Fuels, Refractory and Furnaces

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Lecture No. # 12

Principles of combustion: Flame Temperature

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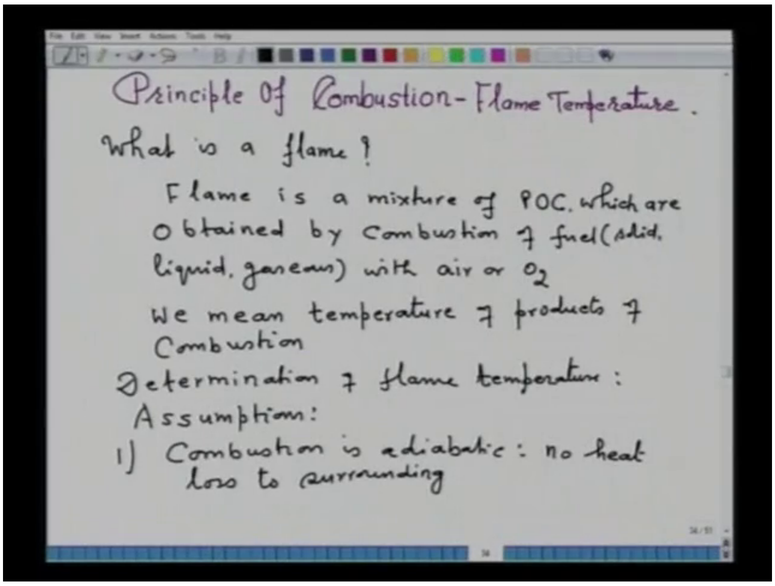

Principle of Combustion - Flame Temperature.

What is a flame?

Flame is a mixture of POC. which are obtained by combustion of fuel (solid, liquid, gaseous) with air or O_2

We mean temperature of products of combustion

Determination of flame temperature:

Assumption:

1) Combustion is adiabatic: no heat loss to surrounding

Today, we will talk on flame temperature. What is a flame? Start with, what is a flame. Flame is a mixture of products of combustion, which are obtained by combusting fuel with air or oxygen. So, in fact, flame, flame is a mixture of, is a mixture of products of combustion, POCstands for products of combustion, which are obtained by combustion of fuel. Now here, the fuel could be, could be solid, could be liquid, or could be gaseous, by combustion of fuel, with air, or could be oxygen. So, when we talk of flame temperature,in fact, we mean the temperature of the products of combustion. So, when we talk of flame temperature,in fact, we mean, we mean temperature of products of combustion; that is what in fact, flame temperature means; that is, In fact, the temperature of the products of the combustion. Now, this temperature called flame temperature, it can be determined, either experimentally, or it can be calculated based on certain assumptions. Now, in an experimental determination, what one needs to do; one needs to direct a pyrometer towards the flame, and through the principle of similarity in the radiation behavior, one can determine the flame temperature; but because of the radiations, and because of the directing of the pyrometer towards a

flame, it is very difficult to measure accurately, the flame temperature, because the flame, it consists of carbon dioxide, carbon monoxide, incandescence particles and so on. It is not an easy task to determine the flame temperature through pyrometer. Hence, it is determined from certain theoretical consideration. So, determination of flame temperature, determination of flame temperature - certain assumptions. Assumption number 1, we

assume combustion is adiabatic, assume combustion is adiabatic. This means, no heat loss, no heat loss to surrounding; that means, whatever heat that is produced through the combustion of fuel, it is used up in raising the temperature of the products of combustion, since we are assuming that, there is no heat loss from the flame to the surrounding.

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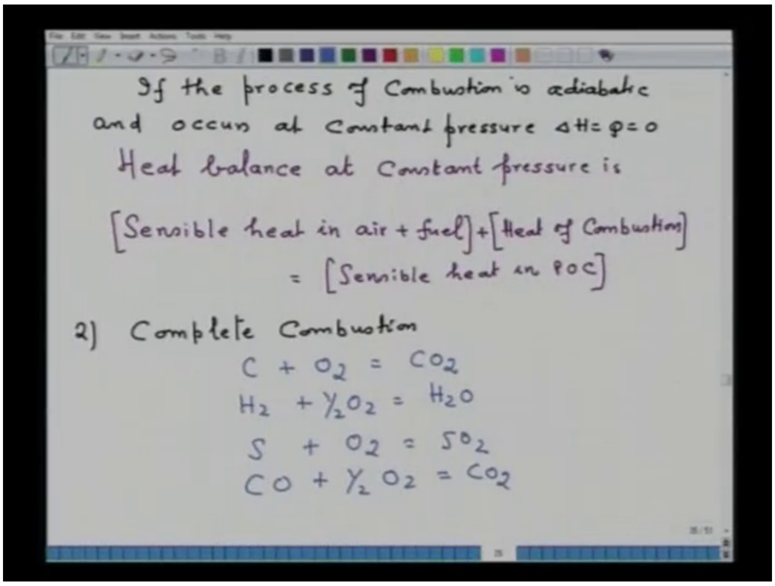

If the process of Combustion is adiabatic and occurs at Constant pressure $\Delta H = Q = 0$

Heat balance at Constant pressure is

[Sensible heat in air + fuel] + [Heat of Combustion] = [Sensible heat in POC]

2) Complete Combustion

$C + O_2 = CO_2$

$H_2 + \frac{1}{2}O_2 = H_2O$

$S + O_2 = SO_2$

$CO + \frac{1}{2}O_2 = CO_2$

Now, if the process is adiabatic, say, if the process, I mean, process of combustion, say, if the process of combustion is adiabatic, and occurs at constant pressure, and occurs at constant pressure, then, from first law of Thermodynamics, we can say, delta H, that is equal to Q, that is equal to 0, and therefore, the heat balance at constant pressure, heat balance at constant pressure is sensible heat in air plus fuel, sensible heat in air plus fuel;

that means, if the air, or fuel, or both are preheated, then, heat is also entering into the process of combustion; sensible heat in air plus fuel, plus heat of combustion, plus heat of combustion. Here, you have to consider all the components which are heat generating; and, all of you know, in solid fuel, carbon, hydrogen and sulphur are the heat generating components; in gaseous fuel, CO, hydrogen and hydrocarbons, they are the heat generating components. So, we have to consider from all sources of heat of combustion; and, that will be equal to sensible heat in products of combustion, sensible heat in product of combustion. So, that is the heat balance. In fact, it is based on the first law of thermodynamics, heat input, that is equal to heat output. So, based on this heat balance, one can proceed to determine the flame temperature. Assumption number 2, we also assume complete combustion, complete combustion. Complete combustion means, carbon plus O2, it gives C O 2; H 2 plus half O 2, that is equal to H 2 O; that is what the complete combustion means; that means, we are assuming complete combustion. S plus O 2, that is equal to S O 2; C O plus half O 2, that is equal to C O 2 and so on. So, if there is a hydrocarbon, then, the products of combustion are C O 2 and H 2 O. This is the assumption number 2.

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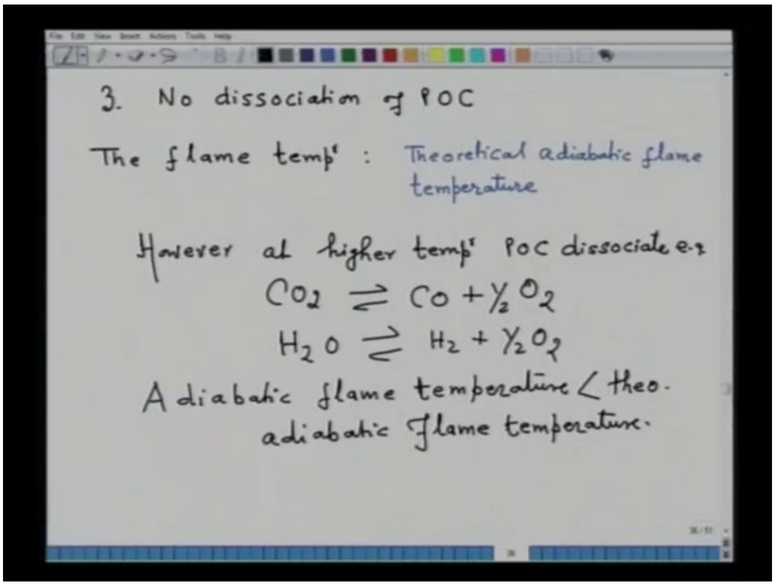

3. No dissociation of POC

The flame temp^r : Theoretical adiabatic flame temperature

However at higher temp^r POC dissociate e.g

$$CO_2 \rightleftharpoons CO + \frac{1}{2} O_2$$

$$H_2O \rightleftharpoons H_2 + \frac{1}{2} O_2$$

Adiabatic flame temperature < theo. adiabatic flame temperature.

Now, assumption number 3, we are also assuming, no dissociation, no dissociation of product of combustion; that means, the products of combustion, once they are formed, they are not dissociating in our this particular assumption. Now remember, if the products of combustion that dissociate, for example, C O dissociates to C O plus half O 2; this association is endothermic; it will consume the heat, as well as C O will also will produce; so, accordingly the flame temperature will be different. So, based on this assumption number 3, which says that, there is no dissociation of the products of combustion, the flame temperature so calculated on this assumption, the flame temperature which is calculated on all these 3 assumptions, particularly no dissociation of POC assumption, this is done with theoretical, theoretical adiabatic flame temperature, or you can also call it to be maximum adiabatic flame temperature. However, at higher temperature, the products of combustion dissociate. Now, however, at higher temperature, products of combustion, they dissociate; say, for example, C O 2,

C O plus half O 2; H 2 O, H 2 plus half O 2; or, other reactions are also possible; H 2 O could dissociate to O H and whatever the reaction maybe. So, what is, what I want to convey from here, that due to the dissociation of products of combustion, the flame temperature will be lower than theoretical adiabatic flame temperature. So, if the products of the combustion are considered in our calculation, then, what temperature we determine, we call as a adiabatic flame temperature, adiabatic flame temperature.

So, the adiabatic flame temperature considers the dissociation of products of combustion; obviously, the dissociation reaction, as I have written, it says that, C O and H 2 are produced; as such, the heat will also be carried by C O and hydrogen; both the reactions are endothermic; so, obviously, the adiabatic flame temperature will be lower than theoretical adiabatic flame temperature, lower than adiabatic flame temperature.

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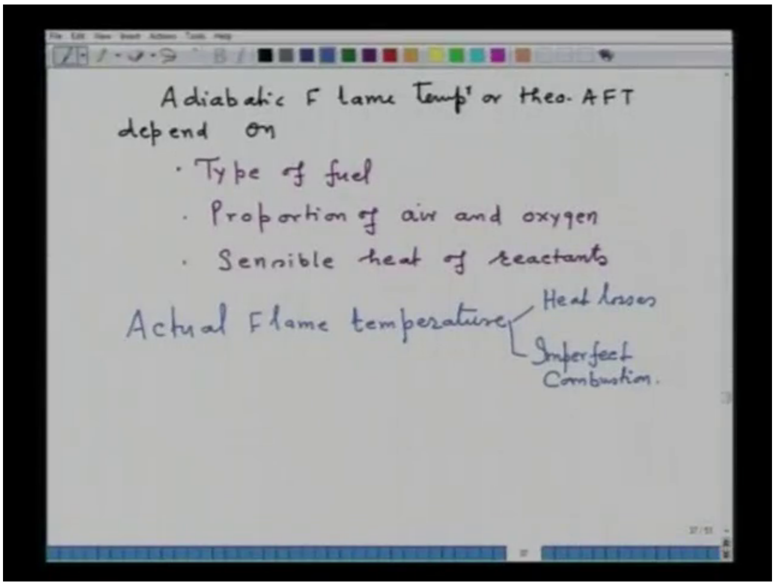

Adiabatic Flame Temp' or theo. AFT
depend on

- Type of fuel
- Proportion of air and oxygen
- Sensible heat of reactants

Actual Flame temperature
- Heat losses
- Imperfect Combustion.

Now, this adiabatic flame temperature, adiabatic flame temperature, or for that matter, theoretical adiabatic flame temperature, both, they depend upon, they depend upon one, type of fuel; what I wanted to say from here, that, whether it is adiabatic flame temperature or theoretical adiabatic flame temperature, or, in general, flame temperature, it is not a characteristic property of the fuel; with that, I mean, that you have one particular type of fuel, you can generate so many adiabatic flame temperature; that means, it depends upon the condition of combustion; one of the factor it depends upon type of fuel. For the same fuel, it also depends upon proportion of air and oxygen; that means, whether combustion is occurring in air, stoichiometric amount of air, or excess amount of air, whatever flame temperature you are determining, it will be different. So, a same, one particular fuel, can give you very different type of flame temperature, depending upon the amount of the air that is being used, whether it is theoretical, or more than theoretical amount of air. Similarly, whether combustion is occurring with oxygen enriched air, the same fuel can give very different flame temperature. So, what I wanted to say from here,

That flame temperature is not a characteristic property of the fuel; it depends upon the condition of combustion. Third factor, on which it depends, is sensible heat of reactants, sensible heat of reactants. So, these, all these three are the important factors that determine the adiabatic flame temperature, or theoretical adiabatic flame temperature. What I wanted to convey, very simple message from here, that a particular fuel which you have selected, you can obtain several adiabatic flame temperature, depending upon, whether you use theoretical air, more than theoretical air, preheated air, or preheated fuel, or whatever,

you can get, n number of adiabatic flame temperature. Also here, we have talked about the theoretical way of determination of flame temperature. We have considered complete combustion; we have considered no product of dissociation; we have considered no heat loss. So, in fact, the actual flame temperature, the actual flame temperature, with that actual flame temperature, I mean, as if you, you would be able to, to measure by pyrometer. So, this actual flame temperature,in fact, it depends upon the heat losses; because no way, you can prevent the heat losses, from flame to surrounding; albeit, you can minimize the heat losses,

in that, you allow the combustion to proceed very fast; you do not allow much time for combustion to occur. So, in that case, the time will be very very small, that is the so called instantaneous combustion, then, possibly, you can minimize the heat losses; but you cannot say the heat losses as zero, as we have assumed for the calculation. Another important thing, as you recall from the earlier lecture, that in spite of having the stoichiometric amount of air, or slightly excess air, if you see the problems which you have solved in the earlier lecture on combustion, you will note that, in spite of using the excess air, there is always carbon monoxide present in the flue gas and that says that, the imperfect combustion, imperfect combustion. What I wanted to say is that,

the actual flame temperature will be less than adiabatic flame temperature, less than theoretical adiabatic flame temperature. It is possible, the actual flame temperature could be 50 to 60 percent that of the adiabatic flame temperature. But even then, the calculation of the flame temperature is very important in fossil fuel combustion. In spite of all these things which I have said, that actual flame temperature is much lower, which is the fact, in spite of that, the calculation of flame temperature is a very important exercise in fossil fuel combustion.

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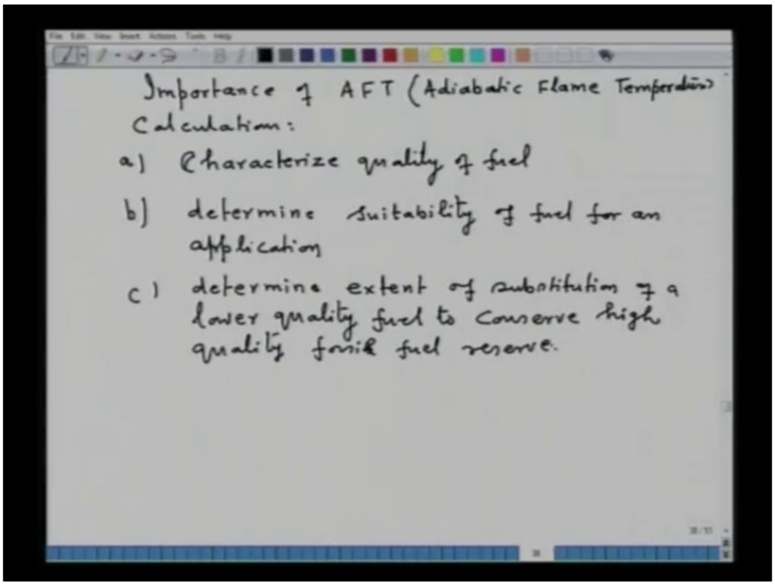

Importance of AFT (Adiabatic Flame Temperature)
Calculation:

a) Characterize quality of fuel

b) determine suitability of fuel for an application

c) determine extent of substitution of a lower quality fuel to conserve high quality fossil fuel reserve.

So, let me list importance of adiabatic flame temperature, importance of… I am now writing A F TT, adiabatic flame temperature, importance of A F TA F T, let me put it, adiabatic flame temperature. Calculations one. Through this calculation, one can characterize, one can characterize quality of fuel; one can characterize quality of fuel. Now, you know that, quality of fuel is judged by the temperature or the so called, by the adiabatic flame temperature. Higher is the adiabatic temperature, flame temperature, higher is the quality of fuel; that means, if we have several type of fuel, for example, solid fuel, you have lignite, you have anthracite, bituminous coal, or among liquid fuel, you have fuel oil, or the gaseous fuel, if you, if you calculate the flame temperature for stoichiometric amount of air, then, you will get series of adiabatic flame temperature. You can order them, in the decreasing order of the flame temperature and you can say, well, this fuel has higher temperature, or it generates higher flame temperature, so, it is a higher quality of fuel; then, the fuel will generate lower flame temperature. So, it gives you a method to classify the fuel, based on the flame temperature, that is the quality of the fuel. Second, adiabatic flame temperature can also be used to determine, to determine suitability of fuel, suitability of fuel for an application. With that, I mean, suppose, you want to heat the furnace at a temperature of, say for example, 1200 degree Celsius; you have a choice of three, four different types of fuel; you have to select, which type of fuel are you going to use; how are you going to select? Because for heating the furnace chamber, it is not only amount of heat is important, it is also important at what rate heat is being transferred; and, the rate is decided by the temperature difference. So, it is here, given different type of fuel, and to select which type of fuel you are going to use for a particular application, you calculate the adiabatic flame temperature, or theoretical adiabatic flame temperature, categorize them in the flame temperature,

and see that, the fuel which gives maximum flame temperature, it will give you higher heat transfer. So, based on the A F TA F T calculation, one can also determine the suitability of fuel for an application. Third, one can also determine, one can also determine the extent of substitution of a low quality fuel, lower quality fuel, to conserve high quality fossil fuel reserve. With that, I mean, suppose, a furnace is operating with combustion of natural gas; natural gas, say, if you consider combustion in stoichiometric amount of air, it generates a very high temperature; very high flame temperature. We can calculate the flame temperature. So, I, we will consider it is a very high quality of fuel. Now, in an application, you, you want to substitute with a lower quality fuel; for example, you want to substitute by producer gas; you want to substitute by blast furnace gas; how will you do it? You calculate the flame temperature of a mixture which consists of natural gas plus blast furnace gas, or coke oven gas, or producer gas, and see that,what should be done, in order to have the same flame temperature as it was for natural gas. So, based on this, you can find out, what percentage of substitution can be done by a lower quality fuel, in order to conserve the high quality fuel reserve. So, that is again a very important, from the point of view of the conservation of fossil fuel reserves; that is one of the very important thing, that if a high quality fuel, normally they are the fossil fuels, if it can be substituted by the low quality fuel, or for that matter, by the renewable type of fuel, for example, bio gas, then here, the calculation of adiabatic flame temperature will help to find out, what percentage of low quality fuel can be substituted, so that, one can conserve the high quality natural fuel.

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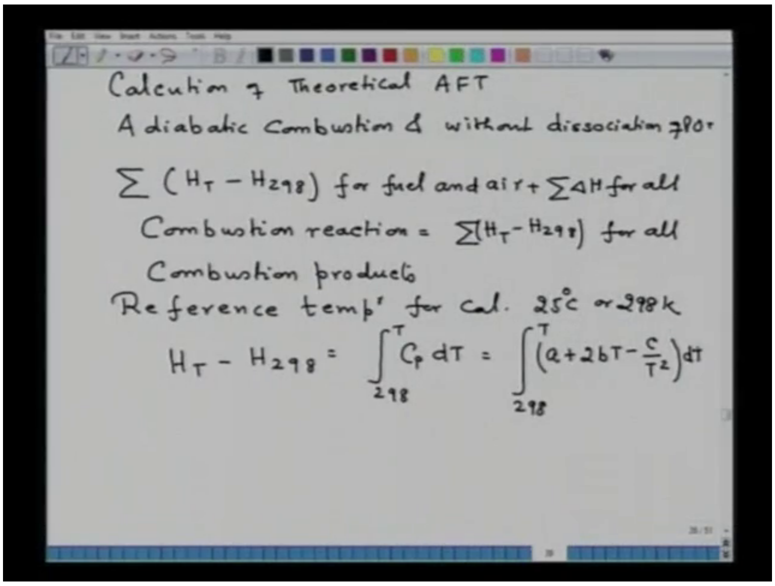

Calculation of Theoretical AFT

Adiabatic Combustion & without dissociation of POC

$\sum (H_T - H_{298})$ for fuel and air $+ \sum \Delta H$ for all Combustion reaction $= \sum (H_T - H_{298})$ for all Combustion products

Reference temp' for cal. 25°C or 298 K

$$H_T - H_{298} = \int_{298}^{T} C_p \, dT = \int_{298}^{T} \left(a + 2bT - \frac{c}{T^2}\right) dT$$

Now, the next thing comes now, how to calculate, say, calculation of theoretical A F T. We are not considering dissociation, because it is a very long exercise, one has to do it. So, I am illustrating the calculation of theoretical adiabatic flame temperature; that means, for adiabatic combustion, you are considering adiabatic combustion, and without dissociation, and without dissociation of P O C. You can write down the heat balance; that means, sigma H T minus H 298 for fuel and air, plus sigma delta H for all combustion reaction, that will be equal to sigma H T minus H 298, for all combustion products, for all combustion products. Now, you note here, H T minus H 8 is the heat in the fuel and air, above reference temperature, which is 298 Kelvin. So, here, the reference temperature for calculation, as all of you know, in thermodynamics, reference temperature for calculation is 25 degree Celsius or 298 Kelvin. You can also write as H T minus H 25. So, it is a standard practice in thermodynamics to have the reference temperature as 25 degree Celsius or 298 Kelvin. Now, note that, H T minus H 298, that is equal to 298, T, C p d T and that is also equal to, as all of you know from basic thermodynamics, a plus 2 b T minus C upon T square. So, that means, one has to know, now here, C p, that consists of the products of combustion. So, one has to take the C p values, integrat it and one can calculate. So, I am giving here, the C p value for most products of combustion.

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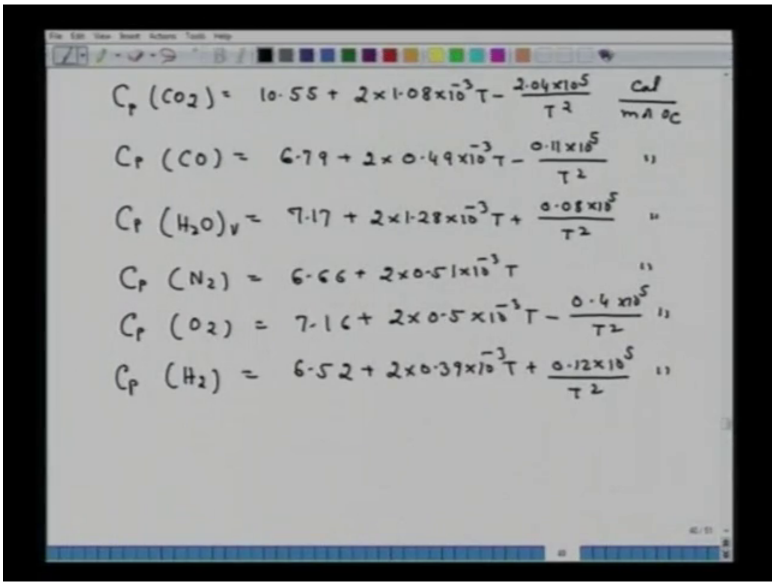

$$C_p(CO_2) = 10.55 + 2 \times 1.08 \times 10^{-3} T - \frac{2.04 \times 10^5}{T^2} \quad \frac{cal}{mol\ ^\circ C}$$

$$C_p(CO) = 6.79 + 2 \times 0.49 \times 10^{-3} T - \frac{0.11 \times 10^5}{T^2} \quad ''$$

$$C_p(H_2O)_v = 7.17 + 2 \times 1.28 \times 10^{-3} T + \frac{0.08 \times 10^5}{T^2} \quad ''$$

$$C_p(N_2) = 6.66 + 2 \times 0.51 \times 10^{-3} T \quad ''$$

$$C_p(O_2) = 7.16 + 2 \times 0.5 \times 10^{-3} T - \frac{0.4 \times 10^5}{T^2} \quad ''$$

$$C_p(H_2) = 6.52 + 2 \times 0.39 \times 10^{-3} T + \frac{0.12 \times 10^5}{T^2} \quad ''$$

So, C p.C O 2, that is equal to 10.55 plus 2 into 1.08 into 10 to the power 1 minus 3T minus 2.04 into 10 to the power 5, T square calorie per mole degree Celsius. C p C O, 6.79 plus 2 into 0.49 into 10 to the power minus 3T minus 0.11 into 10 to the power 5, T square, units same.

The C p H 2 O vapour, that is equal to 7.17 plus 2 into 1.28 into 10 to the power minus 3T plus 0.08 into 10 to the power 5 upon T square calorie per mole degree Celsius; C p nitrogen, 6.66 plus 2 into 0.51 into 10 to the power minus 3T calorie per mole degree Celsius. Then, C p oxygen, 7.16 plus 2 into 0.5 into 10 to the power minus 3Tminus 0.4 into 10 to the power 4 5 upon TT square . Sometimes, you may also need C p of hydrogen; that is equal to 6.52 plus 2 into 0.39 into 10 to the power minus 3T plus 0.12 into 10 to the power 5 upon T square calorie per mole degree Celsius. For very accurate calculation, one has to take these C p values; the C p a plus b T plus C by T square; but these calculations are normally, very, very lengthy calculation and you end up with a non-linear equation and it requires a solution, either by trial and error method, or by graphical method, or whichever way you think you can do it. However, for rough calculation, one can also use the average value. So, I am giving you some average values.

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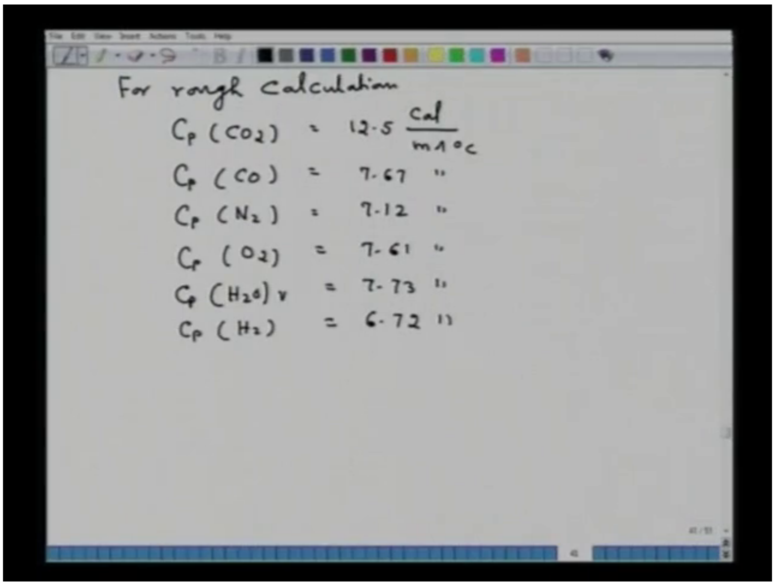

For rough calculation

$C_p\,(CO_2) = 12.5\ \frac{cal}{mol\ ^{\circ}c}$

$C_p\,(CO) = 7.67$ "

$C_p\,(N_2) = 7.12$ "

$C_p\,(O_2) = 7.61$ "

$C_p\,(H_2O)_v = 7.73$ "

$C_p\,(H_2) = 6.72$ "

Say for rough calculation, one can use the average values and I am giving you the average values that, I may use in some of the problem, to illustrate the fundamental concepts of flame temperature. C p C O 2, 12.5 calorie per mole degree Celsius. Mind you, these are the average values which we will be using in some cases, in order to illustrate the fundamental concept; however, remember, I will again stress, please remember, for exact and accurate calculation, one requires to use C p, that is equal to a plus b T plus C by T square; that is the most accurate value. C p C O, 7.67 calorie per mole degree Celsius; C p nitrogen, 7.12 calorie per mole degree Celsius; C p oxygen, 7.61 calorie per mole degree Celsius; C p H 2 O vapour, 7.73 calorie per mole degree Celsius, and C p hydrogen, that is equal to 6.72 calorie per mole degree Celsius. I will again and again stress that, for accurate calculation, the functional relationship of C p, which is equal to a plus b T plus C by T square should be used.

But for a rough calculation, for an order of magnitude calculation, one may use this average value, to find out quickly, the adiabatic flame temperature. There will be a difference between the adiabatic flame temperature calculated by using average values, and that of C p is equal to a plus b T plus C by T square value. This, I will illustrate by solving a particular problem. So, to illustrate the, this scheme of calculation, or the method of calculation, I will illustrate in the following way.

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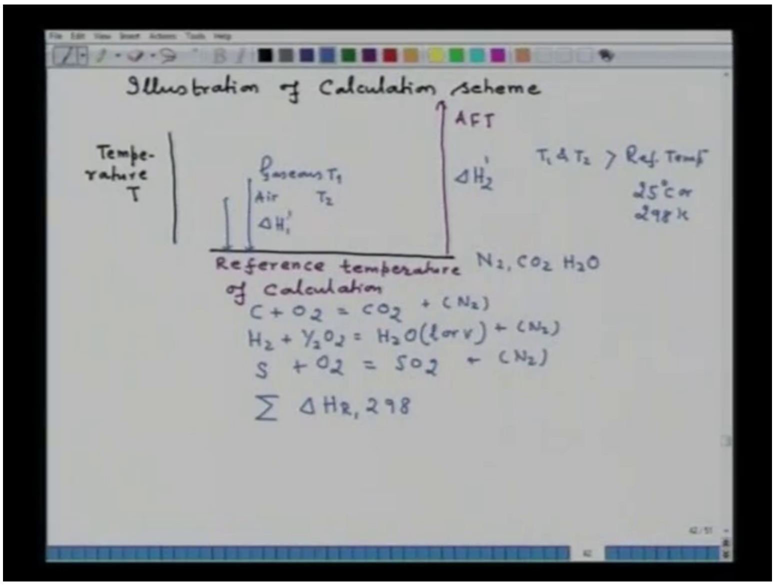

Illustration of Calculation scheme

T_1 & T_2 > Ref. Temp

25°C or 298 K

$C + O_2 = CO_2 + (N_2)$

$H_2 + \frac{1}{2}O_2 = H_2O(l \text{ or } v) + (N_2)$

$S + O_2 = SO_2 + (N_2)$

$\sum \Delta H_{R,298}$

So, illustration of calculation scheme; that is, for example, if this is

the temperature, let us say T, this is the reference temperature for calculation; reference temperature of calculation. I hope, you all must be very clear in your mind that, whenever you want to perform a thermodynamic calculation, you have to start with a reference; and for all heat transfer calculation, or for heat balance purposes, the reference temperature is (( )). However,

you can select any other temperature; there is no problem; but most of the values of C p, or H T minus H 298 as you are noting, they are given at reference temperature 25 degree Celsius. You can calculate on your own also, but what can be said is that, a reference, a specification of reference temperature at the beginning of calculation is the very important and all heat data, you will be calculating on that reference temperature; that is the most important thing here. Then, this one says that, A F T adiabatic flame temperature. Now, let us say, reactants are at this temperature.

Another reactant is at this temperature; for example, you have a gaseous fuel. So, this is a gaseous fuel and this is the air; they are at some temperature T 1; this is at temperature T 2, which is greater than your reference temperature; what I mean, T 1 and T 2 are greater than reference temperature. Now here, reference temperature, I am selecting 25 degree Celsius, or 298 Kelvin. So, what will I do now for calculation? I will bring this temperature to the reference temperature, to this; that means, I will be the calculating sensible heat of gaseous fuel, air, if they are greater than 25 degree Celsius; if not, then, their sensible heat is equal to 0. If it is greater than 25, then, I will be bringing all of them to, all the reactants to a common reference temperature, which is 25 degree Celsius, and that is the sensible heat of the reactants. Now. at the reference temperature, I will carry out the reaction; for example, C plus O 2, that is equal to C O 2; I have to know the heat of combustion of C O 2 at 298 Kelvin; then, H 2 plus half O 2, that is equal to H 2 O; here, I have to specify, whether I am considering liquid, or vapour; then, S plus O 2, that is equal to S O

2. Now, all these products of combustion, C O 2, H 2 O, S O 2, now, mind you, in all these cases, the nitrogen will also be generated. (( )), C plus O 2, C O 2 and in presence of air, you will have nitrogen here also; you will have nitrogen here also; you have nitrogen here also. The products of combustion which are found, for example, over here, they are N 2, C O 2 and H 2 O. So, these products of combustion, raise to a temperature A F T, that is called the adiabatic flame temperature. So, here, we say, let us say, the heat evolved is delta H 2 dash; this here, you have to addall the heat of combustion. So, the sigma delta H R,

298, heat of reaction , heat of combustion, they are one and the same thing; this is, you have to sum total it, and this sensible heat, let us say, it is delta H 1 dash.

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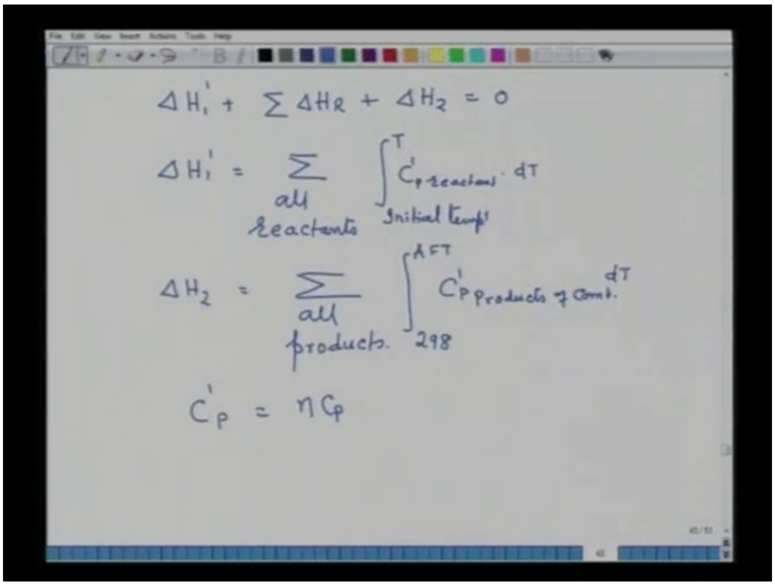

$$\Delta H_1' + \sum \Delta H_R + \Delta H_2 = 0$$

$$\Delta H_1' = \sum_{\substack{\text{all} \\ \text{reactants}}} \int_{\text{Initial temp}}^{T} C'_{p\,\text{reactants}} \cdot dT$$

$$\Delta H_2 = \sum_{\substack{\text{all} \\ \text{products}}} \int_{298}^{AFT} C'_{p\,\text{products of comb.}} \, dT$$

$$C'_p = n C_p$$

Then, this balance becomes delta H 1 dash plus sigma delta H R plus delta H 2, that is equal to 0. So, one can say, delta H 1 dash, that is equal to sigma of all reactants, initial temperature which is 25

degree Celsius, to the temperature at which the reactants are heated, C dash p of all reactant, by d T. Similarly, delta H 2, that will be equal to, all products, 298, if you want to use Kelvin, or 25, if you want to use degree Celsius, to A F T, C dash p of all products of combustion into d T, where C dash p, that is equal to n

into C p. So, that is how, this adiabatic flame temperature can be calculated, Now, I will give you a problem, or rather, two problem; you can solve it.

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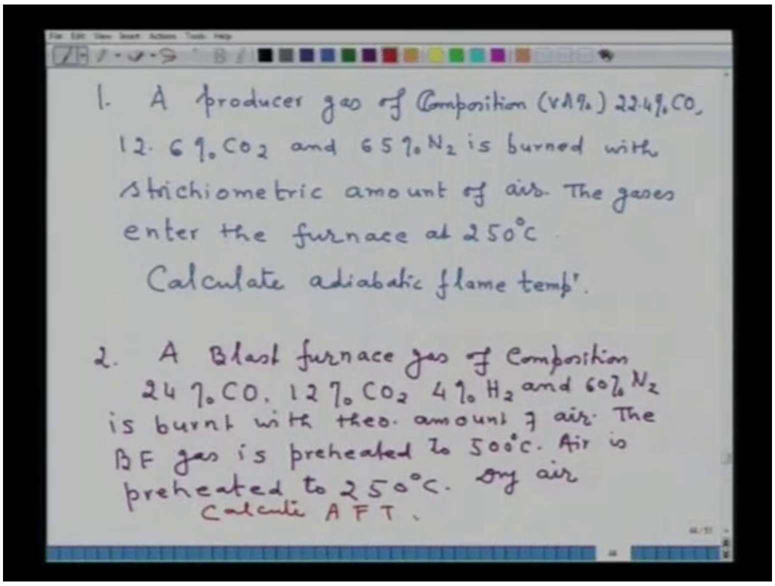

1. A producer gas of Composition (vol%) 22.4% CO, 12.6% CO_2 and 65% N_2 is burned with stichiometric amount of air. The gases enter the furnace at 250°C
Calculate adiabatic flame temp'.

2. A Blast furnace gas of Composition 24% CO. 12% CO_2 4% H_2 and 60% N_2 is burnt with theo. amount of air. The BF gas is preheated to 500°C. Air is preheated to 250°C. dry air
Calculate AFT.

One problem I will give, a producer gas, a producer gas of composition, of composition, is given on volume percent 22.4 percent C O, 12.6 percent C O 2 and 65 percent nitrogen is burnt with stoichiometric amount of air, stoichiometric amount of air. The gases enter the furnace at 250 degree Celsius. You are required to calculate, calculate adiabatic flame temperature.

Of course, this will be theoretical adiabatic temperature, because we have not considered the dissociation of the products of combustion. Another problem you can also solve it. A blast furnace gas of composition 24 percent C O, 12 percent C O 2, 4 percent hydrogen and 60 percent nitrogen is burnt with theoretical amount of air, theoretical amount of air. The BF gas, or the blast furnace gas, I am writing BF, blast furnace gas is preheated, is preheated to 500 degree Celsius; air is preheated to 250 degree Celsius; air is dry; dry air is used for combustion. Calculate A F T.

. Now, in both the problems, you have to do the heat balance. As all of you know, the heat balance cannot be done unless material balance is been done. So, in both the problems, first you have to make material balance, in order to find out the kg or kg moles of the product of combustion, or meter cube of product of combustion, whichever way you want to determine. Once you know the amount of product of combustion, then, you can perform the heat balance and then, you can proceed to calculate adiabatic flame temperature. Now, one of the problem I will be illustrating in the next lecture.