference is there.

Similar analysis also we need like calculating the logarithmic mean temperature difference for a counter flow heat exchanger mode. Then we have to find the heat transfer to the feed water through this energy balance equations.

The rate of heat transfer from flue gas to feed water,

$\dot{Q}_{ECO} = \dot{m}_g c_{pg}(T_{g1} - T_{g2}) = \dot{m}_{fw}(T_{sat} - T_{fw})$

Then you have to use this equation or link this equation to the tube geometry by this overall heat transfer coefficients, outer surface area and LMTD. So, once you know this, our end requirement would be finding the surface area requirement, the number of tubes, the length of the each tube for which the water has to be inserted into the economizer unit.

In terms of overall heat transfer coefficient, $\dot{Q}_{ECO} = U_0 A_0 \Delta T_{LMTD}$

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

$$\Delta T_i = T_{g1} - T_{sat}; \Delta T_e = T_{g2} - T_{fw}; \Delta T_{LMTD} = \frac{(\Delta T_i - \Delta T_e)}{\ln\left(\frac{\Delta T_i}{\Delta T_e}\right)}$$

Overall heat transfer coefficient, $\frac{1}{U_0} = \frac{1}{h_i} + \frac{x_w}{k_w} + \frac{1}{h_0}$

Surface area, $A_0 = n\pi d_0 l$; Steamflowrate, $\dot{m}_s = \left(n\frac{\pi}{4}d_i^2\right)\left(\frac{V_{fw}}{v_f}\right)$

d_0:Outer diameter of tube; 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

k_w:Thermal conductivity of wall material
V_{fw}:Velocity offered water at exit; v_f:Specific volume saturated water

Then next requirement is the air preheater. Air preheater are normally of two types, recuperative type and regenerative type. And they normally use the hot flue gases and then raise the temperature of air. Now, question arises why you require the increase in the temperature of air. Normally for combustion purpose, if you can see here, just below the steam drum, header and down comber unit, we require the fuel and air should enter. So, that air is also sufficiently of high temperature required for appropriate combustion. Now, when this air is being fed, it is better that you preheat the air by using the flue gas. So, for that thing we require an air preheater. And there are two types of air preheater one is recuperative type & other is regenerative type. So, in a regenerative mode normally the heat is stored by an intermediate unit. That intermediate unit could be a ceramic matrix or a steel unit. This will act as an energy storage medium and then whenever required the stored energy can be utilized to preheat the incoming air and the maximum temperature we can go up to is adiabatic flame temperature.

But for the steam generating unit, this is not an advisable option. So, it is better that use the other mode of heat exchanger which is called as recuperator. So, recuperator is a heat exchanger unit in which energy from the steady flow of hot combustion products or flue gases gets transferred to the air supplied for the combustion purposes. So, basically this air preheater unit in a modern steam power generator is a recuperative type air preheater and again it operates in a counter flow heat exchanger mode. But its design is little bit different, this unit normally uses a tubular type, so, this is nothing, but a tubular type air preheater. So, basically the tubular flow heater unit means that we have tubes which allows the flue gas to pass through various tubes and for better circulation of air that means, the passage of air is made in such a way that this air gets maximum interaction with the flue gases to enhance its temperature from T_{a1} to T_{a2}. And for a given mass flow rate of air there is also essential requirement of mass flow rate of flue gas. So, analysis is again like simple type of heat exchanger unit. The only difference is that energy comes from the flue gas, & only air is heated from T_{a1} to T_{a2}.

So, now, to assigning some standard numbers, normally these air preheater units receives flue gases at around 320 to 420 ℃ and the gases are cooled up to 130 to 170℃ . Normally that means, T_{g1} and $T_{g\,2}$are fixed in this range. Then air, normally atmospheric air gets preheated up to maybe 90℃ or it can go up to 260℃ depending on the temperature of flue gas. So, by using this, we can have a typical fuel saving of 4% for preheating the air to 90℃ and you can get up to 12% fuel saving when you use the preheater up to 260℃.

So, in addition to fuel saving the preheated air is also requirement for operation of pulverized coal for drying purposes. Again for the coal firing unit, we also require dry coal to enter into the furnace. So, preheated air has also this additional requirement for the power systems. So, the analysis is similar to any heat exchanger unit and air preheater operates with convection mode of heat exchanger. Here we need to do this energy balance first that is a heat flow into air preheater that is $\dot{Q}_{APH}$ and the heat rejected from the flue gases is getting added to the air to increase its temperature from T_{a1} to T_{a2}.

The rate of heat transfer from flue gas to air, $\dot{Q}_{APH} = \dot{m}_g c_{pg}(T_{g1} - T_{g2})$

$$= \dot{m}_a(T_{a2} - T_{a1})$$

Another expression we can find out the with respect to this heat transfer is by linking this with respect to geometry of the preheating unit through overall heat transfer coefficients, outer surface area and LMTD. Here also LMTD can be calculated in the similar manner as we discussed previously. And of course, we can also link the gas flow rate. So, it is gas flow rate $\dot{m}_g$ for the flue gases and of course, by doing this analysis we can find out A_0, surface area requirement, number of tubes and length of the each tube.

In terms of overall heat transfer coefficient, $\dot{Q}_{APH} = U_0 A_0 \Delta T_{LMTD}$

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

$$\Delta T_i = T_{g1} - T_{a2}; \Delta T_e = T_{g2} - T_{a1}; \Delta T_{LMTD} = \frac{(\Delta T_i - \Delta T_e)}{\ln\left(\frac{\Delta T_i}{\Delta T_e}\right)}$$

Overall heat transfer coefficient, $\frac{1}{U_0} = \frac{1}{h_i} + \frac{x_w}{k_w} + \frac{1}{h_0}$

Surface area, $A_0 = n\pi d_0 l$ Gas flow rate, $\dot{m}_g = \left(n\frac{\pi}{4}d_i^2\right)\rho_g V_g\left(\frac{V_{fw}}{v_f}\right)$

d_0:Outer diameter of tube; l:Length of the tube;x_w:Thickness of tube; n:Number of tubes

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

k_w:Thermal conductivity of wall material ;V_g:Velocityoffluegasatinlet $\left(10\text{-}12\,\frac{\text{m}}{\text{s}}\right)$

ρ_g:Density of flue gas at inlet $\left(=\frac{p}{R_g T_{g1}}\right)$; $p = 1.03$bar; $R_g = 0.287\,\frac{\text{kJ}}{\text{kg.K}}$

So, till this point of time we are covering only heat exchangers or the components of a modern steam generator. Now, we will look into some auxiliary components. The other auxiliary components are fans. We all know that conventional fans have a certain pressure differential. And with respect to steam generating unit we require fans. Why do you require fans? First thing, we need to push the air into the system and air requirement is of many fold, like there is fuel air requirement at the furnace stage itself, so that means, we need to push the air. So, to push sufficient amount of air and to create a pressure differential we require a fan.

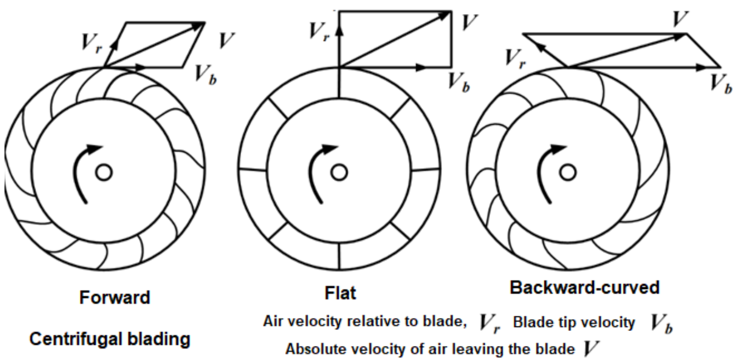
Now, this is one requirement, second requirement is that once the combustion takes place, energy release has taken place, so it generates the flue gas because fuel and air, when they mix, at the end of the combustion it generate the flue gas and the flue gas has to be taken out from the systems. So, again some kind of fan is required to pull it out from the systems. So, basically the role of fans is to assist the large steam generator unit to push the air into this unit through a fan called as forced draft fan and also pull the combustion gas out, for that reason we require an induced draft fan that takes this flue gas out from the systems.

So, push and pull concept is very useful for a steam generating unit and it is one of the most vital requirement for the system. So, there are basically two types of fan forced draft fan and induced draft fan. They should overcome the total air and gas pressure losses within the steam generator. Many modern steam generator used forced draft fans that are placed at the air entrance to the preheater and put the entire system till the stack entrance under positive gauge pressures. So, they are forced draft fan. That means, the system is already in the gage pressure means already the unit is a pressurized unit because we use the forced draft fan to push the air into the systems. And this forced draft fan handle only cold air from the atmosphere. Because of this reason, they have advantage like low maintenance, less consumption power, less capital operating cost, but the only difference is that since it is always pushing the fair into these systems, so the unit is already under pressure and we call this as a pressure furnace.

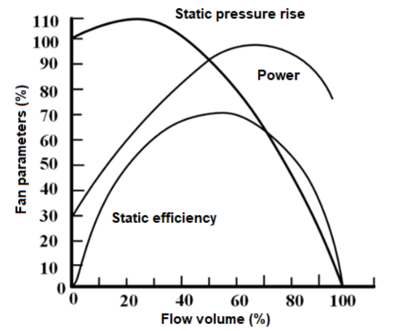
But there are other category of fans which we call as induced draft fans they are located in the gas stream between air preheater and the stack. So, essentially the induced draft fan pulls the combustion products out from the systems towards the stack. So, thereby when you see induced fan designs, they handle hot gases that includes original air also because in the circuit some of the original also gets pulled away and also gas is equivalent to fuel which means power requirement is greater. So, the power requirement for induced draft fan is higher than that of the forced draft fan. But in a balanced draft steam generating unit we have a forced draft fan as well as induced draft fan and they operate in such a way that system is under balanced draft. So, the forced draft will push the air and induced draft fan is will pull the combustion product out of the systems.

And for large power generating plants, the typical fan size should handle about $700\frac{\mathrm{m}^3}{s}$ which is of course a very high volume flow rate, but for a very low pressure like 0.15 bar pressure difference is sufficient to handle this flow rate. And of course, since the plant is continuously running, these fans also need to run 24×7, so their life period is something about 1.5 years.

Now, coming back to the type of fan. So, either it is an induced draft fan or forced draft fan, they are actually of two types- one is centrifugal type, other is axial flow fans. So, the centrifugal fans as you see this figure, the gases are accelerated radially. If you look at this particular figure for the centrifugal blading which shows that absolute velocity of air leaving the blade is $V,$ blade velocity is V_b and relative velocity is $V_r,$ then we can form a velocity triangle involving V_b, V_r & V. So, for forward blade, flat blade and backward curved blade, we can see this orientation of V_b, V_r & V as shown in the diagram below. So, thereby these orientation are used as per requirement; when you push the air we normally require forward blading when we pull the gas out, we normally require backward curved blades.



Centrifugal blading



Characteristic curve for a constant speed centrifugal fan with backward curved blades

So, that way blade design through centrifugal blading will help us in making decision to use the forced and induced draft fans. But there are other category of fans, conventionally we use, similar to our desk fans, in which the gases are accelerated parallel to the rotor axis. So, in a conventional desk fan, when you are sitting in front of it, we can feel of air hitting on our body because the air is being directed axially through its blading. But these axial fans have high efficiency over wide range of loads than constant speed fans, but they incur very high capital cost. But the best way is that we should use a centrifugal type of fan.

Normally the standard characteristics curve shows the flow rate, the power requirement, the pressure rise. All these things are governed through the characteristics curves of fan. That means, this particular curve shows fan parameter like static pressure rise, which normally increases with flow rate and drops subsequently. Then power increases then subsequently after certain flow rate it drops. Static efficiency increases initially then drops. So, basically the characteristics curve says that we should meet a balanced point or range of flow rate at which the fan should be regulated to operate to have maximum potential or maximum ability to have this combined effect of static pressure rise, power requirement and efficiency.

So, basically whether you use backward curve blade or forward curve blade, at the end of the analysis we require, what is the power requirement per unit mass by the fan which is $\dot{w}_f$. And that can be calculated for a steady flow thermodynamic system as follows.

Steady-flow thermodynamic system, $\dot{w}_f = \int v dp = \frac{v\Delta p}{\eta_f}$;

So, v can be taken out from this integration because we are handling the gas which is typically incompressible in nature and this gas is being felt a pressure differential of dp and from this we can calculate the power.

Power required by the fan, $\dot{W}_f = \frac{\dot{m}v\Delta p}{\eta_f}$

Of course, we can introduce the efficiency, η_f at which the fan operates. Then this power requirement can be related to two types of pressure drop one is static pressure drop, other is a velocity head or static head and dynamic head or velocity head. And in terms of the static head we can bring this pressure differential to a unit of meter.

Pressure differential across fan, $\Delta p = (p_2 - p_1) + \frac{1}{2}\rho(V_{s2}^2 - V_{s1}^2)$;

V_s:Gas exit velocity to the stack; Static head: $\frac{p_2 - p_1}{\rho g}$; Velocity head: $\frac{V_{s2}^2 - V_{s1}^2}{\rho g}$;

v:Specific volume of air or gas;

$\dot{m}$:Mass flow rate of air or gas; ρ:Densityofairorgas $\left(= \frac{1}{v}\right)$

So, a velocity head we can obtain from the velocity of the steam or gas, then we can use the static head based on the static pressure difference and that pressure difference is the losses that occur at various components of the steam power unit.

The next segment of our discussion is stack. Normally if you have seen the schematic figure, there is a particular unit where the flue gas comes out from the power steam generating unit and it goes to the stack. So, let us see what does this stack means. And this stack is nothing, but a very high rise structure of certain height H. And ideally speaking, the flue gas has to go out at larger height and when it goes out this flue gas try to expand in the atmospheric medium. So, you can see there are plumes coming up and it is like an expansion of this free jet in an open atmosphere and for which we can make a concentration profile for the flume. And through this expansion process they try to disperse in the atmosphere.

So, essentially the role of stack in a fossil fuel power plant has two major functions- one is assisting the fan to overcome the pressure losses because this itself gives a pressure differential at a larger height with respect to the atmospheric height. And the other one is the most important thing that is to help the dispersing of combustion gases efficiently into the atmospheres. So, essentially this driving pressure between these two is difference in atmospheric density (ρ_a) and average stack density ($\bar{\rho_s}$) and stack density means, whatever gas contains within these things. And this atmospheric density is related to atmospheric pressure, temperature and its gas constant. Even for stack density, it is with respect to stack pressure, gas constant of the stack and average stack temperature.

The driving pressure supplied by a stack, $\Delta p_d = (\rho_a - \bar{\rho}_s) g H$

Atmospheric air density, $\rho_a = \frac{p_a}{R_a T_a}$; Averagestackdensity, $\bar{\rho}_s = \frac{p_s}{R_s \bar{T}_s}$

$$\Rightarrow \Delta p_d = \frac{p_a}{R_a}\left(\frac{1}{T_a} - \frac{1}{\bar{T}_s}\right) gH; \bar{T}_s = \frac{T_i + T_e}{2}; p_a \approx p_s; R_a \approx R_s; H\text{:Stack height}$$

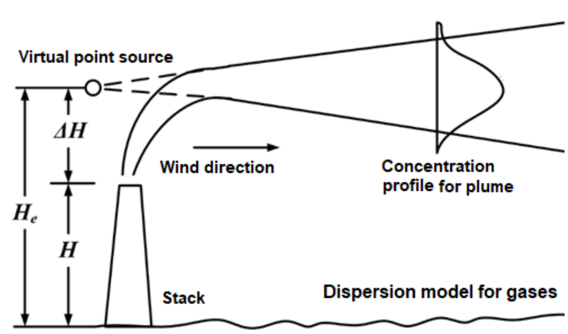
p_a&p_s:Absolutepressuresofatmosphericairandstackgas, respectively

R_a&R_s:Gasconstantsforairandstackgas,respectively

T_a&$\bar{T}_s$:Airandaveragestackgastemperature,respectively

T_i&T_e:Stackinletandexittemperature,respectively

So, they can be related to ideal gas equation and ultimately we can frame these requirement of pressure differential that happens for the stack. So,



this is nothing, but your first objective that is assisting the fan to overcome the pressure losses. If you use the stack ultimately we will be trying to reduce the fan power. But the second main important objective of the stack is the dispersion of flue gases. The dispersion of gases in the atmosphere is defined as the movement of flue gases horizontally as well as vertically and their dilution by the atmosphere.

The horizontal motion is nothing, but the existing wind velocity. That means, we can see the wind velocity at V_w and this is horizontal velocity. This gets assisted based on the direction of the wind. Other part is the vertical part and the vertical component is also governed by the flow rate or the momentum it has achieved while coming out of the stack. So, the combined effect is nothing, but the formation of a plume. So the plume rise is denoted as ΔH and this is above this actual stack height H and it is defined as the height of virtual point source above the stack which is obtained by extending the lines of dispersion backward. So, that means, the 2 flue gas lines of dispersions when extended backward, we arrive at a point that is called as point source and from this point source we can measure this height above H which is nothing, but your ΔH.

Now, to analyze what is this ΔH we need to use some analytical methods that utilizes momentum terms to account for the vertical momentum of the gas caused by the stack exit velocity and buoyancy as the dispersion takes place through buoyancy or density difference of the stack and atmospheric air. So, different models or correlations has been used, but in this lecture I am just covering that to find this effective stack height we have to find this actual H and ΔH is nothing, but your plume height and it is modeled through Briggs correlations through this expressions.

Effective stack height, $H_e = H + \Delta H$; Correlation for plume height, $\Delta H = \dfrac{114 C F^{\frac{1}{3}}}{V_w}$

Now, here the terms associated with this correlation presented below.

Buoyancy flux, $F = \dfrac{g V_s D^2 (T_s - T_a)}{4T_a}, \dfrac{m^4}{s^3}$; g:Gravitational acceleration $\left(= 9.81 \dfrac{\mathrm{m}}{\mathrm{s}^2}\right)$

C:Dimensionless temperature gradient parameter $= 1.58 - 41.4\left(\frac{\Delta\theta}{\Delta z}\right)$

D:Stack diameter; H:Stack height; $\frac{\Delta\theta}{\Delta z}$:Airpotential temperature gradient

$\left(\frac{\Delta\theta}{\Delta z} = 0 \text{ for atmosphere stability}; \frac{\Delta\theta}{\Delta z} = -0.001\text{to}0.013\,\frac{\text{K}}{\text{m}}\right)$

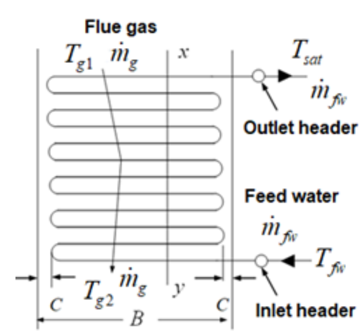
V_s&V_w:Stack gas exit velocity and wind velocity at stack exit, respectively

T_s&T_a:Gas temperature and air temperature at the exit of stack,respectively (K)

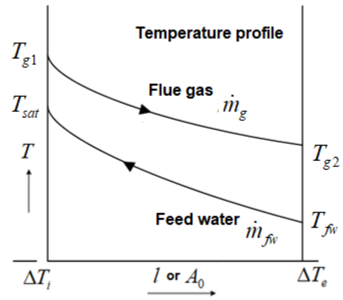
$\frac{\Delta\theta}{\Delta z}$, which is nothing, but air potential temperature gradient and this value ranges from minus 0.001 to 0.013. So, it is better that we assume any value of this from this range and when there is atmospheric stability that mean there is no turbulence/no disturbance this value is 0. So, once you know this then you can calculate ΔH.

So, this is all about the important primary units of heat exchangers and auxiliary units that involves fans and stacks. So, we will try to solve some numerical problems based on our discussion in this lecture.

Q1. Feed water from the high pressure heater enters the inlet header of the economizer at 140 bar & 170°C with flow rate of 580 kg/s. It is heated by the flue gas till it becomes saturated liquid at same pressure and leaves the outlet header to enter into the steam drum. Flue gases flows through the economizer coil at a rate of 1260 kg/s and leaves at 460°C. In order to restrict the erosion rate by fly ash, the flue gas velocity is restricted to 10 m/s and optimum water velocity leaving the coil is 1.2 m/s. The tubes of economizer have inner and outer diameters of 55 mm and 65 mm, respectively. Take overall heat transfer coefficient as, 68 W/m^2 and the specific heat of flue gases is 1.12 kJ/kg.K. Determine the number of coils needed in the economizer and length of each coil.



So, the first problem deals with an economizer and typical circuit diagram I have explained. It is a counter flow heat exchanger. So, its main purpose is that feed water temperature increases to the saturation temperatures and it is done through the flue gases. So, from this figure and given data from here, we can put a condition that is state 1 for the feed water and state 2 for the saturated water that goes out. Now, from the data that is given for feed water is 140 bar, 170℃ , flow rate of 580 kg/s and it is heated till it becomes saturated liquid.



So, we have to use steam table.

State-1: High pressure feed water (140 bar, 170℃)

$$h_1 = 1571.1\ \mathrm{kJ}/\mathrm{kg};\ \ v_1 = 0.001611\ \mathrm{m^3}/\mathrm{kg}$$

State-2: Saturated liquid (140 bar)

$$T_{sat} = 336.7℃;\ \ v_f = 0.001144\ \mathrm{m^3}/\mathrm{kg};\ h_f = 719.2\ \mathrm{kJ}/\mathrm{kg}$$

So, first thing we have to use this heat balance equation.

$$Q_{eco} = \dot{m}_s(h_1 - h_f) = \dot{m}_g C_{pg}(T_{g1} - T_{g2})$$

We have $\dot{m}_s = 580\ \mathrm{kg}/\mathrm{s};\ \dot{m}_g = 1260\ \mathrm{kg}/\mathrm{s}; C_{pg} = 1.12\ \mathrm{kJ}/\mathrm{kg.K}; T_{g2} = 460℃$

$$Q_{eco} = \dot{m}_s(h_1 - h_f) = \dot{m}_g C_{pg}(T_{g1} - T_{g2})$$

$$\Rightarrow T_{g1} - 733 = 350\ \Rightarrow T_{g1} = 1083\mathrm{K} = 810℃$$

Now, $\Delta T_i = T_{g1} - T_{sat} = 810 - 336.7 = 473.3℃$

Then, $\Delta T_e = T_{g2} - T_w = 460 - 170 = 290℃$

From this we can find, $\Delta T_m/LMTD = \dfrac{\Delta T_i - \Delta T_e}{\ln\left(\frac{\Delta T_i}{\Delta T_e}\right)} = 374°\text{C}$

Now once you have known this, then subsequently we know

$Q = U_0 A_0 \Delta T_{LMTD}$

& $Q = \dot{m}_s(h_1 - h_f) = 580(1571.1 - 719.2)$ kJ

Given data, $U_0 = 68\ \text{W/m}^2$

$\Delta T_{LMTD} = 374°\text{C}$

Now, $A_0 = \dfrac{Q_0}{U_0 \Delta T_{LMTD}} = 22019\ m^2$

We know that, $A_0 = n\pi d_0 l$; So, here two unknowns are there what one is n other is l.

Data given that, $d_0 = 65\text{mm}$ & $d_i = 55\text{mm}$

$$\dot{m}_s = \left[n\left(\frac{\pi}{4}d_i^2\right)\right]\frac{V_w}{v_f}$$

Data Given, $V_w = 1.2\ {}^{\text{m}}/_{s}$; $v_f = 0.001611\ {}^{\text{m}^3}/_{kg}$; $d_i = 55$ mm;

Mass flow rate of steam, $\dot{m}_s = 580\ {}^{\text{kg}}/_{\text{s}}$

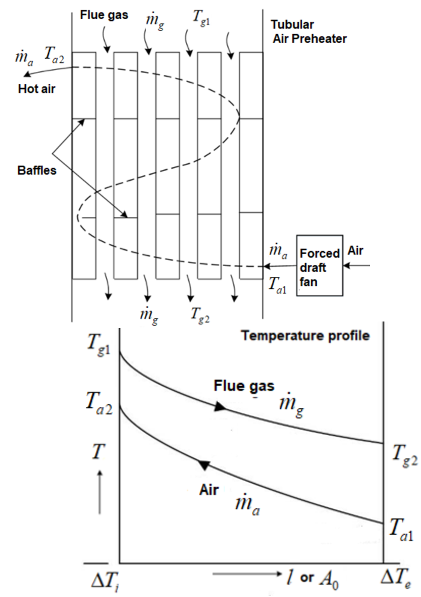
Putting these values, we get, $n = 328$.

Now, $\qquad l = \dfrac{A_0}{n\pi d_0} = \dfrac{22019}{328 \times \pi \times (65 \times 10^{-3})}$

Q2. For the steam generator in Q1, there is a tubular air-preheater following the economizer where the flue gases flows through the tubes and cooled to 160°C. Air enters from outside at 35°C at a rate of 1150 kg/s. The inlet velocity of flue gases is 12 m/s and the tubes have diameters 60 mm (inner) and 65 mm (outer). The overall

heat transfer coefficient is 30 W/m^2.K. For flue gases, take c_p = 1.10 kJ/kg. K and R = 0.287 kJ/kg.K. Find the length and number of tubes.

Next problem is that in connection with this question 1 that is for steam generator unit it uses an air preheaters. So, essentially speaking we need to take some data from our previous question to solve this problem. So, for the question1 we used a tubular air preheater and following the economizer where the flue gas flows through the tubes and cool down to 160°C.



So, the same problem is here, but here we have air entry at T_{a1} temperature mass flow rate $\dot{m}_a$ and air goes out at $\dot{m}_a$ and T_{a2}. So, for solution of this problem, we have to again use the similar approach.

Air, $T_i = 35°\text{C}$; $T_o = ??$; $\dot{m}_a = 1150\ \text{kg}/\text{s}$

From Q: 1 data, For Flue gas,

$\text{T}_{g1} = 460°\text{C}$; $\text{T}_{g2} = 160°\text{C}$; $\text{C}_{pg} = 1.1\ \text{kJ}/\text{kg. K}$; $\dot{m}_a = 1260\ \text{m}/\text{s}$

So, you again here use energy balance between flue gas and air.

$$\dot{Q} = \dot{m}_a C_{pa}(T_o - T_i) = \dot{m}_g C_{pg}(T_{g1} - T_{g2})$$

$$\Rightarrow T_o = 395°\text{C}$$

Once you know T_o & T_i, we can find out

$$\Delta T_i = T_{g1} - T_{g2} = 65°\text{C}$$

$$\Delta T_e = T_{g2} - T_i = 125°\text{C}$$

$$\Delta T_{LMTD} = \frac{\Delta T_i - \Delta T_e}{\ln\left(\frac{\Delta T_i}{\Delta T_e}\right)} = 92.3°\text{C}$$

$$Q = U_0 A_0 \Delta T_{LMTD} = \dot{m}_g C_{pg}(T_{g1} - T_{g2}) = 1260(1.1)(460 - 160)$$

Given, $U_0 = 30\ \text{W/m2. K}$

$\Rightarrow A_0 = 150612\ \text{m}^2$

We know that, $A_0 = n\pi d_0 l$; Here, $A_0 = 150612\text{m}^2, d_0 = 65mm, d_i = 60mm$

mass flow rate of flue gas, $\dot{m}_g = \left[n\left(\frac{\pi}{4}d_i^2\right)\right]\frac{V_g}{v_{g1}}$

For Specific volume of Flue gas, $v_{g1} = \frac{RT_{g1}}{p} = \frac{0.287(460 + 273)}{101.325} = 2.07\frac{\text{m}^3}{\text{kg}}$

And $V_g = 1260\frac{\text{m}}{\text{s}}$; $\dot{m}_g = 1260\frac{\text{kg}}{\text{s}}$

$A_0 = n\pi d_0 l$ So, in this equation now we will be able to find out what is n.

$$n = \frac{1260 \times 2.07 \times 10^6 \times 4}{\pi \times (60)^2 \times 12} = 76861$$

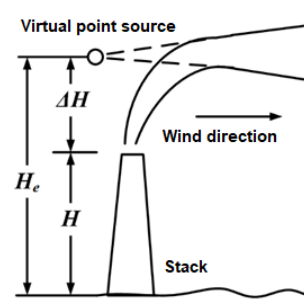
So, this is the number of tubes required.

$$l = \frac{A_0}{n\pi d_0} = \frac{150162}{76861 \times \pi \times 65 \times 10^{-3}} = 9.56\ \text{m}$$

Q3. In a modern steam generator unit, flue gases are emitted from a stack (220 m height & 4 m diameter) at a rate of 1000 kg/s. The temperature of flue gases and ambient are emitted at 100°C & 5°C, respectively. The prevailing wind speed is 14 m/s and the atmosphere condition is neutral stability. Calculate the effective height of the stack.

Third problem is based on the stack. So, I have mentioned the modern steam generated unit uses a stack and that stack height or effective stack height is H_e.

Effective stack height, $H_e = H + \Delta H$;



Braggs Correlation for plume height, $\Delta H = \dfrac{114CF^{\frac{1}{3}}}{V_w}$

So, essentially speaking we are looking at the stack which is original height is H and this plumes comes up and somewhere we have a virtual point where they meet and this is your ΔH.

Now, let us see what each term is all about. So, first term we calculate

$$F = \frac{gV_s^2 D(T_s - T_a)}{4T_a}$$

Data given, $T_s = 100°\text{C} = 373\text{K}; T_a = 5°\text{C} = 278\text{ K};\ \dot{m}_s = 1000\text{ kg/s}$

$$\rho_s = \frac{p}{RT_s} = \frac{101325}{287 \times 373} = 0.9465\text{ kg/m}^3$$

Velocity of stack gas, $V_s = \dfrac{\dot{m}_s}{\rho_s A} = 84\ m/s$

Given data, Wind speed, $V_w = 14\ m/s$

Now, $\text{F} = \dfrac{9.81 \times 84^2 \times 4 \times (373 - 278)}{4 \times 278} = 1126.4\text{ m}^4/\text{s}^3$

The next term which we are going to find out C which is a non dimensional term

$$C = 1.58 - 41.4\left(\frac{\Delta\theta}{\Delta z}\right)$$

Let us take an approximate for $\left(\frac{\Delta\theta}{\Delta z}\right)$ to it a value as 0.005 for an atmospheric stability conditions.

Now, putting the assumed value, $C = 1.373$

So, essentially speaking, we have all the parameters. So, we can find out this plume height

$$\Delta H = \frac{114CF^{\frac{1}{3}}}{V_w} = \frac{114 \times 1.373 \times (1126.4)^{\frac{1}{3}}}{14} = 116 \text{ m}$$

So, plume height is 116m. Effective stack height, $H_e = H + \Delta H = 220 + 116 = 336$m. So, this problem demonstrates how the stack height can be calculated for a steam power generator unit. So, with this I conclude for this lecture today. Thank you for your kind attention.