POWER PLANT SYSTEM ENGINEERING

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Module 2

Lec 15: Fuels and Combustion (Part II)

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering Module 2, Vapor Power System Part 3. So, in this lecture our main focus would be to deal with contents of Fuels and Combustion. So, the word fuels in a steam power systems is derived from the word that is coal or any kind of fuel oil either it can be liquid fuel or it can be also to some extent gaseous fuels, but main constituents is coal. But to deal with this coal, we need to review some of the thermodynamic aspects and that is derived with certain concept in defining the certain parameters. These parameters are heat of combustion, then heating value of the fuel, combustion temperatures. Then after defining all these parameters, we will be able to find how this combustion reaction happens for the coal and to some extent we will deal with some of the liquid fuels and biomass, how they are characterized. But our main focus would be coal combustion.

Before you go to that coal part, let us try to understand or review some of the basic concepts of thermodynamic systems that is closed and open systems. As you see here the closed systems does not allow the mass and energy interactions to be possible. It is a system that has its own boundary and whatever energy which is available in the system that is mainly internal energy. Whereas in an open systems, it allows both mass and energy interactions and for which the system is defined in terms of control volume. Now, in same philosophy if you try to look at a reactor in which this combustion is going to happen, for example, we can view a reactor as a container in which there is an entry for carbon and oxygen at certain reference pressure and temperatures, and once the carbon and oxygen react with each other, the reactor gives out the product which is carbon dioxide, but at same reference pressure and temperature.

What I am trying to say here that such a system can be either viewed as a closed systems or open system. So, when you deal with the reaction that is happening within the reactor, then we can take it as a closed systems. But if you deal with complete system involving entry of carbon and oxygen and exit of carbon dioxide then you can view it as an open systems. With this philosophy, heat as an energy interaction for a thermodynamic system, is interpreted as heat of combustions. So, here heat release is interpreted as heat of combustion.

Now, with this basic philosophy, let us try to define the heat of combustion for open systems. So, if you refer this figure, basically this carbon and oxygen are treated as reactants and the output from this reactor which is CO_2 is treated as product. And through this process, hypothetically if there is some heat coming in and there is work transfer, then complete equation that is first law for an open systems can be represented as below equation.

$$H_R + \Delta Q = H_P + \Delta W; \sum_R mh + \Delta Q = \sum_P mh + \Delta W; \sum_R nMh_f + \Delta Q = \sum_P nMh_f + \Delta W$$

H_R&H_P:Enthalpies of reactants and products, respectively

(Evaluated for their constituents at the irrespective pressures and temperatures)

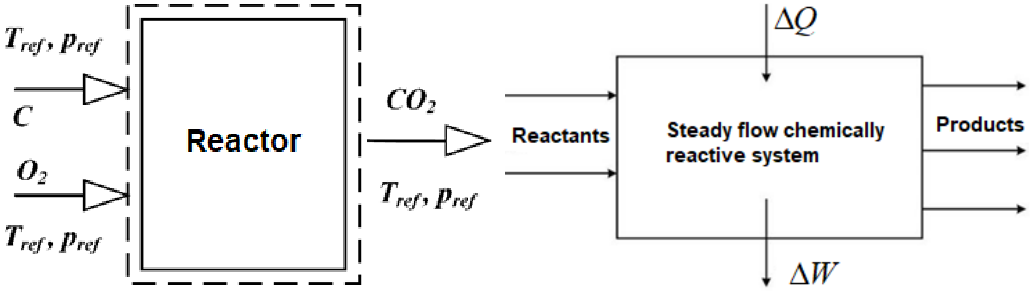
ΔQ:Net heat added to the system; ΔW:Net work done by the system

(ΔQ is usually negative for combustion system ,since heat is rejected by the system)

Now, if you split this reactants then the reactants can come up with many number of constituents. So, it is a summation of all the reactants with this corresponding mass and enthalpy and rest of the parameter remain same.

Mass of each constituents, $m = nM$; n: Number of moles M: Molecular weight

h:Specific enthalpy of each constituents;h_f:Enthalpy of formation



So, this is how we view this enthalpy of formations and later we will see how this enthalpy of formation is related to heat of combustion. Now, let us see same concept for different example, like for the combustion of ethane, ethane takes 3.5 times O_2 to form CO_2 and H_2O it is a complete combustion for which CO_2 and H_2O are the final products.

Ethane combustion: $C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$

Now, to define the concept of enthalpy of formation or heat released during this formation let us try to understand how ethane is formed. So, if you take a reference condition of 1 atm and 25°C then the chemical formula for ethane is C_2H_6, so two carbon atoms reacts with 3 molecules of hydrogen to form ethane. And during this formation of ethane, there is a heat release that is 2817.3 kJ/kg.

Formation of C_2H_6at 1atm & 25^0C : $2C + 3H_2 \rightarrow C_2H_6 + 2817.3\,\frac{\text{kJ}}{\text{kg}}$

Similarly enthalpy of formation of CO_2 can be interpreted as 8946.8 kJ/kg. Formation of CO_2 at 1atm & 25^0C : $C + O_2 \rightarrow CO_2 + 8946.8\,\frac{\text{kJ}}{\text{kg}}$

Heat releases during the formation(Exothermic reaction)

$$\Rightarrow h_f = -2817.3\frac{\text{kJ}}{\text{kg}}(C_2H_6)h_f = -8946.8\frac{\text{kJ}}{\text{kg}}(CO_2)$$

This is the experimental evidence and when there is a plus sign associated with enthalpy in a chemical equation, we call it as an exothermic reaction. So, we can say that heat released during this formation is negative quantity and this is how the enthalpy of formation is related to an exothermic reactions.

Now, interpreting same thing for a closed system, for instance if you arrest the entry for reactants and products and we say that both reactants and products are within this reactor, means we will replace this reacting system as a simple closed system reactor, so that ΔQ & ΔW will be 0. The reactor already contains fuel plus air and when they react with each other it produces energy. But that energy is arrested within this reactor itself and that too is interpreted in terms of rising its internal energy. And since in this case, there is no work output, so it is a non-flow work and such an example can be interpreted as a bomb. So, bomb means, already fuel is there and when you just ignite this fuel, it releases the energy. So, an explosion of bomb can be treated as a fuel burning in a closed system. So, same philosophy we can also analyze how much internal energy changes during this process.

So, for this closed system reactor, we can write the first law of thermodynamic equation in terms of internal energy for reactants and products, ΔQ and non-flow work ΔW_{nf}. And since both the terms will not be there, by neglecting this, there is heat release. So, this heat release, ΔQ is interpreted as change in increase in the internal energy.

First law of thermodynamics for closed system: $U_R + \Delta Q = U_P + \Delta W_{nf}$

For gases, enthalpy, $H = U + pV = U + nR_0T; pV = nR_0T$

$$\Rightarrow \sum_R \left(nMh_f - nR_0T\right) + \Delta Q = \sum_P \left(nMh_f - nR_0T\right) + \Delta W_{nf}$$

U_R&U_P:Internal energies of reactants and products, respectively

(Evaluated for their constituents at their temperatures)

ΔQ:Net heat added to the system; ΔW:Net non-flow work done by the system

(ΔQ is usually negative for combustion system, since heat is rejected by the system)

Mass of each constituents, $m = nM$;

n: Number of moles & total number of moles remains same. M: Molecular weight

p: Pressure; T:Temperaure; h_f:Enthalpy of formation

R_0:Universalgascostant $\left(= 8.314 \frac{\mathrm{J}}{\mathrm{mole.K}}\right)$

So same analysis of open systems can be extended for closed systems by replacing this enthalpy with internal energy.

So, this is how the closed system analysis is done to interpret heat of combustion. Now, having said all these things, we are now in a position to define the heating value. Normally the standard practice is not to define the fuel potential in terms of heat of combustion rather fuel potential is defined by an unanimous parameter which is called as heating value. So, normally there are two types of heating values that are interpreted- one is higher heating value, other is the lower heating value. There is a difference because of the heat release of water vapor in the products.

So, if you see our earlier reactions, in a complete combustion reaction, formation of water is always there. Now if enthalpies of this water vapors are taken into account then we call this as a higher heating value & if it is not taken into account, it is called as lower heating value of the fuel. So, heating value is defined as the heat released for a complete combustions that begins at standard temperature that is 25℃ and the products of the combustion are cooled to same temperature in a steady adiabatic systems without involving work. So, basically we can recall the equations for an open systems and arrest the term like $\Delta W = 0$ that means, no pdV work and ΔQ is called as heating value that means, heat released during this combustion and that is nothing, but the difference between the total enthalpy for reactants and products.

Recall first law of thermodynamics expression for an open system:

$$\sum_R nMh_f + \Delta Q = \sum_P nMh_f + \Delta W; \text{Take}, \Delta Q = HV \& \Delta W = 0$$

$$\Rightarrow HV = \left[\sum_{P} nMh_f - \sum_{R} nMh_f\right]_{T_1} = -\Delta Q; T_1\text{:Standard temperature}\left(25^0\mathrm{C}\right)$$

ΔQ:Net heat added to the system; ΔW:Net work done by the system

(ΔQ is usually negative for combustion system, since heat is rejected by the system)

Mass of each constituents, $m = nM$; n: Number of moles M: Molecular weight

HV:Heating value(Enthalpy of combustion); h_f:Enthalpy of formation

So, that is the reason heating value is the just the negative of heat of combustions. So, make sure that heating value is always treated as a positive quantity. Heat of combustion is mostly negative for an exothermic reactions, but when you define this heating value which is just negative of that heat of combustion so, the heating value is always interpreted as a positive quantity. I have explained that heating value for an open system is nothing, but the enthalpy of combustion and we have higher heating value, we have lower heating value.

Further point I need to mention that the heating value depends on whether the reactants fuels are in the liquid or vapor state because it takes certain quantity of energy to vaporize the liquid fuel. So, as long as complete combustion occurs the heating value of the fuel does not change. When you say heating value of open system it is nothing, but heat of combustion. When you say heating value for a closed systems it is known as internal energy of combustion that means, it increases the only internal energy.

So, with this thermodynamic background, now let us see, how you are going to calculate this heating value for coal and this coal is the main source of energy for the steam power systems. Normally for the coal we say the heating value as calorific value of the coal means, either you call this heating value or calorific value of the coal. And it is the property of fundamental importance which is defined as the heat transferred when the products of complete combustions of a sample of coal are cooled to initial temperature of air and fuel and to do this we need to have a standard test which is done with a bomb calorimeter- a device that measures the heating value of the coal.

Now for the coal also, two heating values are cited- higher heating value and lower heating value. So, higher heating value assumes that water vapors in the products condenses and thus it includes the heat of vaporization of water vapors formed by the combustion. Whereas, lower heating value assumes that water vapors formed by the combustion leaves as vapor itself. So, its value is further reduced by a quantity which is enthalpy of vaporization. So, there are lot of researches and lot of analysis was done, people have tried to find out some experimental evidence using this bomb calorimeter and side by side there are analytical analysis for various types of coals which was done earlier. And the most important formula was defined which is called as Dulong & Petit formula. In previous lectures, I have also explained similar formula that is Dulong formula, where the heating value was expressed in terms of Btu/lbm.

But here in SI units, the unit of this Dulong formula was modified with Dulong & Petit formula. And this formula is used to estimate higher heating value of anthracite and bituminous coal. So, this formula is mainly used for anthracite and bituminous coal. But this formula is not generally used for low grade fuels as it is for high grade fuels because its value underestimates. In an ultimate analysis, where the coal contains carbon, hydrogen, oxygen and sulfur, and for these four items as they only take part in a combustion reaction, the formula states that once you know their mass fractions then heating value of the fuel can be expressed by this expression.

Dulong and Petit formula for anthracite and bituminous coal:

$$HHV = 33.83C + 144.45\left(H - \frac{O}{8}\right) + 9.38S\,\frac{\mathrm{MJ}}{\mathrm{kg}}$$

h_{fg}:Latent heat of vaporization at partial pressures of water vapour in combustion products

$C, H, O \& S$: Mass fractions of carbon, hydrogen, oxygen and sulphur in coal

And this expressions was routinely used and tested using bomb calorimeter for various coal samples and finally, this formula was unanimously accepted.

So, for a given coal and ultimate analysis if you know the constituents then we can find out high heating value. Once you know this high heating value, we should be able to calculate low heating value of fuel by following equation.

$$LHV = HHV - m_w h_{fg} = HHV - 2.395 m_w \frac{\mathrm{MJ}}{\mathrm{kg}}$$

Now, enthalpy of vaporization for water=2.395 MJ/kg.

So, basically speaking if you know the mass of water vapor then we can calculate the lower heating value of the fuel.

Then let us move on to next parameter which is called as combustion temperature. So, always we say that when a reaction happens there is a heat release. And of course, when a heat release is taking place and we are trying to see the value of upper limit of temperature that can happen during this kind of heat release processes and mainly for fossil fuel situations. So, for this we just need to define some parameter which is called as combustion temperature. One frequently used parameters is the adiabatic combustion or adiabatic flame temperature. So, it means that normally heat of combustion for gases has effects in increasing the enthalpy for an open systems and internal energy for the closed systems.

Through this increase in enthalpy or internal energy, the temperature also increases. Now, if you look at the temperature that released for a flue gases they are interacted with various heat transfer surfaces of the components like water tubes, super heaters, reheaters of the steam generator unit. So, one way to design such kind of components is that we just have to have an estimate for the upper limit of temperature that these component has to face from the flue gases. For this reason it is very essential that you define this upper limit of temperature and we call this as a adiabatic combustion or adiabatic flame temperature. So, what does this adiabatic flame temperature mean? So, it is defined as the maximum temperature that we can obtain either for an open system or closed systems.

So, in a sense that adiabatic flame temperature can be defined for an open system and can be closed systems as well. So, in one way, we need to define the adiabatic flame temperatures typically for a constant volume process and for a constant enthalpy process. So, for an open systems if you say maximum temperature, we can arrest that means, if you recall the combustion equations for reactants, products involving heat transfer and work transfer this is the general equations

Adiabatic combustion or Adiabatic flame temperature at constant pressure

Open system: $\sum_R nMh_f + \Delta Q = \sum_P nMh_f + \Delta W; h_f$:Enthalpy of formation

$$\text{Take}, \Delta Q = 0 \;\&\; \Delta W = 0 \Rightarrow \sum_R nMh_f = \sum_P nMh_f$$

When the enthalpies of reactants and products are equal, under those circumstances, whatever temperature rise can happen within the reactor, we call that as adiabatic flame temperature or adiabatic combustion temperature at constant pressure.

Now, when you interpret same concept for a constant volume systems we replace these equations in terms of internal energy.

So, basically this internal energy is represented as $U = H - pV$. Now considering $pV = nRT$ we rewrite this equation in this form.

Adiabatic combustion or Adiabatic flame temperature at constant volume

Closed system: $\sum_R \left(nMh_f - nR_0T_1\right) + \Delta Q = \sum_P \left(nMh_f - nR_0T_1\right) + \Delta W_{nf}$

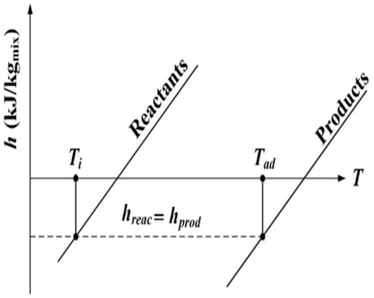
Take, $\Delta Q = 0 \;\&\; \Delta W_{nf} = 0 \Rightarrow \sum_R \left(nMh_f - nR_0T_1\right) = \sum_P \left(nMh_f - nR_0T_1\right)$

So, based on this we arrive at this particular expressions which is for which enthalpy of reactants and enthalpy of products match.

ΔQ:Net heat added to the system; ΔW:Net work done by the system

Mass of each constituents, $m = nM; n$: Number of moles M: Molecular weight

T_1:Standard reference temperature$\left(=25^0\text{C}\right)$; R_0: Universal gas constant $\left(= 8.314\frac{\text{J}}{\text{mole.K}}\right)$



So, under that situations the maximum temperature that we can achieve is known as adiabatic combustion temperature. So, if you refer this particular figure which talks about enthalpy & temperature- one for reactants other for product. So, basically there is a heat release. So, you have a negative sign here. So, we are looking at the enthalpy value in the negative directions. Now, if you keep on increasing the temperatures, the reactants vanishes and products are formed. And one particular point of time the enthalpy of reactants and product matches and coordinates of that point is called as adiabatic flame temperature.

So, with this viewpoint now let us see how we can go for the combustion analysis for the coal. So, our main target for the combustion of coal, which means it is a high temperature oxidation with fuel elements. Now, if you take coal or any fuel oil which are nothing, but the constituents of fossil fuel, on mass basis they mainly contain components like carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), moisture (M) and ash (A**)**. So, this was explained in our earlier lectures the constituents of coal. Now, if you take their total mass we can say

$$\text{C} + \text{H} + \text{O} + \text{N} + \text{S} + \text{M} + \text{A} = 100\% \text{ by mass}$$

But main issue is that out of these elements, the combustible elements are only carbon, hydrogen, and sulphur. So, they can take part in this oxidation process and why we include nitrogen, because nitrogen is already there in the air itself. So, if you see this combustible reaction with carbon & similarly with hydrogen and sulphur,

$C + O_2 \rightarrow CO_2$; $2\ H_2 + O_2 \rightarrow 2H_2O$; $S + O_2 \rightarrow SO_2$

So this is the situation for complete combustions. Now, when there is incomplete combustions we may not get CO_2 rather we can arrive at CO that means, carbon does not get excess oxygen or it could not be oxidized to form CO_2 rather it forms CO.

Incomplete combustion: $2C + O_2 \rightarrow 2CO$

So, under such situations it is an incomplete combustions, but our main philosophy is that we must supply sufficient oxygen for complete combustions. Now to get oxygen, we have to rely on air. For the reaction process normally, we do not supply oxygen rather we supply air. So, air requirement is very vital for a steam power systems. So, to burn the fuel completely there are four conditions that should be satisfied.

1. First we should supply enough air for complete combustions.
2. When you say enough air we should make a proper mixing of fuel and air. So, we require enough turbulence and thorough mixings.
3. Then for this air and fuel mixing, your furnace temperature should be very high so which that it can ignite the fuel and mixture so that means, we should maintain very high furnace temperatures.
4. Last thing is that we have to provide a large furnace volume to allow sufficient time for complete combustions that means, we have to allow a large area or large volume so that all the fuel components are burnt completely.

Although these are hypothetical statements, complete mixing of fuel and air is virtually impossible. For that reason, normally we have to bear with supplying excess air so that necessity of oxygen can be realized during this combustion process.

Now, let us try to analyze the oxidation processes of the combustible elements that is carbon, hydrogen and sulphur. So, if you take a complete analysis with all the components by mass and you add them then you get,
Ultimate analysis: $C + H + O + N + S + M + A = 1$.

Now we say that out of these constituents only carbon, hydrogen and sulphur take part in the oxidation process. Already oxygen is there but to make their complete oxidation process we have to supply excess oxygen.

So, for a complete combustion of carbon with oxygen, we require that 12 kg of carbon and for 12 kg of carbon, the oxygen requirement will be 32 kg because its molecular weight is 32 so that it forms 44 kg of carbon dioxide.

C (12 kg) + O_2 (32 kg) → CO_2 (44 kg) ⇒ C (C kg) + O_2 (2.67C kg) → CO_2 (3.67C kg)

Similarly, for hydrogen and oxygen combustion, we require 4 kg of hydrogen with 32 kg of oxygen to give 36 kg of water.

$2H_2$ (4 kg) + O_2 (32 kg) → $2H_2O$ (36 kg) ⇒ $2H_2$ (H kg) + O_2 (8H kg) → $2H_2O$ (9H kg)

So, likewise for sulphur we require equal amount of sulphur & oxygen, that is 32 kg of sulphur and 32 kg of oxygen and it gives SO_2 that is sulphur dioxide of 64 kg.

S (32 kg) + O_2 (32 kg) → SO_2 (64 kg) ⇒ S (S kg) + O_2 (S kg) → SO_2 (2S kg)

Now, but our main role in this analysis is to find out what is our oxygen requirement. So, for example, if you say C kg of carbon the oxygen requirement will be proportionate that is 32/12=2.67C kg and for H kg of hydrogen oxygen requirement will be 8 H kg and for S kg of sulphur oxygen requirement will be S kg.

So, the total oxygen requirement for this combustible element would be 2.76 C + 8 H + S, but already coal contains one unit of oxygen. So, our requirement is one less unit of O, because already some oxygen is present in the coal. So, this is the oxygen requirement.

Thus, oxygen requirement for 1 kg of fuel is, $W_{O2} = 2.67C + 8H + S – O$

But then we cannot get oxygen directly for such a large amount. So, we have to rely on the oxygen supply from air, but again air contains 23.2% of oxygen by mass. So, correspondingly, to burn 1 kg of fuel up for complete combustions the total theoretical air requirement would the following equation.

Theoretical air for 1kg of fuel for complete combustion: $W_T = \frac{W_{O2}}{0.232}$

$$\Rightarrow W_T = \frac{2.67}{0.232}C + \frac{8}{0.232}\left(H - \frac{O}{8}\right) + \frac{1}{0.232}C = 11.5C + 34.5\left(H - \frac{O}{8}\right) + 4.3S$$

So, if you know carbon, hydrogen, oxygen, sulphur constituents by mass, total theoretical quantity of air can be calculated. Then, but actual quantities is something represented by excess air because it is not always possible for a complete mixing. So, we always have to rely on excess air. So, when the excess air is supplied, we need to define another parameter which is called as a dilution coefficient which is defined below.

Dilution coefficient:$d = \frac{W_A}{W_T}$; W_A:Actual amount of air

Now, from this also one can calculate the percentage of excess air required as per the below equation.

Percentage of excess air, $W_E = \frac{W_A - W_T}{W_T}$;

So, this analysis will tell us the requirement of air for 1 kg of fuel. So, this is all about the coal analysis.

Now, let us talk something on liquid fuel and this is very conceptual and we are not going deep into this, because liquid fuels utilization is very rare for steam power applications. Because we require very large quantity of fuel which you can get from the coal. However, liquid fuels are very much essential for combustion in IC engine i.e., internal combustion engine. Because technically, this liquid fuels are excellent sources of energy with nearly constant heating values. Whereas, in case of coal, there are variety of heating values depending on the different grades of the coal. But liquid fuels have nearly a constant range of heating values. They are easy to handle, store and burn. Many a times, the crude oils is refined, fractionally distilled or cracked into products with various formation like gasoline, aviation fuel, diesel fuels, fuel oil, lubricating oils. All these things are obtained through various chemical processes.

The other category of the fuels is also known as synthetic fuels or synfuels. They are gaseous and liquid fuels that are produced largely from coal and various waste/biomass. And the conversion of coal to these fuels is obtained through gasification or liquefaction.

So, gasification or liquefaction are some of the techniques, in which we can convert the coal into liquid fuels. Now, for such fuels, we define a parameter which is normally called as flash point, which is the lowest temperature that allows inflammable vapors to be formed and it is found by heating the fuel slowly, sweeping a flame across the liquid surface and noting the temperature at which distinct flash occurs. So, there are flash point apparatus by which we can measure the flash point for any given fuel. The crude oil have low flash point and they require special handling procedures, but the most suitable crude for direct burning of the is the low sulphur contents.

So, now coming back to more details on the liquid fuels, the crude oil contains 83-87% of carbon, 11-14% of hydrogen with varying amount of sulphur, oxygen, nitrogen, other particulate and water.

And normally these liquid fuels are represented in terms of hydrocarbons with a molecular formula of C_mH_n, where m stands for number of carbon and n stands for number of hydrogen, but their interlinking is done in variety of ways like they can be paraffins (C_mH_{2n+2}) or they can be olefins (C_nH_{2n}), they can be dialofins (C_nH_{2n-2}), they can be cycloparaffins (C_nH_{2n}), they can also be aromatics (benzene - C_nH_{2n-6} & naphthalene C_nH_{2n-12}) And of course, this value of n depends on the m also. So, these are the chemical formulas for various hydrocarbon fuels. And when you deal with IC engine combustions normally this type of liquid fuels come into existence.

And the last component is deriving the fuel from the biomass. So, biomass is a renewable source of energy or is an alternative energy resources, which we can obtain from plants. So, these are organic matters derived from the plants or grown in the land or we can get these through aquatics. They can be forest crops, residues and they can be animal manure. They are treated in a specific way, so that the fuel can be used for variety of applications. Hence they are treated as a renewable source of energy at par with solar energy. And the solar energy is also utilized to grow the plants of high energy contents through photosynthesis.

Now, these biomass can be converted to liquid or gaseous fuels, thereby increasing its energy density and making it possible for transportation over long distances. The possible way of biomass conversions is through biogas conversion route. So, biogas conversion has two routes one is thermochemical conversion which is called as gasification or liquefaction. The other route is anaerobic digestions and fermentations. So, for which we can create biogas plants to produce methane and carbon dioxides with minimal impurities. So, this is grossly I have discussed about the liquid fuels, their utilities & their applications. So, this is all about the fuels and combustions and here our main focus would be solid fuels which is coal. Now, with this we are now in a positions to solve some numerical problems based on the coal combustion.

Q1. (a) Compute the required motor capacity for a FD fan at room temperature (30°C) with the following data: - Coal analysis: carbon: 78%; hydrogen: 3%; sulphur: 1%; oxygen: 3%; nitrogen: 1.1%; water: 3.3%; - Coal rate: 10 tonnes/hr; - Excess air: 30%; - Plenum chamber pressure: 1.8 kN/m^2; - Mechanical efficiency of fan: 65%.

So, the first problem is based on coal analysis and in our previous lectures we defined one of the auxiliary components of steam power systems that is fans. So, there are two types of fan- one is forced draft fan & other is induced draft fan. So, the main distinction of these two fans is that forced draft fans normally handles only air, because it supplies air requirement for the combustion and induced draft fan is used to take the combustion products out of the plant, so this mainly deal with the air requirement or air which is already present in the systems or various components, at the same time it has to also take out the products of combustions. So, our main focus in the first problem is that for a steam power systems, we need to find out the motor capacity for a forced draft fan which operates at 30℃ with given data.

So, basically coal, which is a fuel is coming from one end and for the coal the mass percentage are carbon 78 %, hydrogen 3 %, sulfur 1 %, oxygen 3 %, nitrogen 1.1 %, water 3.3 % and coal feed rate is 10 tons/hr. And we require air from the atmosphere which needs to be sucked into to the systems with excess air requirement of 30 % and this is should be used to burn the coal. To calculate the fan power we also require the plenum chamber pressure which is already mentioned as 1.8 kN/m^2 and mechanical efficiency as 65%. So, please recall our earlier lectures on fans where we have written the expressions for Power requirement of a forced draft fan

$$(\dot{W_f})_{FD} = \frac{\dot{m} v_{air} \Delta p}{\eta_f}; \qquad \text{Data given}, \Delta p = 1.8 \, {}^{\text{kN}}/_{m^2}; \; \eta_\text{f} = 0.65;$$

$$\text{Specific volume of air}, v_{air} = \frac{RT}{p};$$

$$\text{Given}, T = 30°\text{C} = 303K; p = \text{atmosperic pressure} = \; 101325 \; {}^{N}/_{m^2}$$

$$So, \qquad v_{air} = \frac{287 \times 303}{101325} = 0.858 \; {}^{m^3}/_{kg}$$

So, this is all the parameter are known, but we do not know the value of $\dot{m}$, which is the mass of air requirement. This mass of the air requirement, we need to find stepwise. First thing we need to find out is the theoretical air requirement for a coal combustions. So, you recall our expression

$$\dot{W}_T = 11.5C + 34.5\left(H - \frac{O}{8}\right) + 4.3S$$

Out of this we already know from the given data, $C = 0.78, H = 0.03, O = 0.03, S = 0.01$

So, putting this number we can write

$$\dot{W}_T = 9.907 \, {}^{\text{kg air}}/_{\text{kg fuel}}$$

So, this is the stoichiometric requirement, but we are supplying excess air. So, total requirement of excess air will be 30% higher than this.

So, with 30% excess air, $\dot{W}_T = 9.907 \times 1.3 = 12.9 \, {}^{\text{kg air}}/_{\text{kg fuel}}$

Now, fuel supply or coal feed rate, 10 tons/hr or 10000 kg / hr

$$\text{So}, \dot{m_{air}} = \dot{W}_T \times \frac{10000}{3600} = 35.83 \text{ kg/s}$$

Now Power requirement of a forced draft fan

$$(\dot{W_f})_{FD} = \frac{\dot{m} v_{air} \Delta p}{\eta_f} = \frac{35.83 \times 0.858 \times 1800}{0.65} = 85132 \text{ W} \approx 85.132\text{KW}$$

So, this is how we calculate the power requirement for forced air fan.

Q2. (a) For the above unit, in Q1, if the draught produced by an ID fan is 2.5 kN/m^2 and the gas temperature is 180°C and the fan efficiency is 55%, find the motor capacity of the ID fan. (b) Calculate heating value of the coal.

Now, in the same problem we have just twisted that for the same unit or same coal feed rate if we need to use an induced rod fan that operates with a pressure differential of 2.5 kN/m^2, the gas temperature is 180 ℃ and fan efficiency is 55% then it is asked to find the motor capacity.

a) So, in our previous analysis we get , $\dot{m_{air}} = 35.83$ kg/s

The induced draft fan uses the combustion products & these combustion products are obtained from the rate at which the coal is feed. The coal is feed at the rate 10000 kg/hr.

$$\text{So}, \quad \dot{m_{gas}} = \frac{10000}{3600} = 2.78 \text{ kg/s}$$

At this rate the combustion product or gaseous product or flue gas are generated. So, gas means here it is flue gas.

So Total mass, $\dot{m} = \dot{m_{air}} + \dot{m_{gas}}$

Now, we also need to calculate the specific volume.

We already know, Specific volume of air, $v_{air} = 0.858 \ {}^{m^3}/_{kg}$

$$v_{air} = \frac{RT_{air}}{p}; v_{fg} = \frac{RT_{fg}}{p}$$

Assuming that flue gas is released to atmosphere, so this pressure can be taken as equal. And given, $T_{fg} = 180°\mathrm{C}$

$$\text{So, we can find a relations}, v_{fg} = \frac{(180+273)}{30+273} \times 0.858 = 1{,}28\ {m^3}/{kg}$$

Now, we are in a position to obtain the power requirement for induced draft fan.

$$(W_f)_{ID} = \frac{(\dot{m}_{air} + \dot{m}_{gas}) v_{fg}\, \Delta p}{(\eta_f)_{ID}}$$

So, here data is given $(\eta_f)_{ID} = 55\%$ and $\Delta p = 2500\ N/m^2$

So, power requirement for induced draft fan $(W_f)_{ID} = 224640\ \mathrm{W} \approx 224.64\ \mathrm{KW}$

b) Second part calculate the heating value of the fuel using Dulong & Petit formula.

So, we recall Dulong & Petit formula.

$$HHV = 33.83C + 144.45\left(H - \frac{O}{8}\right) + 9.38S \frac{\mathrm{MJ}}{\mathrm{kg}}$$

Already we have the percentage by mass data for carbon hydrogen and oxygen.

$C = 0.78, H = 0.03, O = 0.03, S = 0.01$

So, inserting this number we can find, $HHV = 30.27\ \mathrm{MJ/kg}$.

So, this is about linking this fan problem with the coal analysis. So, this is a good problem where it links the different components of a steam power systems.

Q3. The bed particles of medium size 420 μm is fluidized by air under ambient conditions where the air density is 1.2 kg/m^3 and the viscosity is, 1.8 × 10^{-5} kg/m.s. The density of loosely packed bed is 1620 kg/m^3 and the density of solid is 2780 kg/m^3. Find the voidage of the bed and the minimum fluidization velocity.

Now, we will revisit another problem, which was discussed in our previous lectures which is called as fluidized bed combustion. So, fluidized bed combustion means, in a combustion unit, which is a fluidized bed, at the initial state the coal particles form a bed, which is in the collapsed state. Now, when the fluid or air is inserted into the bed it tries to spread. So, it becomes fluidized inside this chamber. So, for this fluidized conditions our main requirement is the minimum fluidization velocity, it means to make this condensed state or collapsed state coal particles to fluidized particles or fluidized state what is the minimum velocity requirement.

So, here basically there are three densities;

One is density of bed that is $\rho_b = 1620\mathrm{kg/m^3}$

Second is density of solid that is coal density, $\rho_s = 2780\ \mathrm{kg/m^3}$

Third is air density, $\rho_{air} = 1.2\ \mathrm{kg/m^3}$

In addition to that we have viscosity of air, $\mu_{air} = 1.8 \times 10^{-5}\ \mathrm{kg/m.s}$

And diameter of this fluid particle is $d_p = 420\mu\mathrm{m}$.

So, with this data we are going to calculate the voidage and minimum fluidization velocity.

So, first expression we recall

Voidage, $\alpha = 1 - \frac{\rho_b}{\rho_s} = 1 - \frac{1620}{2780} = 0.417$

So, voidage is a straightforward answer. We get the voidage as 0.417.

Now, to go for the next study that is fluidization velocity, we have to recall Reynolds number and this Reynolds number has an empirical relations with a number, which is called as Archimedes number (A_r). If you recall our previous lectures, the expression for Reynolds number is

Reynolds number, $\mathrm{Re} = (C_1^2 + C_2 A_r)^{0.5} - C_1; C_1 = 27.2 \& C_2 = 0.0408$

Archimedes number, $A_r = \dfrac{\rho_a(\rho_s - \rho_a) g d_p^3}{\mu_{air}^2};$

So, all data is given here and when we insert these numbers we arrive at

$A_r = 7480$

Then we can rewrite this Reynolds number as

$$\text{Reynolds number, Re} = \frac{\rho_a d_p U_m}{\mu} = (C_1^2 + C_2 A_r)^{0.5} - C_1$$

$$= (27.2^2 + 0.048 \times 7480)^{0.5} - 27.2 = 5.95$$

$$\Rightarrow U_m = \frac{5.95 \times 1.8 \times 10^{-5}}{1.2 \times 420 \times 10^{-6}} = 0.2 \text{ m/s}$$

So, the answer for minimum fluidization velocity is 0.2m/s. So, it means that we must supply this air at velocity of 0.2m/s, to bring this collapse state of particles into fluidized state. So, this is all about this lecture today. Thank you for your attention.