Lecture 13

Flame Temperature

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Key words: Flame temperature, Combustion, furnaces

Exercise- 1 Flame temperature with theoretical air

Calculate theoretical maximum adiabatic flame temperature of fuel gas of composition 96 % CH₄, 0.8 % CO₂ and 3.2 % N₂ when burnt with theoretical air. Assume fuel and air are mixed at 25°C

Consider 1 mole of fuel gas

\[
\text{CH}_4 + 2\text{(O}_2 + 3.76 \text{N}_2 ) = \text{CO}_2 + 2\text{H}_2\text{O(g)} + 7.52 \text{N}_2
\]

POC Amount (kg mole)

CO₂ 0.968
H₂O 1.920
N₂ 7.52

Heat balance: Reference Temperature 25°C Or 298 K.

Sensible heat in air & fuel + Heat of combustion = Heat in products of combustion 1)

Sensible heat of reactants = 0 since they are Supplied 25°C .

\[
-\Delta H^\text{Comb}_{298} = 0.968 (94.05 \times 10^3) + 1.920 (57.80) \times -10^3 [0.96 \times 17.89] \times 10^3 = 184 \times 103 \text{ kcal.}
\]

This heat of combustion raises the temperature of POC to the flame temperature.

The heat capacity of POC i.e. Cp’

\[
\text{Cp’} = n \text{ CO}_2 \text{ C}_p \text{ CO}_2 + n \text{ H}_2 \text{ OC}_p \text{ H}_2\text{O} + n \text{ N}_2 \text{ C}_p \text{ N}_2
\]
Where nCO2, nN2 and nH2O are moles of CO2, N2, H2O respectively.

\[ C_p^1 = 0.968 \left(10.55 + 2.16 \times 10^{-3} T - \frac{2.04 \times 10^5}{T^2} \right) + 1.92 \left(7.17 + 2.56 \times 10^{-3} T + \frac{0.08 \times 10^5}{T^2} \right) + 7.25 \left(6.66 + 1.02 \times 10 - 3T \right) = 72.27 + 14.41 \times 10 - 3 T - \frac{2.11 \times 10^5}{T^2} \text{kcal kg mole}^{-1} \text{K} \] - (3)

By 1 and 3

\[ 184 \times 10^3 = \int_{298}^{T_f} c^1 \ p dT \] - (4)

By 3 and 4

\[ 184 \times 10^3 = \int_{298}^{T_f} \left(72.27 + 14.41 \times 10^{-3} T - \frac{2.11 \times 10^5}{T^2} \right) dT \]

Solution gives \( T_f = 2300 \text{K} \).

Consider the use of expression \( C_p = a + b \ T \) and recalculating flame temperature Calculating \( C_p^1 \) and making heat balance gives

\[ 0.0072 \ T_f^2 + 72.27 \ T_f - 206 \ 157 = 0. \]

This is a quadratic equation whose solution gives

\[ T_f = 2319 \text{K}. \]

Let us calculate flame temperature by using average \( C_p \) values of POC. Average \( C_p \) values of POC are given in lecture 12.

\[ 184000 = 0.96 \times 12.5 \ (T_f - 25) + 1.92 \times 7.73(T_f - 25) + 7.12 \times 7.25(T_f - 25) \]

Solution gives \( T = 2643 \text{K} \).

We note that the accuracy of calculation depends on \( C_p \) values. For accurate calculations \( C_p = a + b \ T + \frac{c}{T^2} \) must be used. However using \( C_p = a + bT \), though simplifies calculation but flame temperature is slightly greater (a difference of 20 K in this example). Use of average \( C_p \) values though simplifies the flame temperature calculation but calculated flame temperature is greater than earlier ones.

**Exercise 2. Effect of excess air on AFT**
Consider the fuel in 1. Now it is burnt with a) 20% excess air and b) 50% excess air calculate AFT in each case.

In the following calculations we will be using

\[ C_p = a + bT \]

However, readers may perform calculation using

\[ C_p = a + bT + C/T^2 \]

Take 20% excess air

Amount of POC:
- \( \text{CO}_2 = 0.968 \)
- \( \text{H}_2\text{O} = 1.92 \)
- \( \text{O}_2 = 0.40 \)
- \( \text{N}_2 = 9.056 \)

We can calculate

\[ C_p^1 = 87.18 + 16.11 \text{ T (kcal \, |kg \, mol)} \]

Heat of combustion = \( 184 \times 10^3 \text{ kcal} \).

Heat balance

\[ 184000 = \int_{298}^{T_f} (87.18 + 16.11T) \, dT \]

Integration yields

\[ 184000 = 87.18 \, T_f - 25979.6 + 8.05 \times 10^{-3} \, T_f^2 - 715.3 \]

Rearrangement.

\[ 8.05 \times 10^{-3} \, T_f^2 + 87.18 \, T_f - 210695 = 0 \]

\( T_f = 2034 \text{ K.} \)

Similarly for 50% excess

POC:
- \( \text{CO}_2 = 0.968 \)
- \( \text{H}_2\text{O} = 1.92 \)
- \( \text{O}_2 = 1.0 \)
\[
N_2 = 11.31
\]

Heat balance yields.

\[
9.18 \times 10^{-13} T_f^2 + 102.88 T_f - 215474 = 0
\]

\[
T_f = 1819 \text{ K}
\]

We note that increase in excess air decreases flame temperature. This is due to increase in \( N_2 \) and \( O_2 \) in the POC.

Similar calculations can be done by enriching air with \( O_2 \).

**Exercise-3:**

Calculate AFT when producer gas of composition 22.4% CO 12.6% CO\(_2\) and 65% \( N_2 \) is burned with theoretical air. The air and producer gas enter at 250\(^\circ\)C.

**Hint** Heat balance would be

Sensible heat in air + sensible heat in producer gas + heat of combustion = sensible heat in POC.

**Steps:**

1. Calculate composition of POC
2. Calculate sensible heats in air and POC
3. Calculate heat of combustion
4. Do heat balance and find AFT.

**Ans** \( T_f = 1472.5 \text{\(^\circ\)C} \) when \( C_p = a + bT \) is used

Assignment

1) Calculate AFT when producer gas of composition 22.4% CO 12.6% CO\(_2\) and 65% \( N_2 \) is burned with theoretical air. The air and producer gas enter at 250\(^\circ\)C.
2) Calculate the adiabatic flame temperature for combustion of blast furnace gas analyzing 24% CO, 12% CO₂, 4% H₂ and 60% N₂ under the following conditions

- When theoretical air is used
- When air is 30% excess than theoretical
- When 30% excess air is preheated to 227°C and 327°C

3) Calculate theoretical maximum adiabatic flame temperature of fuel gas of composition 96 % CH₄, 0.8 % CO₂ and 3.2 % N₂ when burnt with theoretical air. Assume fuel and air are mixed at 25°C