ESO201A

Lecture#29

(Class Lecture)

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Adiabatic Flame Temperature

Consider a given combustion process that takes place adiabatically and with no work or changes in kinetic or potential energy involved. For such a process (Fig. 1) the temperature of the products is referred to as the adiabatic flame temperature. With the assumptions of no work and no changes in kinetic or potential energy, this is the maximum temperature that can be achieved for the given reactants because any heat transfer from the reacting substances and any incomplete combustion would tend to lower the temperature of the products.

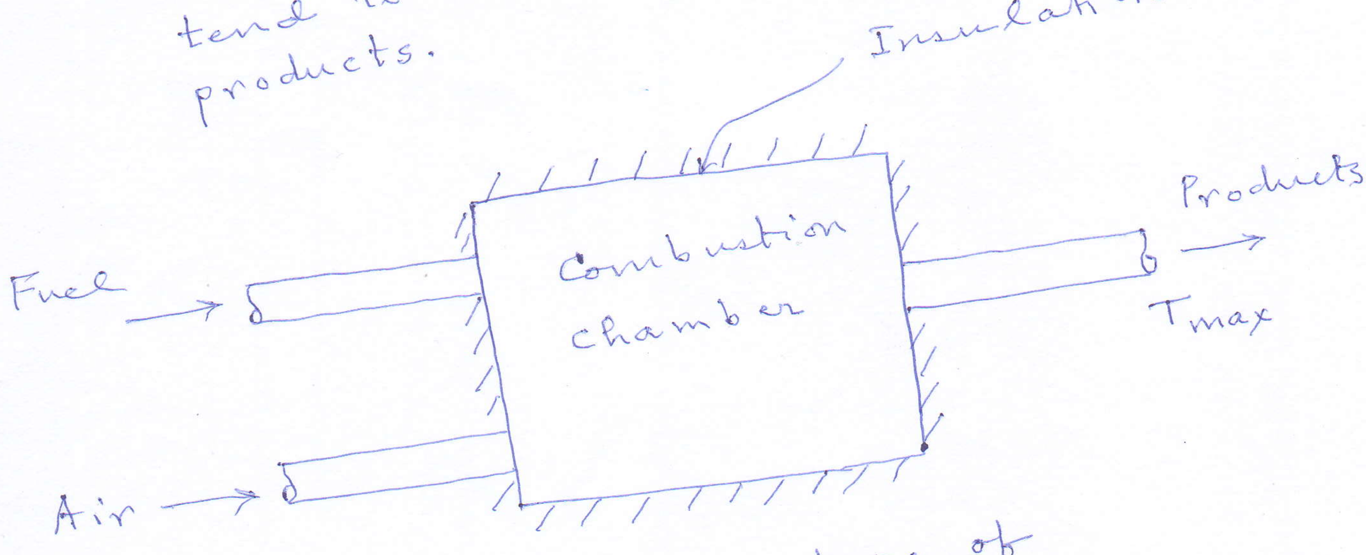

Fig. 1 The temperature of a combustion chamber becomes maximum when the combustion is complete and $Q = 0$, $W = 0$, $\Delta KE = 0$, $\Delta PE = 0$ and the fuel-air mixture is stoichiometric

For a given fuel and given pressure and temperature of the reactants, the maximum adiabatic flame temperature that can be achieved is with a stoichiometric mixture. The adiabatic flame temperature can be controlled by the amount of excess air that is used. This is important, for example, in gas turbines, where the maximum permissible temperature is determined by metallurgical considerations in the turbine and close control of the temperature of the products is essential.

The adiabatic flame temperature of a steady-flow combustion process is determined from the application of first law to the combustion chamber by setting $Q = 0$, $W = 0$, $\Delta KE = 0$, $\Delta PE = 0$.

$$\cancel{Q}^{0} - \cancel{W}^{0} = H_{products} - H_{reactants}$$

$$H_{products} = H_{reactants}$$

$$\Rightarrow H_{products} = \sum_{p} N_e (\bar{h}_f^o + \Delta\bar{h})_e$$

where $H_{products} = \sum_{p} N_e (\bar{h}_f^o + \Delta\bar{h})_e$

$H_{reactants} = \sum_{r} N_i (\bar{h}_f^o + \Delta\bar{h})_i$

In other words,

$$\sum_p N_e (\bar{h}_f^o + \bar{h} - \bar{h}^o)_e = \sum_r N_i (\bar{h}_f^o + \bar{h} - \bar{h}^o)_i$$

Once the reactants and their states are specified, the enthalpy of the reactants Hreact can be easily determined. The calculation of the enthalpy of the products Hprod is not so straightforward, however, because the temperature of the products is not known prior to the calculations.

Therefore, the determination of the adiabatic flame temperature requires the use of an iterative technique. A temperature is assumed for the product gases, and Hprod is determined for this temperature. If it is not equal to Hreact, calculations are repeated with another temperature. The adiabatic flame temperature is then determined from these two results by interpolation.

When the oxidant is air, the product gases mostly consist of N_2, and a good first guess for the adiabatic flame temperature is obtained by treating the entire product gases as N_2.

Example Problem # 1

Liquid octane at standard reference state is burned with 400% theoretical air at the same state in a steady-state steady-flow process. Determine the adiabatic flame temperature.

Solution: Control volume: Combustion chamber

Inlet state for fuel: 0.1 MPa, 25°C

Inlet state for air: 0.1 MPa, 25°C

Process: steady state

Assumption: All gases are ideal gases

The combustion reaction is :

$$C_8H_{18}(l) + 4(12.5)O_2 + 4(12.5)(3.76)N_2$$

$$\longrightarrow 8CO_2 + 9H_2O(g) + 37.5O_2 + 188N_2$$

$$H_{react} = \sum_r N_i(\bar{h}_f^\circ + \Delta\bar{h})_i$$

$$= (1)(\bar{h}_f^\circ)_{C_8H_{18}(l)}$$

$$= \boxed{-249,950 \text{ KJ/Kmol fuel}}$$

$$H_{prod} = \sum_p N_e(\bar{h}_f^\circ + \Delta\bar{h})_e$$

$$= 8(-393,520 + \Delta\bar{h}_{CO_2}) + 9(-241,820 + \Delta\bar{h}_{H_2O})$$

$$+ 37.5\,\Delta\bar{h}_{O_2} + 188\,\Delta\bar{h}_{N_2}$$

<u>Iteration #1</u>

Assuming $T_p = 900$ K,

$$H_{Prod} = 8(-393,520 + \bar{h}_{900K,CO_2} - \bar{h}_{298K,CO_2})$$

$$+ 9(-241,820 + \bar{h}_{900K,H_2O} - \bar{h}_{298K,H_2O})$$

$$+ 37.5(\bar{h}_{900K,O_2} - \bar{h}_{298K,O_2})$$

$$+ 188(\bar{h}_{900K,N_2} - \bar{h}_{298K,N_2})$$

$$\Rightarrow H_{prod} = 8(-393,520 + 37,405 - 9364)$$
$$+ 9(-241,820 + 31,828 - 9904)$$
$$+ 37.5(27,928 - 8682)$$
$$+ 188(26,890 - 8669)$$

$$= 8(-365,479) + 9(-219,896)$$
$$+ 37.5(19,246)$$
$$+ 188(18,221)$$

$$= -2,923,832 + (-1,979,064)$$
$$+ 721,725 + 3,425,548$$

$$= \boxed{-755,623 \text{ kJ/kmol fuel}}$$

$H_{prod, iter \#1} \neq H_{react}$

Iteration # 2

$$T_{prod} = 1000 \text{ K}$$

$$H_{prod} = 8(-393,520 + 42,769 - 9364)$$
$$+ 9(-241,820 + 35,882 - 9904)$$
$$+ 37.5(31,389 - 8682)$$
$$+ 188(30,129 - 8669)$$

$$\Rightarrow H_{prod} = 8\,(-360{,}115) + 9\,(-215{,}842) + 37.5\,(22{,}707) + 188\,(21{,}460)$$

$$= \boxed{62{,}494.5 \text{ kJ/kmol fuel}}$$

$$H_{prod,\, iter\,\#2} \neq H_{react}$$

Since $H_{prod} = H_{react} = -249{,}950$ kJ/kmol fuel, we find by linear interpolation that the adiabatic flame temperature is 961.79 K. Because ideal-gas enthalpy is not really a linear function of temperature, the true answer will be slightly different from this value.

Example Problem #2

Liquid octane (C_8H_{18}) enters the combustion chamber of a gas turbine steadily at 1 atm and 25°C, and it is burned with air that enters the combustion chamber at the same state. Determine the adiabatic flame temperature for (a) complete combustion with 100% theoretical air, (b) complete combustion (but with free O_2 in the products) with 400% theoretical air, and (c) incomplete combustion (some CO in the products) with 90% theoretical air.

Solution:

(a) Combustion equation:

$$C_8H_{18}(l) + 12.5\,(O_2 + 3.76\,N_2)$$

$$\longrightarrow 8\,CO_2 + 9\,H_2O + 47\,N_2$$

Since $H_{prod} = H_{react}$

$$\sum_p N_e(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_e = \sum_r N_i(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_i$$

The above equation reduces to

$$\sum_p N_e(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_e$$

$$= \sum_r N_i \bar{h}_f^\circ$$

$$= (N\bar{h}_f^\circ)_{C_8H_{18}}$$

since all reactants are at the standard reference state and $\bar{h}_f^\circ = 0$ for O_2 and N_2. The $\bar{h}_f^\circ$ and $\bar{h}$ values of various components at 298K (considering all gases as ideal gases) are shown in Table 1.

Table 1

Substance	$\bar{h}_f^\circ$ kJ/kmol	$\bar{h}_{298K}$ kJ/kmol
$C_8H_{18}(l)$	-249,950	—
O_2	0	8682
N_2	0	8669
$H_2O(g)$	-241,820	9904
CO_2	-393,520	9364

Substituting we have

$$(8)\left[\left(-393{,}520 + \bar{h}_{CO_2} - 9364\right)\right]$$

$$+ (9)\left[\left(-241{,}820 + \bar{h}_{H_2O} - 9904\right)\right]$$

$$+ 47\left[\left(0 + \bar{h}_{N_2} - 8669\right)\right]$$

$$= (1)(-249{,}950)$$

$$\Rightarrow 8\,\bar{h}_{CO_2} + 9\,\bar{h}_{H_2O} + 47\,\bar{h}_{N_2}$$

$$= 5{,}646{,}081 \text{ kJ}$$

The only unknown in the above equation is the temperature of the products T_{prod} since for ideal gases $h = h(T)$

A trial-and-error approach is used to determine the temperature of the products.

A first guess is obtained by dividing the right hand side of the equation by the total number of moles, which yields

$5,646,081 / (8 + 9 + 47)$

$= 88,220$ kJ/kmol

This enthalpy value corresponds to about 2650 K for N_2 (Table A-18). Noting that the majority of the moles are N_2, we see that T_{prod} should be close to 2650 K, but somewhat under it. Therefore, a good first guess is 2400 K.

At this temperature,

$$8\bar{h}_{CO_2} + 9\bar{h}_{H_2O} + 47\bar{h}_{N_2}$$

$$= 8(125,152) + 9(103,508) + 47(79,320)$$

$$= 5,660,828 \text{ kJ}$$

This value is higher than 5,646,081 kJ. Therefore, the actual temperature is slightly under 2400 K. Next we choose 2350 K. It yields

$$8(122,091) + 9(100,846) + 47(77,496)$$

$$= 5,526,654$$

which is lower than 5,646,081 kJ.

Therefore, the actual temperature of the products is between 2350 and 2400 K. By linear interpolation, it is found to be $T_{prod} = 2395\,K$.

(b) The balanced equation for the complete combustion process with 400% theoretical air is

$$C_8H_{18}(l) + 4(12.5)(O_2 + 3.76N_2)$$
$$\longrightarrow 8CO_2 + 9H_2O + 37.5O_2 + 188N_2$$

$$\Rightarrow C_8H_{18}(l) + 50(O_2 + 3.76N_2)$$
$$\longrightarrow 8CO_2 + 9H_2O + 37.5O_2 + 188N_2$$

By following the procedure in (a), the adiabatic flame temperature in this case is determined to be $T_{prod} = 962\ K$.

Notice that the temperature of the products decreases significantly as a result of using excess air.

(c) The balanced equation for the incomplete combustion process with 90% theoretical air is

$$C_8H_{18}(l) + (0.9)(12.5)(O_2 + 3.76N_2)$$
$$\rightarrow 5.5\,CO_2 + 2.5\,CO + 42.3\,N_2 + 9\,H_2O$$

$$\Rightarrow C_8H_{18}(l) + 11.25\,(O_2 + 3.76N_2)$$
$$\rightarrow 5.5\,CO_2 + 2.5\,CO + 42.3\,N_2 + 9\,H_2O$$

Following the procedure in (a), we find that the adiabatic flame temperature in this case is

$T_{prod} = 2236\ K.$

Conclusions

Notice that the adiabatic flame temperature decreases as a result of incomplete combustion or using excess air. Also, the maximum adiabatic flame temperature is achieved when complete combustion occurs with the theoretical amount of air.