Process Integration
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Module - 6
Integration and placement of equipment
Lecture - 5
Integration of Furnace

Welcome to the lecture series on process integration. This is module 6, lecture number 5, and the topic of the lecture is integration of furnaces. Furnaces are frequently used as hot utility systems that mean supplies hot utility to the process.

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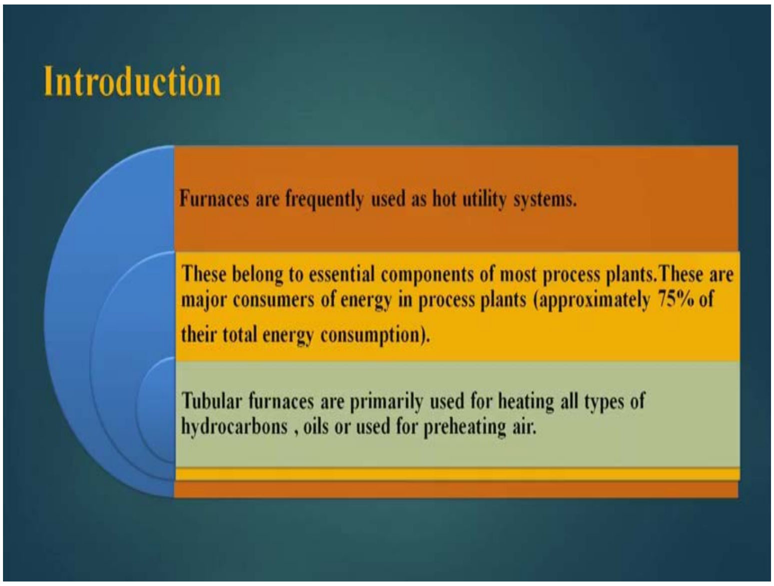

Introduction

Furnaces are frequently used as hot utility systems.

These belong to essential components of most process plants.These are major consumers of energy in process plants (approximately 75% of their total energy consumption).

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These furnaces belong to essential; these are essential components of most process plants. This consumes major energy of the process plant approximately 75 percent of the total energy consumption. Tubular furnaces are primarily used for heating all types of hydro carbons oils, or used for preheating up here. This shows the diagram of a furnace.

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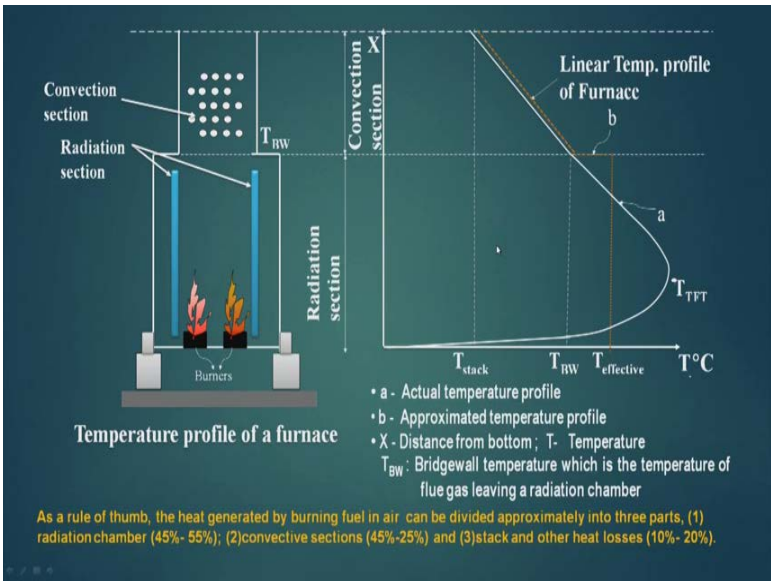

Temperature profile of a furnace

- a - Actual temperature profile
- b - Approximated temperature profile
- X - Distance from bottom ; T- Temperature

T_{BW} : Bridgewall temperature which is the temperature of flue gas leaving a radiation chamber

As a rule of thumb, the heat generated by burning fuel in air can be divided approximately into three parts, (1) radiation chamber (45%- 55%); (2)convective sections (45%-25%) and (3)stack and other heat losses (10%- 20%).

Here, the burners are there the oil is fired, these are the flames and these are the radiation section, this section is radiation section. And the air is goes out from the radiation section, as got temperature T b w and then it goes to the convection section, where it exchanges heat with liquid or may be a gas and then it comes out and called T stack. Here, whatever the temperature here is T stack. Now, if you see the temperature profile of this, we find that the temperature profile is like this.

The maximum temperature in this temperature profile is T t f T that is theoretical flame temperature, which is called adiabatic flame temperature also. The temperature of the air increases by receiving heat from the burning of the fuel, it reaches to the highest temperature theoretical flame temperature, and then it goes down when it radiates heat after this. So, this is the radiation section and then this is the convection section, where there is a linear temperature profile of the furnace.

Now, this temperature profile can be approximated by another temperature profile, which is shown by this red line from this to this, then there is sudden jump in temperature and this is the T effective temperature. So, in the radiation section, we can assume that the temperature is T effective when it goes out from the radiation temperature; it has a temperature T b w which is called Bridge wall temperature. And then when it goes out of the furnace, then its temperature is called T stack.

As a rule of thumb, the heat generated by burning fuel in air can be divided approximately into three parts. Part one is the radiation chamber, where the heat handle is about 45 percent to 55 percent, the second part is the convective section this one, where the heat handle is about 45 percent to 25 percent. The third section when is goes out its stack section, where the stack and other heat losses take place and this is about 10 to 20 percent.

So, this is the figure of heat, which is being handled by furnace. This is the vertical distance when you go up from here to here and this is the actual temperature profile of the furnace. Now, this furnace needs to be integrated with the process. Now, when we integrate the furnace to the process, there major two problems for optimization appears, the furnace integration based on pinch analyses this called optimization of stack temperature. And evaluation of convective section arrangement using capital and energy trade off.

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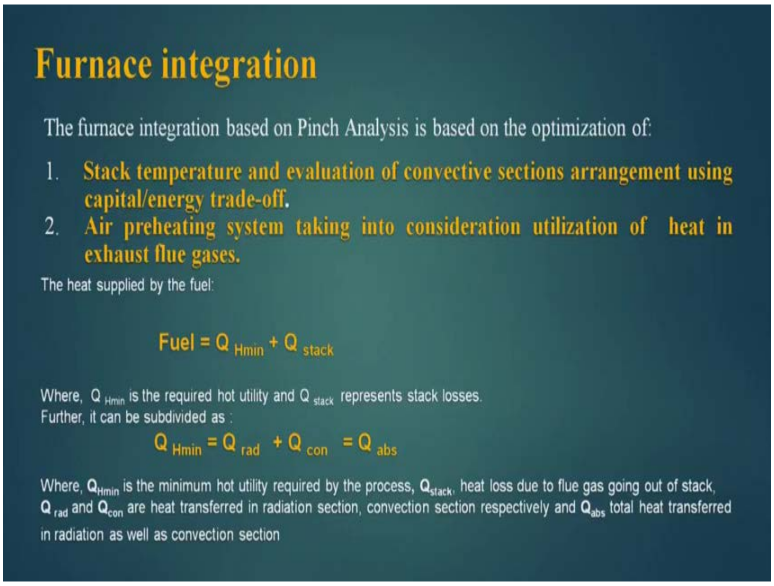

Furnace integration

The furnace integration based on Pinch Analysis is based on the optimization of:

1. **Stack temperature and evaluation of convective sections arrangement using capital/energy trade-off.**
2. **Air preheating system taking into consideration utilization of heat in exhaust flue gases.**

The heat supplied by the fuel:

$$\text{Fuel} = Q_{Hmin} + Q_{stack}$$

Where, Q_{Hmin} is the required hot utility and Q_{stack} represents stack losses.
Further, it can be subdivided as :

$$Q_{Hmin} = Q_{rad} + Q_{con} = Q_{abs}$$

Where, Q_{Hmin} is the minimum hot utility required by the process, Q_{stack}, heat loss due to flue gas going out of stack, Q_{rad} and Q_{con} are heat transferred in radiation section, convection section respectively and Q_{abs} total heat transferred in radiation as well as convection section

Now, when the furnaces integrated, we have to find out what should be the stack temperature. If you want to decrease stack temperature, then more area has to be provided into the convective section. A time will come, when the added area will not prove to be advantageous as far as the heat picked up is concerned and that is why there is a capital and energy trade off in this area. So, this capital and energy trade off will decide, what should be the stack temperature.

Further there are also some process parameters and the shape of the GCC, which will also predict what, should be the stack temperatures. So, all these treat bits all this will see in the later on in this lecture. The second part is that air preheating system has to be designed and we have to find out, up to what temperature the air preheating should take place. This is also the based on capital energy trade off and will see fix that what should be my maximum here pre-heat temperature, and what should be my minimum stack temperature.

These are two important parameters, which has to be found out based on economic analyses, when we integrating furnace. Now, the heat supplied by the fuel is Q H minimum plus Q stack. What is this? When we are dealing with a process and drawing a GCC of the process, from the GCC we calculate, what is Q H minimum that is minimum hot utility demand. When a particular delta T minimum has been fixed, so q H minimum is the function of delta T minimum. So, when you are designing, we are assuming a delta T minimum and for that a Q H minimum can be computed.

We have seen in the super targeting that we can optimize the delta T minimum, so based on that optimum delta T minimum also we can find out a Q H minimum. Now, the fuel which will be band in the furnace will supply the Q H minimum plus the stack losses. So, when we add this to, we can find out what is the fuel requirement in the furnace.

Now, if you see what the Q H minimum is, Q H minimum can be broken into two parts that Q radiation and Q convection and combine this together, we can say Q abs. So, the Q H minimum is now equal to Q radiation that means, the heat transferred in the radiation section of the furnace plus Q convection. That means, heat transferred in the convection section of the furnace.

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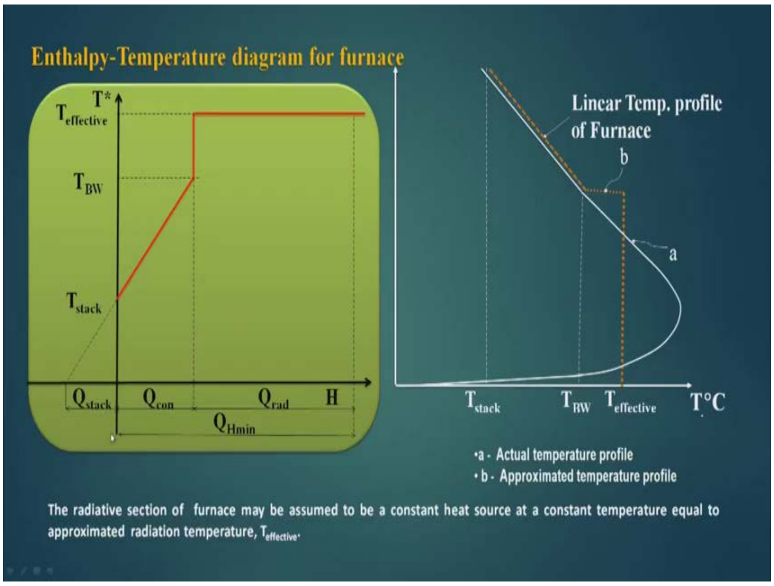

Enthalpy-Temperature diagram for furnace

- a - Actual temperature profile
- b - Approximated temperature profile

The radiative section of furnace may be assumed to be a constant heat source at a constant temperature equal to approximated radiation temperature, $T_{effective}$.

Now, this is an approximated temperature profile of the furnace. Here in the radiation temperature, the temperature is assumed to be constant and equal to T effective and this is the temperature. It is a constant temperature T effective and this is the convection section. So, in the radiation section, this gives this much amount of heat Q radiation and this convection section gives this much amount of heat, which is called Q convection and this is the amount of heat, which is called the Q stack that means stack losses.

From this stack, the hot gases are coming out at T stack and this T stack will take with it Q stack amount of heat to the outer atmosphere, and hence it is called stack losses. This amount of is stack losses and Q H minimum is this Q convection plus Q radiation. So, this is the amount which is Q H minimum and this Q H minimum has to be supplied by the furnace to the process.

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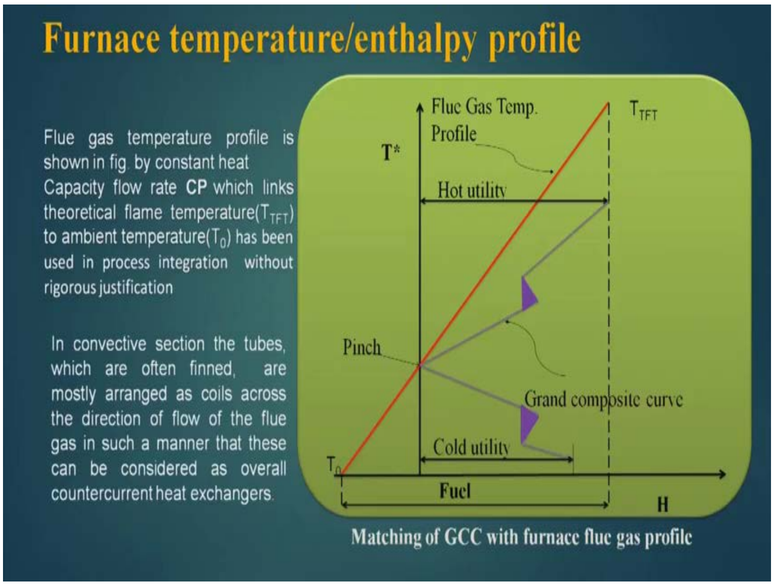

Furnace temperature/enthalpy profile

Flue gas temperature profile is shown in fig. by constant heat Capacity flow rate **CP** which links theoretical flame temperature(T_{TFT}) to ambient temperature(T_0) has been used in process integration without rigorous justification

In convective section the tubes, which are often finned, are mostly arranged as coils across the direction of flow of the flue gas in such a manner that these can be considered as overall countercurrent heat exchangers.

Matching of GCC with furnace flue gas profile

Now, if you see the grand composite curve of the process, this is the grand composite curve of the process, this is the pinch point, and this is the hot utility requirement and this is the cold utility requirement. Now, the furnace profile because furnace will work as a hot utility, the furnace temperature profile has to be matched with this grand composite curve for a better heat transfer or meeting the hot utility demand at the lowest cost. So, here we see this is the hot gas temperature profile, which is in the furnace.

The highest temperature of the hot gas in the furnaces T f T that is theoretical claim temperature, then it comes down to a temperature of atmosphere. So, this is the loss that is stack loss and this is the amount of fuel in terms of enthalpy, required to generate this curve. Fuel gas profile is shown in the figure by a constant heat capacity flow rate CP line and slope of this fuel gas temperature profile is depends upon the capital CP. That is heat capacity flow rate of the hot gas because the slope of this line is 1 by capital CP or 1 by heat capacity flow rate.

Now, this links the T f T to T 0, so this line the one extreme is T f t, the other extreme is T 0. In convection section, the tubes which are often finned are mostly arranged as coils across the direction of the flow of the flue gas, in such a manner that these can be considered as overall counter current heat exchangers.

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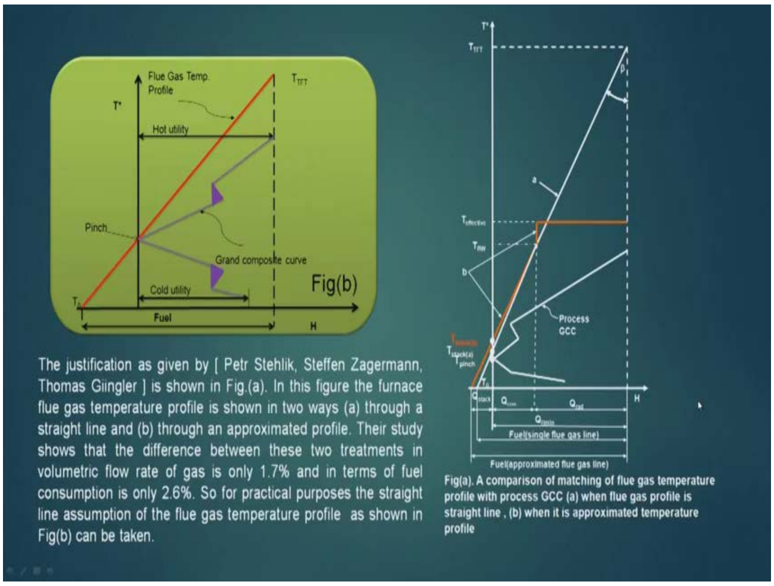

The justification as given by [Petr Stehlik, Steffen Zagermann, Thomas Giingler] is shown in Fig.(a). In this figure the furnace flue gas temperature profile is shown in two ways (a) through a straight line and (b) through an approximated profile. Their study shows that the difference between these two treatments in volumetric flow rate of gas is only 1.7% and in terms of fuel consumption is only 2.6%. So for practical purposes the straight line assumption of the flue gas temperature profile as shown in Fig(b) can be taken.

Fig(a). A comparison of matching of flue gas temperature profile with process GCC (a) when flue gas profile is straight line , (b) when it is approximated temperature profile

Now, this figure will like to find out if I am representing my fuel gas profile with this line or the fuel gas profile with this red line, what is the difference? Now, we have seen that in a furnace, what is the actual temperature profile? That actual temperature profile can be represented in two ways, one way is this and another way is this straight line. So, this is the approximate temperature profile of the furnace. Now, this is the process GCC and here there is temperature T stack this point and this is the pinch point.

So, these line can move up to the pinch point, it cannot go below the pinch point, but it can move up to the pinch point. So, it if it moves in this direction, the stack losses will decrease, that means if the angle this beta angle is less, then it will be stack losses will be less. So, the question is now whether to represent the hot utility temperature profile by this line or by this red line. Now this can be clarified by theta ((Refer Time: 16:23)) as shown in figure a.

In this figure, the furnace flue gas temperature profile is shown in two ways, a through straight line and b through an approximate profile, approximate profile is this and straight is this. The study shows that the difference between these two treatments in volumetric flow rate of gas is only 1.7 percent and in terms of fuel consumption it is only 2.6 percent. So, for all practical purposes this straight line assumption of the flue gas temperature as shown in figure b.

This is the straight line representation of flue gas temperature profile can be accepted. So, when we prove thus this temperature profile creates very less error as compared to the other temperature profiles or actual temperature profiles, then for rest of this lectures while doing integration will presume that, this temperature profile of the furnace works well.

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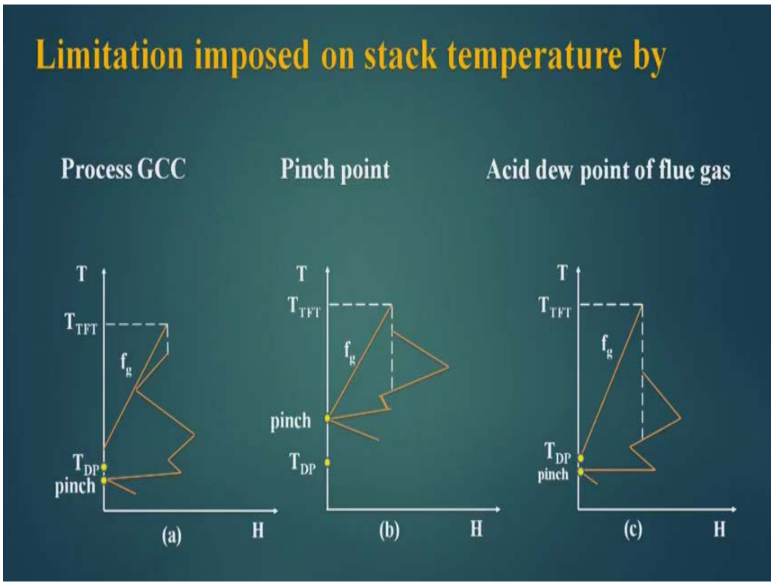

Limitation imposed on stack temperature by

Process GCC

Pinch point

Acid dew point of flue gas

Now, this is a case when this is the pinch point and up to this pinch point, the stack temperature is not able to reach due to this portion of the GCC. So, the process GCC is now containing the stack temperature, so this is such a situation that then obviously, the stack temperature will be far more than the process pinch point, it can be more than the acid due point also. And hence a lot of stack losses will take place and in a such a cases what we can do to decrease the stack loss, we can pre-heat here with the heat, which is available with the hot gas and can thus improve the efficiency of the furnace.

Here, the slope of this line is being controlled by the pinch because it is touching the pinch and T d p is here is a dew point. How this point want to clarify that, this stack temperature can be brought down up to T d p, not below this. Because of this stack temperature below is a dew point, then the whatever acid component of the gas are present in the flue gas, may be due to the burning of Sulphur. Those will condense and they will form acid, and this acid will attack this stack or the heat exchangers.

And hence it is not advisable to bring down this stack temperature below acid dew point, which is T d p. In this case the T d p is below pinch and I can bring down this stack temperature up to this, but this pinch point is controlling. It will not allow me to bring down the temperature. Here also there is a chance that I can use the stack for heating, that means whatever the temperature of this stack gas that can be utilize for heating or pre-heating of the here.

Now there is a third case, when T d p is above the pinch, in that case I can bring down this stack temperature up to T d p only, I cannot go below T d p because it is not allowed. So, here we have seen that process GCC is controlling this stack temperature; here we saw that the pinch is controlling this stack temperature, and here we saw that acid dew point of the flue gas is controlling this stack temperature.

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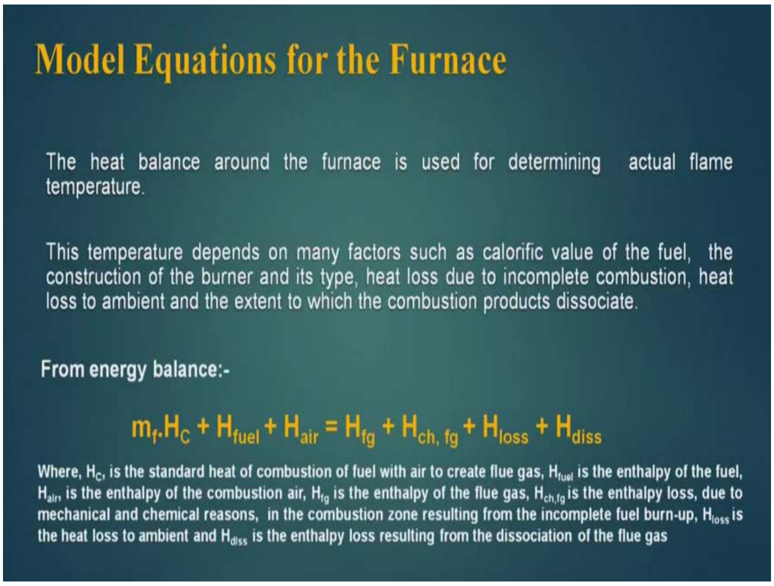

Model Equations for the Furnace

The heat balance around the furnace is used for determining actual flame temperature.

This temperature depends on many factors such as calorific value of the fuel, the construction of the burner and its type, heat loss due to incomplete combustion, heat loss to ambient and the extent to which the combustion products dissociate.

From energy balance:-

$$m_f . H_C + H_{fuel} + H_{air} = H_{fg} + H_{ch,\, fg} + H_{loss} + H_{diss}$$

Where, H_C, is the standard heat of combustion of fuel with air to create flue gas, H_{fuel} is the enthalpy of the fuel, H_{air}, is the enthalpy of the combustion air, H_{fg} is the enthalpy of the flue gas, $H_{ch,fg}$ is the enthalpy loss, due to mechanical and chemical reasons, in the combustion zone resulting from the incomplete fuel burn-up, H_{loss} is the heat loss to ambient and H_{diss} is the enthalpy loss resulting from the dissociation of the flue gas

So, this 3 situation may arise, when we are integrating the furnace with a GCC, now let us built the model equations for the furnace, if we take the heat balance around the furnace to find out the actual flame temperature. Now, this temperature depends on many factors such as calorific value of the fuel, the construction of the burner and its type, heat loss due to incomplete combustion, heat loss to ambient and the extent to which the combustion product dissociate. So, these are factors which will decide what the actual flame temperature is.

Now, to quantify all these factors before hand is difficult and hence to calculate actual flame temperature is difficult in a furnace. So, we will substitute it with another temperature, which is theoretical flame temperature. From the heat balance, we can write down this m f into H c is equal to H fuel plus H air equal to H f g plus H c H f g plus H loss plus H dissociation.

And where H c is the standard heat of combustion of the fuel with air to create flue gas, H fuel is the enthalpy of the fuel, H air is the enthalpy of the air, H f g is the enthalpy of the flue gas, H c H f g is the enthalpy loss due to the mechanical and chemical reasons in the combustion zone resulting from the incomplete fuel burn up, H loss is the heat loss to ambient and H dissociation is the enthalpy loss resulting from the dissociation of the flue gas. So, the parameters which are involved in predicting the actual flame temperatures, we have written here.

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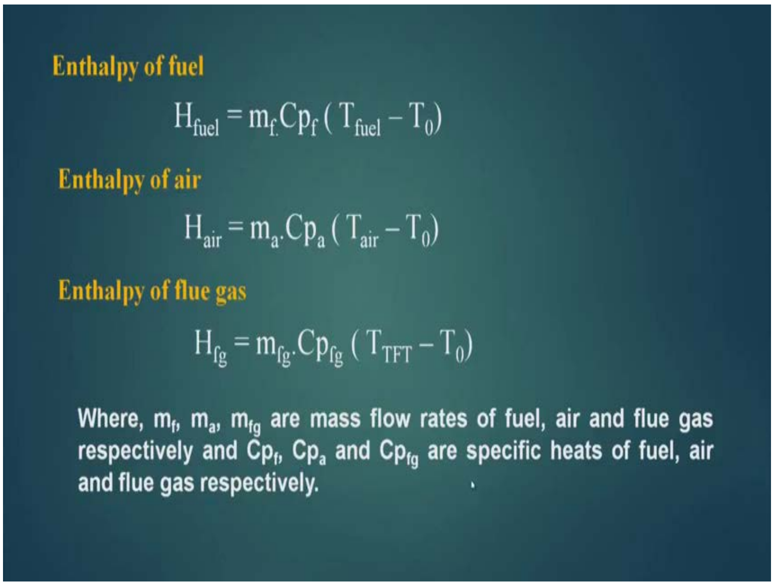

Enthalpy of fuel

$$H_{fuel} = m_{f}.Cp_{f}\,(T_{fuel} - T_{0})$$

Enthalpy of air

$$H_{air} = m_{a}.Cp_{a}\,(T_{air} - T_{0})$$

Enthalpy of flue gas

$$H_{fg} = m_{fg}.Cp_{fg}\,(T_{TFT} - T_{0})$$

Where, m_f, m_a, m_{fg} are mass flow rates of fuel, air and flue gas respectively and Cp_f, Cp_a and Cp_{fg} are specific heats of fuel, air and flue gas respectively.

And many of these factors are unrolled or difficult to find out and hence when calculating a theoretical flame temperature will set them to 0. Now for fuel enthalpy H fuel can be written as m f mass flow rate C p f specific heat of the fuel T fuel minus T 0, where we have taken T 0 as the reference temperature. Similarly, enthalpy of the air we can calculate H air is equal to m a mass flow rate of the air C p a into T air minus T 0, where T 0 is the reference temperature.

Enthalpy of flue gas can be similarly explained M f g mass flow rate of the flue gas in C p f g and T f T that is theoretical temperature minus T 0. So, because we are interested in calculating theoretical temperature, now all the computation should be based on theoretical flame temperature other than actual flame temperature. Where Mf Ma Mfg are mass flow rates of the fuel air and flue gas respectively. And C p a and C f g are the specific heats of fuel air and flue gas respectively.

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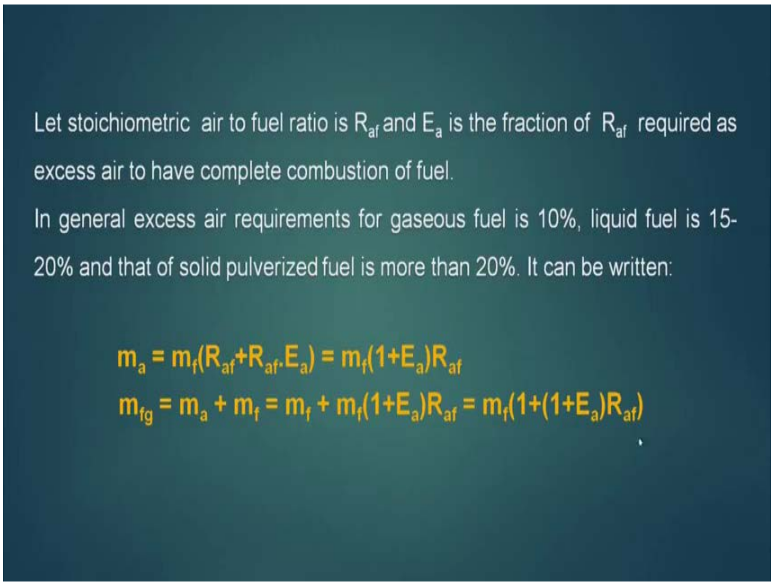

Let stoichiometric air to fuel ratio is R_{af} and E_a is the fraction of R_{af} required as excess air to have complete combustion of fuel.

In general excess air requirements for gaseous fuel is 10%, liquid fuel is 15-20% and that of solid pulverized fuel is more than 20%. It can be written:

$$m_a = m_f(R_{af}+R_{af}.E_a) = m_f(1+E_a)R_{af}$$

$$m_{fg} = m_a + m_f = m_f + m_f(1+E_a)R_{af} = m_f(1+(1+E_a)R_{af})$$

Now, let us assume something stoichiometrically air to fuel ratio is R a f and E a is the fraction of R a f required as excess air to have complete combustion of the fuel. It is generally done that the stoichiometric air is not able to do the complete combustion of the fuel and hence we increase the amount of air to have complete fuel combustion. And what is that increase in the amount of air, in general excess air requirements for gaseous fuel is about 10 percent, liquid fuel is about 15 to 20 percent and that of solid pulverized fuel is more than 20 percent.

So, if I do this two terms I include and based on this two terms I can write down now, the actual mass of air, which will be required after including the excess here is this m f R a f plus R a f into E a, which is the extra fraction of R a f required to complete combustion based on this percentage. So, we can express m a is equal to m f 1 plus E a into R a f. Similarly, m f g which is a summation of m a and m f can be written in terms of m f with this expression. Now, the actual flame temperature T t f T is difficult to calculate.

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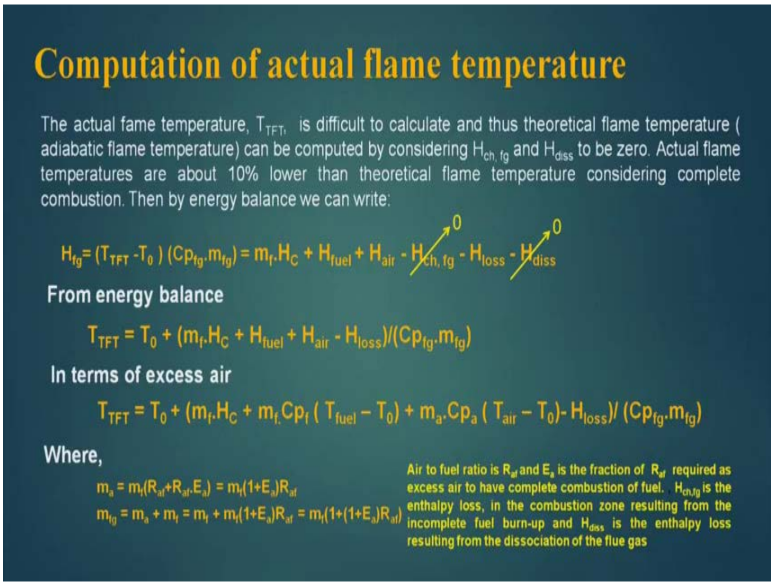

Computation of actual flame temperature

The actual fame temperature, T_{TFT}, is difficult to calculate and thus theoretical flame temperature (adiabatic flame temperature) can be computed by considering $H_{ch,\,fg}$ and H_{diss} to be zero. Actual flame temperatures are about 10% lower than theoretical flame temperature considering complete combustion. Then by energy balance we can write:

$$H_{fg} = (T_{TFT} - T_0)(Cp_{fg}.m_{fg}) = m_f.H_C + H_{fuel} + H_{air} - \overset{0}{\cancel{H_{ch,\,fg}}} - H_{loss} - \overset{0}{\cancel{H_{diss}}}$$

From energy balance

$$T_{TFT} = T_0 + (m_f.H_C + H_{fuel} + H_{air} - H_{loss})/(Cp_{fg}.m_{fg})$$

In terms of excess air

$$T_{TFT} = T_0 + (m_f.H_C + m_f.Cp_f\,(T_{fuel} - T_0) + m_a.Cp_a\,(T_{air} - T_0) - H_{loss})/\,(Cp_{fg}.m_{fg})$$

Where,

$$m_a = m_f(R_{af} + R_{af}.E_a) = m_f(1+E_a)R_{af}$$

$$m_{fg} = m_a + m_f = m_f + m_f(1+E_a)R_{af} = m_f(1+(1+E_a)R_{af})$$

Air to fuel ratio is R_{af} and E_a is the fraction of R_{af} required as excess air to have complete combustion of fuel. $H_{ch,fg}$ is the enthalpy loss, in the combustion zone resulting from the incomplete fuel burn-up and H_{diss} is the enthalpy loss resulting from the dissociation of the flue gas

Now the actual flame temperature is not T t f t, actual flame temperature is difficult to calculate. And thus theoretical flame temperature that is called adiabatic temperature can be computed by considering H c H H f g and H dissociation to be 0. Actual flame temperatures are about 10 percent lower than the theoretical flame temperature considering complete combustion. Then by energy balance, we can write down H f g, this is enthalpy of flue gas is equal to T t f T minus T 0 into C p f g into m f g is equal to m f H c plus H fuel plus H air and minus H c H f g minus heat loss minus H dissociation.

So, these two terms we are setting to 0 because I am thinking that this ideal burning of fuel takes place and that’s why these two terms are 0. So, whatever temperature will calculate based on this will be the theoretical flame temperature. So, T f T is equal to T 0 and thus so T f T minus T 0 equal to this will go this way written by this. So, in terms of excess here, this is the temperature so here I am reproducing again m a is equal to this in terms of m f and m f g is equal to in terms of m f.

So, air to fuel ratio is R a f and E a is the fraction of R a f required as excess air to have complete combustion of fuel. H c, H f g is the enthalpy loss in the combustion zone resulting from the incomplete fuel burn up and H dissociation is the enthalpy loss resulting from the dissociation of the flue gas.

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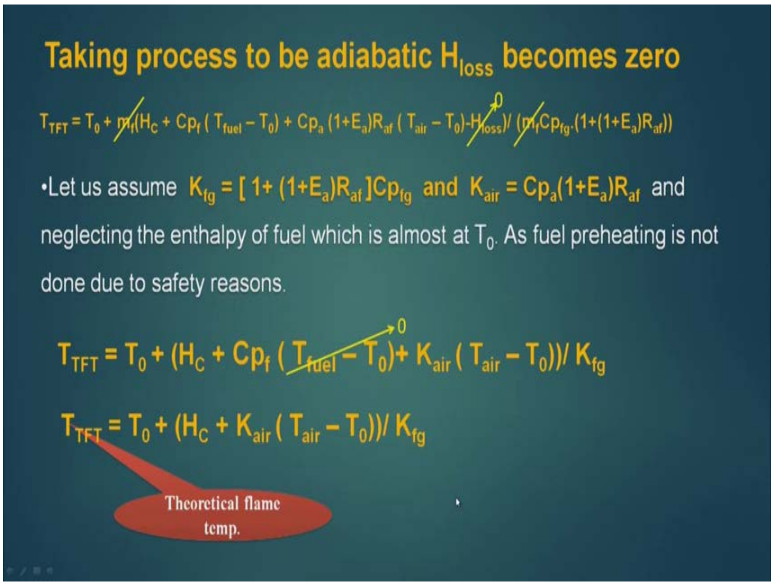

Taking process to be adiabatic H_{loss} becomes zero

$T_{TFT} = T_0 + \cancel{m_f}(H_C + Cp_f(T_{fuel} - T_0) + Cp_a(1+E_a)R_{af}(T_{air} - T_0) - \overset{0}{\cancel{H_{loss}}}) / (\cancel{m_f}Cp_{fg}.(1+(1+E_a)R_{af}))$

- Let us assume $K_{fg} = [1 + (1+E_a)R_{af}]Cp_{fg}$ and $K_{air} = Cp_a(1+E_a)R_{af}$ and neglecting the enthalpy of fuel which is almost at T_0. As fuel preheating is not done due to safety reasons.

$$T_{TFT} = T_0 + (H_C + Cp_f(\cancelto{0}{T_{fuel} - T_0}) + K_{air}(T_{air} - T_0)) / K_{fg}$$

$$T_{TFT} = T_0 + (H_C + K_{air}(T_{air} - T_0)) / K_{fg}$$

Now, taking process to be adiabatic H loss becomes 0. Let us assume that K f g is equal to 1 plus 1 E a R f into C p g, this whole turn is being represented by K f g and this whole turn is now represented by K air. And If I substitute this, I get a relationship like this T f T is equal to T 0 plus H c plus C p f T fuel minus T 0 plus K air T air minus T 0 divided by K f g. Now, if I consider there is no fuel pre-heating in general fuels are not preheated, due to the safety reasons, and if I consider that then the T fuel will be equal to the T zero, that is the ambient temperature of the reference temperature.

And hence T fuels minus T 0 will 10 to 0 and T f t, which is the theoretical flame temperature will be this equal to, so we started with actual flame temperature. Then one by one, we set those parameters, which are difficult to calculate, then we consider that this process is working as adiabatic, that is H loss is 0. And from that we are able to find out this temperature which is T t f T and which a theoretical flame temperature is and basically, it is called also adiabatic flame temperature. So, to and all our calculations and processing are of integration of the furnace will be based on this T f t, which is theoretical flame temperature and this is called theoretical flame temperature.

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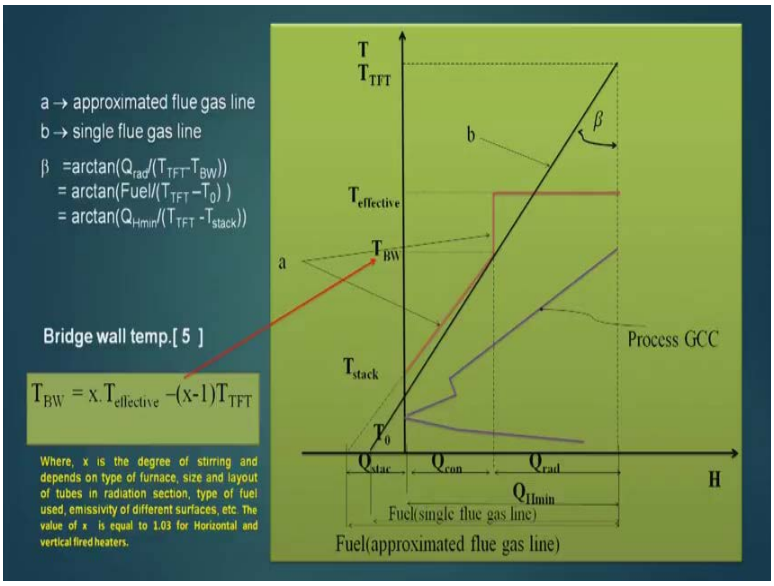

a → approximated flue gas line

b → single flue gas line

$\beta = \arctan(Q_{rad}/(T_{TFT}-T_{BW}))$
$= \arctan(Fuel/(T_{TFT}-T_0))$
$= \arctan(Q_{Hmin}/(T_{TFT}-T_{stack}))$

Bridge wall temp.[5]

$T_{BW} = x.T_{effective} - (x-1)T_{TFT}$

Where, x is the degree of stirring and depends on type of furnace, size and layout of tubes in radiation section, type of fuel used, emissivity of different surfaces, etc. The value of x is equal to 1.03 for Horizontal and vertical fired heaters.

Now, let us see if you are doing integration, then this a is the approximate fuel gas line, this is the approximate flue gas line and b is the single flue gas line. And we have seen that if you are going for a single flue gas line, we are not committing much of mistake. Now, from this we can write down that the stand beta is equal to Q radiation, this much or this much, Q radiation divided by T f T minus T b w. Now, this distance this T b w is T f t, so this is the distance and Q radiation is this from here to here, this is Q radiation from here to here.

So, tan theta is equal to this distance Q radiation divided by this distance from here to here, which is nothing but T t f T theoretical flame temperature minus T b w. So, when we take beta this is arc tan Q radiation divided by T f T minus T b w. Similarly, we can find out that this beta is equal to fuel divided by T f T minus T 0, so this is the fuel, which has been consumed in this. Now, this distance which is fuel divided by this distance, which is T f T minus T 0.

Similarly, this beta is also equal to arc tan Q H minimum, this is Q H minimum, and this is Q H minimum divided by T f T minus T stack. So, this is the stack temperature, now this distance from here to this point this T f T minus T stack and this whole distance is basically Q H minimum. So, this relationship we can find out. Now, the bridge wall temperature because it involves bridge wall temperature here.

The bridge wall temperature can be computed as x into T effective minus x minus 1 into T f t, whereas, where x is the degree of stirring and depends on the type of furnace, size and layout of tubes in the radiation section, type of fuel used, emissivity of the different surfaces extra. The value of x is equal to 1.03 for horizontal and vertical quad heaters, so knowing the value of x and T effective and T t f t, we can compute the T b w value.

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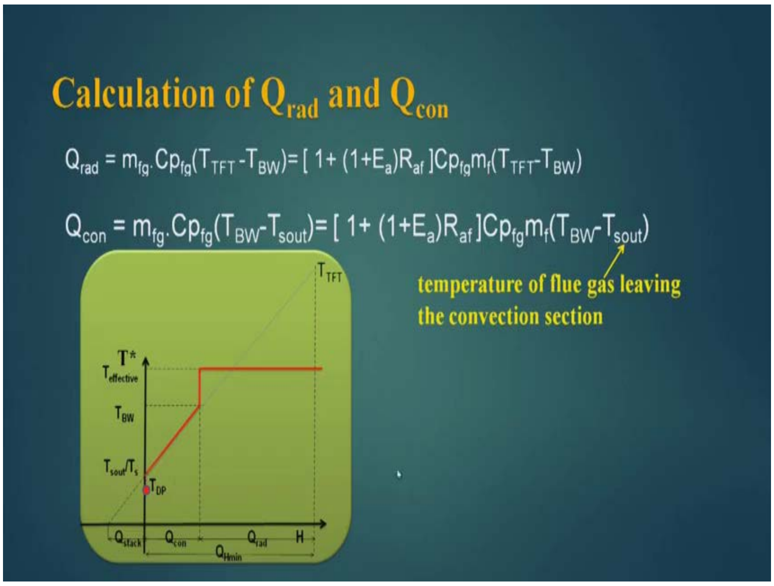

Calculation of Q_{rad} and Q_{con}

$$Q_{rad} = m_{fg}.Cp_{fg}(T_{TFT} - T_{BW}) = [\,1 + (1+E_a)R_{af}\,]Cp_{fg}m_f(T_{TFT} - T_{BW})$$

$$Q_{con} = m_{fg}.Cp_{fg}(T_{BW} - T_{sout}) = [\,1 + (1+E_a)R_{af}\,]Cp_{fg}m_f(T_{BW} - T_{sout})$$

temperature of flue gas leaving the convection section

Now, computation of Q radiation and Q convection, now Q radiation can be given by this formula and Q convection is given by this. So, this is the Q convection area because in the convection this temperature drops down from here to here. So, this is the distance, which is given by Q convection and this is the distance, which is given by Q radiation. So, you can calculate this and T s out is the temperature of the flue gas leaving the convection section, this is the T out T s out, which is leaving the convection section.

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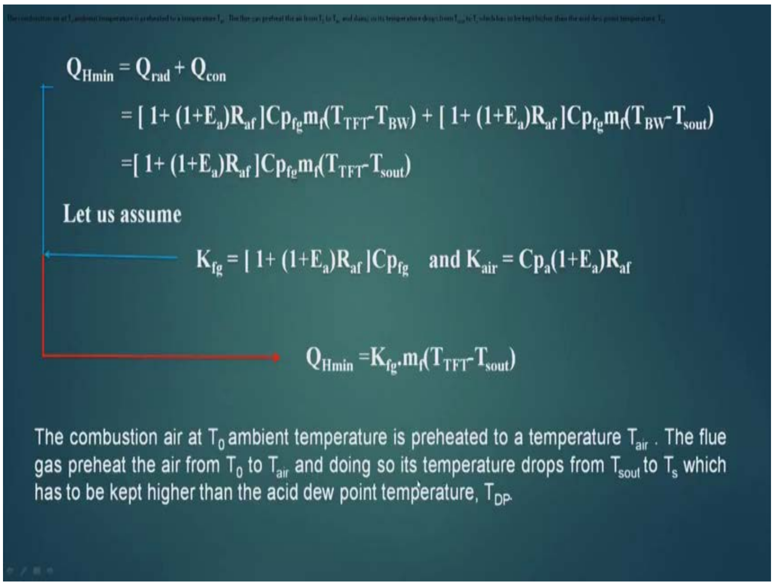

$$Q_{Hmin} = Q_{rad} + Q_{con}$$

$$= [\,1+(1+E_a)R_{af}\,]Cp_{fg}m_f(T_{TFT}-T_{BW}) + [\,1+(1+E_a)R_{af}\,]Cp_{fg}m_f(T_{BW}-T_{sout})$$

$$=[\,1+(1+E_a)R_{af}\,]Cp_{fg}m_f(T_{TFT}-T_{sout})$$

Let us assume

$$K_{fg} = [\,1+(1+E_a)R_{af}\,]Cp_{fg} \quad \text{and } K_{air} = Cp_a(1+E_a)R_{af}$$

$$Q_{Hmin} = K_{fg}.m_f(T_{TFT}-T_{sout})$$

The combustion air at T_0 ambient temperature is preheated to a temperature T_{air} . The flue gas preheat the air from T_0 to T_{air} and doing so its temperature drops from T_{sout} to T_s which has to be kept higher than the acid dew point temperature, T_{DP}.

Now, Q H minimum is equal to Q radiation Q convection and we can develop a equation for that, so this is the value for Q H minimum. Now, let us assume K f g equal to this and K air equal to this, so we can substitute the values here. And you can have Q H minimum equal to K f g m f in the brackets T f t minus T s out. The combustion air at T 0 ambient temperature is pre-heated to a temperature of T air.

When we are doing the pre-heating of air, the flue gas pre-heat the air from T 0 to T air and doing so, the temperature drops from T s out to T s, which has to be kept higher than the acid dew point temperature T d p. Now, what does it mean that, if the air that is flue gas is coming out at T s out and T s out is a higher temperature than T d p that is acid dew point. I have already told that the flue gas temperature can be brought down up to T d p or a little bit more than the T t p so that the acid vapours, which are present in the flue gas low condensed.

And obviously, they will condense there going to you know material metro part of the equipment, which is handling this. So, T hours can be brought down to little bit more than T d p or say theoretically equal to T d p and this can be used for pre-heating the air. So, after pre-heating the air, if the T s out becomes T s, then this T s should be more than the T d p.

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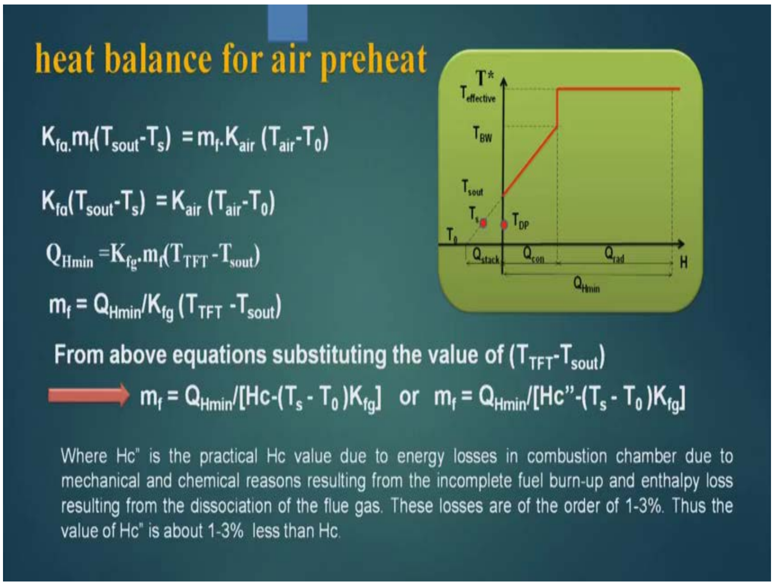

heat balance for air preheat

$$K_{fa.}m_f(T_{sout}-T_s) = m_f.K_{air}(T_{air}-T_0)$$

$$K_{fa}(T_{sout}-T_s) = K_{air}(T_{air}-T_0)$$

$$Q_{Hmin} = K_{fg}.m_f(T_{TFT}-T_{sout})$$

$$m_f = Q_{Hmin}/K_{fg}(T_{TFT}-T_{sout})$$

From above equations substituting the value of $(T_{TFT}-T_{sout})$

$$m_f = Q_{Hmin}/[Hc-(T_s-T_0)K_{fg}] \quad \text{or} \quad m_f = Q_{Hmin}/[Hc''-(T_s-T_0)K_{fg}]$$

Where Hc" is the practical Hc value due to energy losses in combustion chamber due to mechanical and chemical reasons resulting from the incomplete fuel burn-up and enthalpy loss resulting from the dissociation of the flue gas. These losses are of the order of 1-3%. Thus the value of Hc" is about 1-3% less than Hc.

So, heat balance for air pre-heat, so K f g into m f T s out minus T s. So, for heating the air and bringing down T s out temperature to T s, this m f k air T air minus T 0, air is entering at T 0 temperature and being heated up to T air temperature. So, m f m f cancels out and we can write down this now, Q H minimum is K f g m f T f T minus T s out this we know. From above equation substituting the value of T f T minus T s out, I can find this which is the m f, which is mass of the fuel is equal to Q H minimum divided by H c minus T s minus T 0 into K f g.

I can write down m f is equal to Q h minimum H c double dash minus this value. Now, H c double dash is the practical H c value, due to the energy losses in combustion chamber, due to the mechanical and chemical reasons resulting from the incomplete fuel burn up and enthalpy loss, resulting from the dissociation of the flue gas. These losses are of the tune up 1 to 3 percent, thus the H c double dash value is 1 to 3 percent less than the H c values.

So, if I put this here, I will be able to estimate the actual value of the mass of the fuel, which will be required. And why we want this, because for economic calculations of the tradeoff, I should know what is the mass of the fuel because the cost of the mass will fell has to be handed up.

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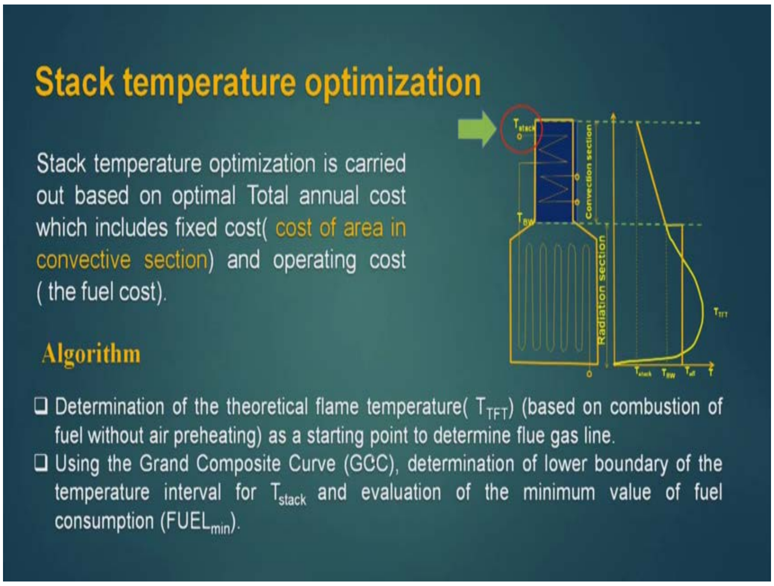

Stack temperature optimization

Stack temperature optimization is carried out based on optimal Total annual cost which includes fixed cost(cost of area in convective section) and operating cost (the fuel cost).

Algorithm

- ☐ Determination of the theoretical flame temperature(T_{TFT}) (based on combustion of fuel without air preheating) as a starting point to determine flue gas line.
- ☐ Using the Grand Composite Curve (GCC), determination of lower boundary of the temperature interval for T_{stack} and evaluation of the minimum value of fuel consumption ($FUEL_{min}$).

Now, let us come to this stack temperature optimization had already told that, we have to decide a stack temperature and this decision will be based on trade off. Stack temperature optimization is carried out based on optimal total annual cost, which includes fixed cost that means cost of area in the convection section and operating cost, which includes the fuel cost. Now, this is my system, from here to here is the radiation sections this temperature T b w and this is the convection section.

So, I am interested in finding out what is the T stack temperature? This is the temperature here of the hot gases, which is coming out and this is my convection section. And so there are heat exchangers available in the convection section which exchanges heat with this hot gas. So, I should know about this heat exchangers there area, so that I can compute the cost of these heat exchangers. So, this is the convection section and this is my temperature profile, this is the temperature profile in the radiation section, and this is the temperature profile in the convection section.

So, what will be my algorithm, determining the theoretical flame temperature, this I know we have developed expressions to calculate this theoretical flame temperature, based on combustion of the fuel without air pre-heating. As a starting point to determine, the flue gas line using the grand composite curve GCC determines the lower boundary of the temperature interval of T stack. And evaluation of the minimum value of the fuel consumption, this is fuel minimum.

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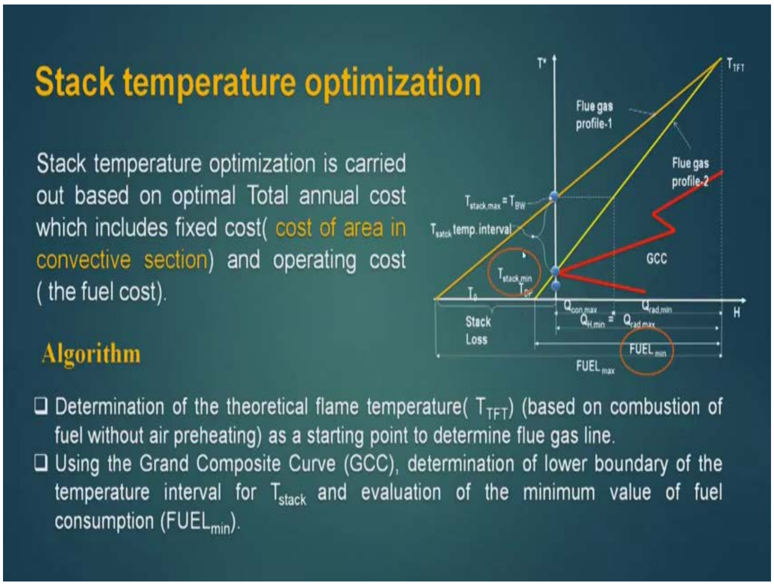

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So, I am integrating the furnace with the g c c, the furnace part comes from here and the g c c part we have to add and g c c part will decide what should be my minimum stack temperature. So, here it shows clearly that if it is the line available I can bring this line to here, when this pinch point will control my T stack temperature. So, this is my range from T b w to this pinch point and here the pinch point is above the T d p.

If this T d p will be above the pinch point, then the T d p will control the T stack rather than this pinch point. And this is the fuel minimum, if it is this that line of the furnace flue gas, so this is the stack loss and this is the Q h minimum. So, the minimum fuel will equal to Q h minimum plus this stack loss. So, I can calculate fuel minimum here, this amount from here.

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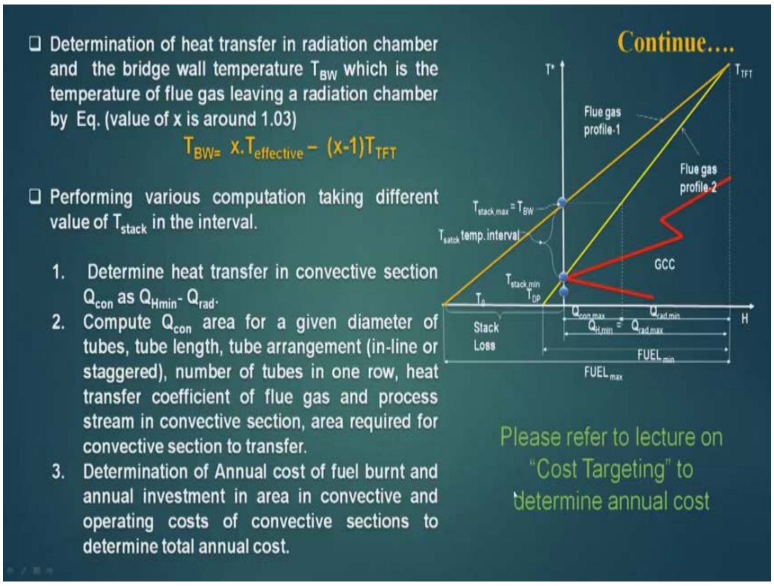

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- ☐ Determination of heat transfer in radiation chamber and the bridge wall temperature T_{BW} which is the temperature of flue gas leaving a radiation chamber by Eq. (value of x is around 1.03)

$$T_{BW} = x.T_{effective} - (x-1)T_{TFT}$$

- ☐ Performing various computation taking different value of T_{stack} in the interval.

1. Determine heat transfer in convective section Q_{con} as $Q_{Hmin} - Q_{rad}$.
2. Compute Q_{con} area for a given diameter of tubes, tube length, tube arrangement (in-line or staggered), number of tubes in one row, heat transfer coefficient of flue gas and process stream in convective section, area required for convective section to transfer.
3. Determination of Annual cost of fuel burnt and annual investment in area in convective and operating costs of convective sections to determine total annual cost.

Please refer to lecture on "Cost Targeting" to determine annual cost

So, this T stack has to be optimized and I have to find out a value of this T stack based on the optimization. Now, determine the heat transfer in radiation chamber and the bridge wall temperature T b w, which is the temperature of the flue gas leaving the radiation chamber and the equation is this. I had already explained this equation, where x value is around 1.03 and then perform various computation taking the different values of T stack.

So, what we have to do, determine heat transfer in the convection section, if I know the T b w, this is the point I know T f t this is value and this is the Q radiation. So, if I know this angle, I can find out this Q radiation amount or this is the gap between this point and this point. So, I know Q radiation, I know q H minimum from the GCC, so I can find out Q convection. And once Q convection is available to ask, we can design a heat exchanger, which will transfer Q convection.

So, we can find out the area of the heat exchanger, which is in the convection section, which can transfer Q convection and this is the Q convection from here to here and this is a fuel gas line in the convection section. Then determination of annual cost of the fuel burnt, we have can calculate the amount of fuel which is required that is minimum fuel, which is required from here and we can do the costing of that fuel, this fuel is minimum.

So, fuel cost is known and from the area in the convection section, we can find out the annualized capital cost and then we can add them to find out the total cost. Now, please refer to the lecture on cost targeting to determine the annual cost, if are not able to understand refer to this lecture cost targeting, where it is very clearly given, how to calculate the tag that is total annual cost.

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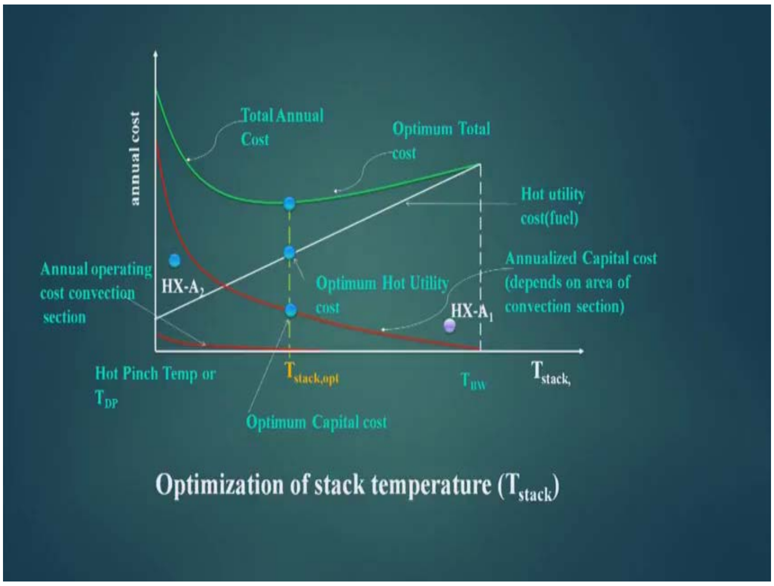

Optimization of stack temperature (T_{stack})

Now, this is the total annual cost, this is the hot utility cost that is the cost of the fuel, this is the annual capitalized cost this depends upon the area of the convection section, this is the annual operating cost of convection section and then we add them together, this is the total annual cost, which we get. So, the minimum point we can pick up and then we can draw a line, we can vertically draw a line to this perpendicular to this axis that gives me T stack optimum.

So, if I keep the value of the T stack at this point, then the total annual cost of operating the convection section will be minimum. So, this is how T stack is optimized and once the T stack has been optimized, then I can optimize the my T air temperature that means optimum of temperature of the air up to which it should be pre-heated.

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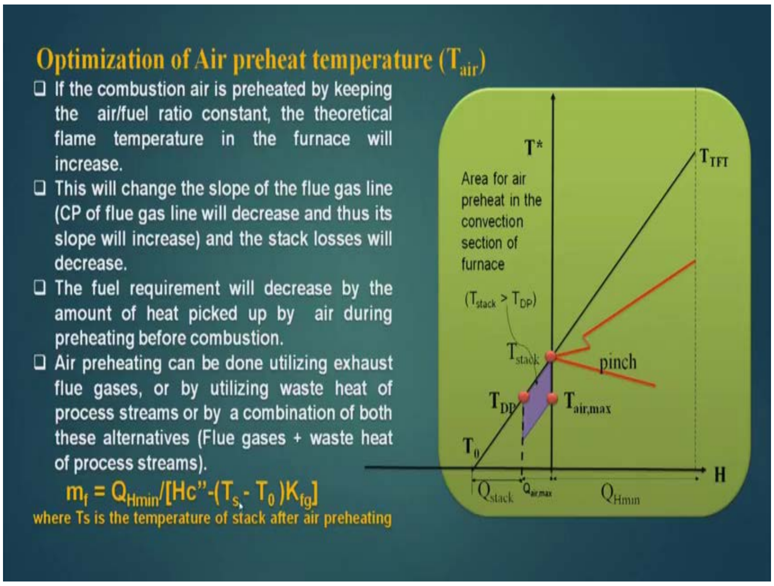

Optimization of Air preheat temperature (T_{air})

- ☐ If the combustion air is preheated by keeping the air/fuel ratio constant, the theoretical flame temperature in the furnace will increase.
- ☐ This will change the slope of the flue gas line (CP of flue gas line will decrease and thus its slope will increase) and the stack losses will decrease.
- ☐ The fuel requirement will decrease by the amount of heat picked up by air during preheating before combustion.
- ☐ Air preheating can be done utilizing exhaust flue gases, or by utilizing waste heat of process streams or by a combination of both these alternatives (Flue gases + waste heat of process streams).

$$m_f = Q_{Hmin}/[Hc'' - (T_s - T_0)K_{fg}]$$

where Ts is the temperature of stack after air preheating

Now, the next is optimization of air pre-heat temperature, which is T air. If the combustion of the air is pre-heated by keeping the air to fuel ratio of constant, the theoretical flame temperature in the furnace will increase. This we know that if we keep the air to fuel ratio constant and start preheating the air, the theoretical flame temperature will increase. This will change the slope of the flue gas lines CP of the flue gas line will decrease and thus the slope will increase and the stack loss will decrease.

Now, say this is this is operating at this T stack. Now I start ending the preheated air to the furnace, so what will happen this T f T f t will increase, why this T f T increases? I have to pass through this optimization stack temperature; this is somewhere come here, so this stack loss will be less. We will let us see here, this is one line a little bit of T f t has been increased, so little bit less stack loss then the second comes here a bit of T f t has been increased. So, stack loss has decreased then this third part when I increasing the T f t for more, this stack losses decreased.

And the angle is also changing, which is decreasing. So, says that this is the slope of the flue gas line CP of the flue gas line will decrease and thus its slope will increase. The fuel requirement will decrease by the amount of heat picked up by the air during the preheating before combustion. Now, if I am pre-heating the air, then obviously there will be a saving in the fuel and how much saving now, the amount of heat which will be picked up by the fuel, amount of heat which will be picked up the air before the combustion.

So, what we found that fuel were heating the air this T f t is increasing and once T f t is increasing, we have different lines here. And based on this slope of the lines, we can find out what is this CP value of the gas line. If the CP is more, the slope is less and if this c p is less, then this slope will be what because it is 1 by CP. Now, if we see this place now, the T here can be heated up to a point, which is called T air max. Basically, the T air will be heated up from the T 0 here, this is T 0 point to T max and this T max will be little bit less than the T d p.

So, the pre-heat can be done utilizing exhaust flue gas. Now, this air preheating can be either be done by using the exhaust heat from the flue gas or it can be heat by the lower pinch area of the GCC. So, this is also heat shows it can be heated by this or it can be heated by both. So, this basically this T 0 is here, so from T 0 to T air it can be heated up by the flue gas or by the lower pinch area because this is a heat source. So, here the m f this fuel requirement can be computed from here Q h minimum divided by H c double dash minus T s minus T 0 where, T s is the temperature, which this T stack will acquire after it gives heat to the air and this T s cannot be less than this T d p.

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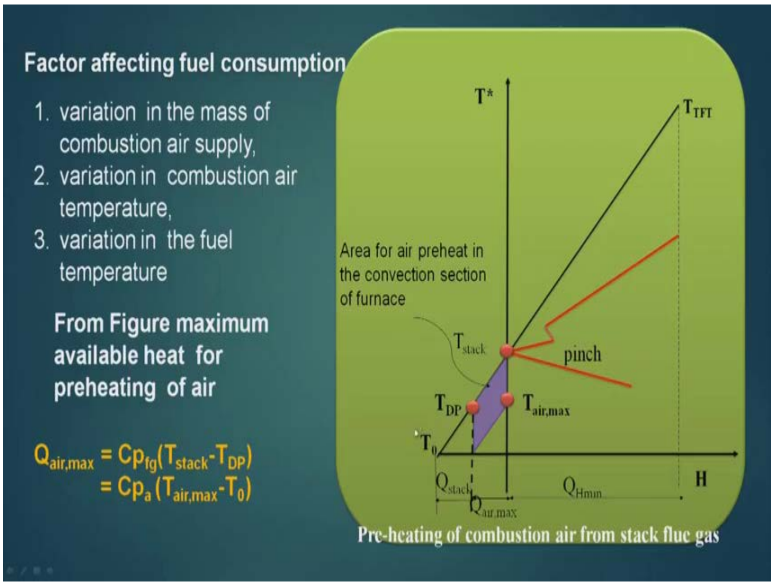

Factor affecting fuel consumption

1. variation in the mass of combustion air supply,
2. variation in combustion air temperature,
3. variation in the fuel temperature

From Figure maximum available heat for preheating of air

$$Q_{air,max} = Cp_{fg}(T_{stack}-T_{DP}) = Cp_a(T_{air,max}-T_0)$$

Pre-heating of combustion air from stack flue gas

Now, what we see that the variation in the mass of the factors that are affecting the fuel consumption, variation in the mass of combustion air supply this will also affect. And when this is affecting basically, when the air of the mass is changing basically this slope will also change. Variation in the combustion air temperature, if the combustion air temperature is rising obviously, there will be a decreasing the fuel amount and variation in the fuel temperature.

Basically, variation in the fuel temperature we are not doing because due to this safety reason, we are not heating the fuel or only heating the air. Now, from this figure we can write down the Q air max that the maximum heat, which can be pushed to the air for pre-heating is this C p f g T stack minus T d p, that means T stack can be brought down to up to the T d p not less than that, that I have already explained, why this cannot be done.

And this is equal to C p a T air max minus T 0 that means T 0 to T air max, this can be heated up to this. And obviously, T air max temperature will be little bit less than the T d p or to be calculated based on the economic analysis, because this is a counter current exchanger, this is in this direction, this is in this direction.

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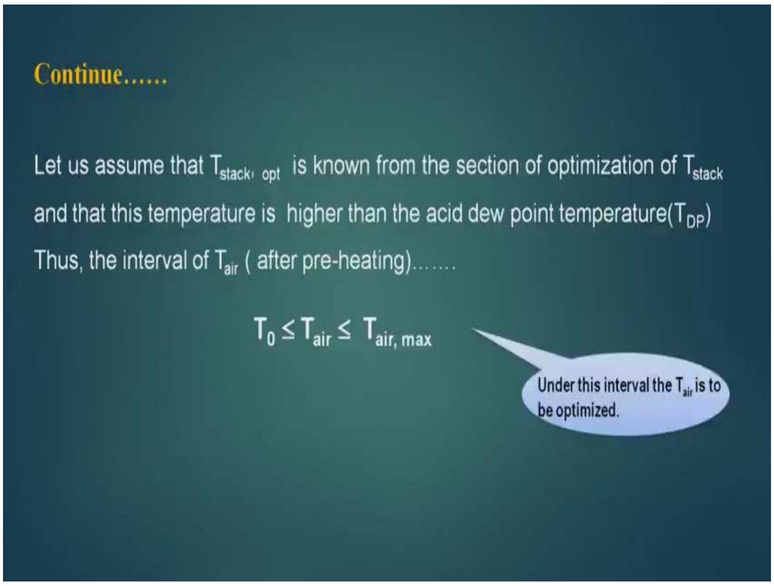

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Let us assume that $T_{stack, opt}$ is known from the section of optimization of T_{stack} and that this temperature is higher than the acid dew point temperature(T_{DP}) Thus, the interval of T_{air} (after pre-heating)……

$$T_0 \le T_{air} \le T_{air, max}$$

Under this interval the T_{air} is to be optimized.

So, how this will be done? Let us assume that the T stack optimization optimum is known from the section of optimization of T stack. So, we have already shown that how the stack temperature can be optimized. So, after we do the optimization of stack temperature, we know the T stack optimum value and this temperature is higher than the acid dew point T d p then, there is a chance of heating the air by the stack gases, which are coming from the stack.

Now, if it shows then, my T air temperature will be within this limit, T air maximum and T 0. So, within this limit I have to find out T air optimum. Now, this T air optimum is up to the temperature of reach, the T the temperature of the air should be increased will be calculate based on optimization.

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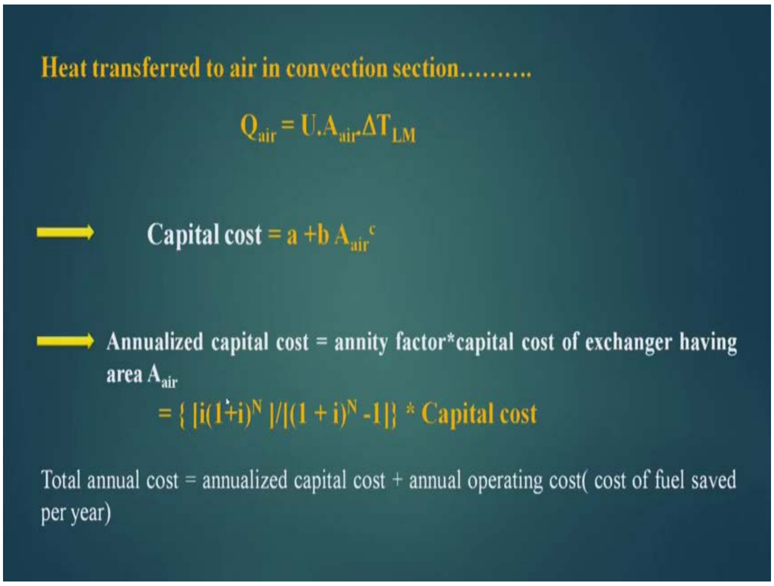

Heat transferred to air in convection section……….

$$Q_{air} = U.A_{air}.\Delta T_{LM}$$

- Capital cost = $a + b A_{air}^{c}$
- Annualized capital cost = annity factor*capital cost of exchanger having area A_{air}

$$= \{ [i(1+i)^N]/[(1+i)^N - 1] \} * \text{Capital cost}$$

Total annual cost = annualized capital cost + annual operating cost(cost of fuel saved per year)

Now, if you see the heat transferred to the air in the convection section can write down Q air is equal to U into A air into delta T l m normal temperature. And the capital cost of the heat exchanger, which will have A air that means area can be computed by this equation where, a plus b into A air that means area of the heat exchanger, which is heating the air to the power c. Now the annualized capital cost equal to annity factor into capital cost of the heat exchanger having area A air.

So, this is the capital cost, we have to multiply with a annity factor to find out annualized capital cost and that annity factor is this. So, this is the annity factor, this is the N that is the life span of the heat exchanger and this is the interested i into capital cost. And then total annual cost will be the annualized capital cost, which will be computed from this line plus annual operating cost, which is the cost of the fuel saved per year.

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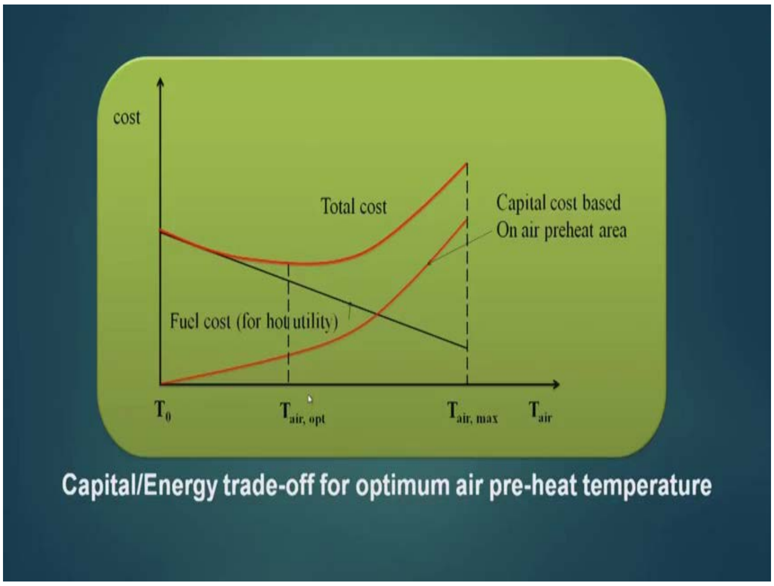

Capital/Energy trade-off for optimum air pre-heat temperature

So, this is the capital cost line of the air pre-heater and this is the fuel cost it goes down, so more is the capital cost, less will be the fuel cost. So I will get an optimum value here somewhere, so this will give me T air optimum. So, what we have calculated, we have calculated T air optimum and T stack optimum both and this is the requirement.

When we started our lecture, we told that when we are integrating the furnace with the GCC, these are the two pertinent parameters we have to calculate that is T stack optimum and T air optimum. And then these two parameters were computed based on the capital cost energy trade off.

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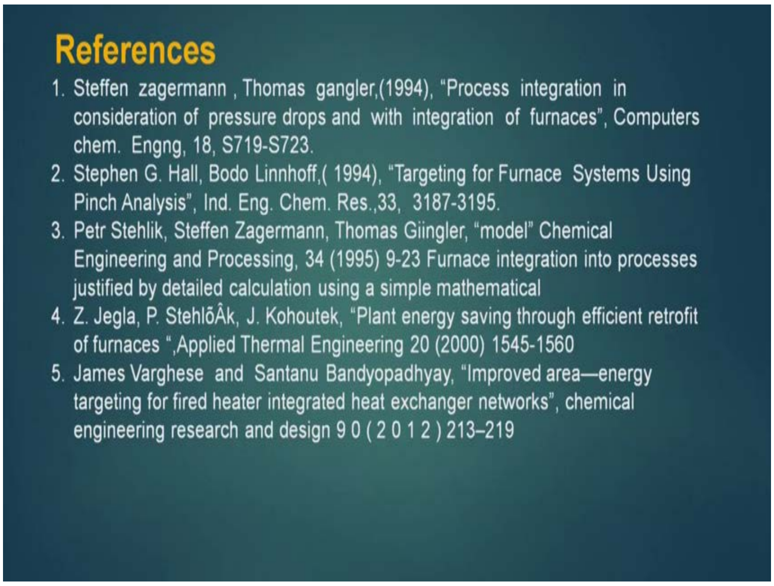

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So, these are the references.

Thank you.