Module 5: Combustion Technology

Lecture 33: Combustion air calculation
Keywords: Heat of combustion, stoichiometric air, excess air, natural gas combustion

Combustion air calculation

The reaction of fossil fuels such as, coal or natural gas with oxygen liberate heat and the heat is used for various purposes. The main combustion products of burning of fuels are carbon dioxide and water. Combustion is the reaction of a fuel substance with air or pure oxygen to form combustion products. The combustion process is always exothermic and it liberates heat. The combustion reaction may be written as:

\[ \text{Fuel} + O_2 \rightarrow \text{Products} + \text{Heat} \]

In solid fuel, carbon is the main combustible component which is combined with an equivalent amount of oxygen to form carbon dioxide. Carbon monoxide may also be formed for incomplete combustion, which is further reacted to form carbon dioxide. The hydrogen and sulphur converts to H\textsubscript{2}O vapour and sulphur dioxide respectively.

The various reactions observed in the combustion of coal are as follows:

\[ C + O_2 = CO_2 \quad (1) \]
\[ C + \frac{1}{2}O_2 = CO \quad (2) \]
\[ CO + \frac{1}{2}O_2 = CO_2 \quad (3) \]
\[ H_2 + \frac{1}{2}O_2 = H_2O \quad (4) \]
\[ S + O_2 = SO_2 \quad (5) \]
A definite amount of oxygen is required for the conversion of carbon to carbon dioxide. As per the stoichiometry of equation (1), 32 kg of oxygen combines with 12 kg carbon in the first reaction to form 44 kg of carbon dioxide. So, 1 kg of carbon requires 2.667 kg of oxygen. Similarly, 1 kg of carbon requires 1.33 kg of oxygen to form 28 kg of carbon monoxide. 1 kg of sulphur requires 1 kg of $O_2$. The theoretical air can be calculated for a particular coal if carbon, hydrogen, nitrogen, oxygen and sulfur contents in weight percent are known by ultimate analysis.

**Calculation of theoretical combustion air**

Calculation on weight basis:

Let the ultimate analysis of a coal sample is as follows:

Carbon: 73%; hydrogen: 4.5%; oxygen 5.9%; nitrogen: 1.5%; sulphur: 5%; water 2.1%; ash 8%

Oxygen required for burning of carbon, hydrogen and sulphur are as follows:

Basis: 1 kg coal burned

\[
\begin{align*}
C: & \quad 0.73 \times 2.667 \text{ kg} = 1.9469 \text{ kg of oxygen} \\
H: & \quad (0.045 \times 8) - 0.059 = 0.301 \text{ kg of oxygen} \\
S: & \quad 0.05 \times 1 \text{ kg} = 0.05 \text{ kg of oxygen}
\end{align*}
\]

(1 kg of hydrogen consumes 8 kg of oxygen and 0.059 kg of oxygen is initially present in coal which should be subtracted from the total required oxygen)

Total oxygen required to accomplish the complete burning = 1.9469+0.301+0.05 = 2.298 kg
Air contains Oxygen: Nitrogen in the proportion of 79:21 or 1 mole of oxygen is accompanied by 3.762 mole of nitrogen. Total moles of air are equal to 4.762 moles.

One kg of oxygen equivalents to $4.762 \times \frac{29}{32} = 4.3155$ kg ~ 4.32 kg of air, because, molecular wt of air and oxygen are 29 and 32 respectively. Therefore, total amount air needed for the burning of above coal sample will be $2.298 \times 4.32 = 9.927$ kg, which is the theoretical air requirement.

Therefore, oxygen or theoretical air may be approximately determined by the general equations as,

Oxygen required per kg coal = $2.667 C + (H \times 8 - O) + S$ kg

Air required per kg carbon = $4.32 \times (C \times 2.667 + (H \times 8 - O) + S)$

= $11.521 C + 34.56 H + 4.32(S-O)$ kg

Where C, H, O and S are weight on the basis of 1 kg fuel and the oxygen present in the fuel is subtracted from the required oxygen for burning of fuel as shown in the equation.

Calculation on volume basis:

The volume of air requirements may also be determined in Nm$^3$ per kg of fuel. 1 kmol is equivalent to 22.4 Nm$^3$.

1 kg of oxygen is equivalent to $(1/32)$ kmol = $(1/32) \times 22.4 = 0.7$ Nm$^3$

So, 1 kg carbon required $32/12$ kg oxygen = $(32/12) \times (1/32) \times 22.4 = 1.886$ Nm$^3$
Volume of oxygen required = \((1.866C + 5.56H + 0.7S - 0.7O)\) Nm³/kg

As the volume ratio of air: oxygen is 1: 0.21.

Therefore, the volume of air = Volume of oxygen /0.21

\[
= \frac{1}{0.21} (1.866C + 5.56H + 0.7S - 0.7O)\ Nm^3/kg\ coal
\]

\[
= 8.89 (C + 0.375S) + 26.5H - 3.3O\ Nm^3/kg\ coal
\]

A common example of burning of gaseous fuel is the combustion of natural gas which mainly contains methane. One molecule of methane reacts with two molecules of oxygen to produce one molecule of carbon dioxide and two molecules of water vapor.

\[
CH_4 + 2O_2 = CO_2 + 2H_2O
\]  \hspace{1cm} (6)

**Excess air calculation**

In a combustion process, the complete burning can not be accomplished with the exact theoretical amount of air. Therefore it is essential to supply an excess amount of air for the combustion of fuel. The volume of twice the theoretical air may be used; otherwise, it is decided based on the nature of the fuel used and the method of burning process.

The valid reason for incomplete combustion of fuel in presence of theoretical amount of air may be due to the fact that each particle of oxygen in the air does not have the intimate contact with the fuel particles in the combustion process. Therefore an excess air is to be supplied.

It was observed that 50 per cent more than the theoretical amount of air is usually needed. If less than this amount of air is supplied, the carbon burns to monoxide instead of dioxide.
An excess of air is also a source of waste, as the products of combustion will be diluted and carry off an excessive amount of heat in the chimney gases, or the excess air will so lower the temperature of the furnace gases as to delay the combustion to an extent that will cause carbon monoxide to pass off unburned from the furnace.

**Calculation flue gas volume of combustion of methane**

Stoichiometric equation is \( CH_4 + 2O_2 = CO_2 + 2H_2O \) with pure oxygen

\[
CH_4 + 2O_2 + 7.524 \; N_2 = CO_2 + 2H_2O + 7.524 \; N_2
\]

(2 mole oxygen= 7.524 moles of nitrogen, that means, 7.524+2=9.524 moles of air)

1 mole of methane requires 9.524 moles of stoichiometric air or 9.524 ml of air at STP per ml of methane.

Flue gas composition:

**Example 1**: In combustion of pure methane gas with 5% of excess air, determine the gas composition of flue gas in volume %.

**Solution**: 
Basis: 1 mole of methane burning

If 5% excess air is used, according to the following equation, oxygen in air is, \( 2+ 2\times0.05=2.1 \) moles and nitrogen in air is, \( 7.7524+7.524\times0.05=7.9 \) moles.

\[
CH_4 + 2.1O_2 + 7.9 \; N_2 = CO_2 + 2H_2O + 7.9 \; N_2 + 0.1 \; O_2
\]

Total number of moles in flue gas = 1 mole CO\(_2\) + 2 moles H\(_2\)O + 7.9 mole N\(_2\) + 0.1 mole O\(_2\) = 11 moles
Composition in volume percent is CO$_2$=0.0909; H$_2$O = 0.182; N$_2$= 0.718; O$_2$ = 0.00909

According to the wet (water is liquid) analysis.

**Example 2**: Methane is burned with 18 % excess air in respect of volume. Determine the carbon dioxide percentage in the flue gas dry basis.

Solution: The reaction is $CH_4 + 2O_2 = CO_2 + 2H_2O$

Basis: 1 m$^3$ methane burning

The volume of stoichiometric air = $2/21 \times 100 = 9.524$ m$^3$

The volume of actual air = $9.524 \times (1+0.18)$ m$^3$ = 11.238 m$^3$

Volume of Nitrogen = $11.238 \times 0.79 = 8.878$ m$^3$

Volume of Carbon dioxide = 1 m$^3$

Volume of Oxygen = $2 \times 0.18 = 0.36$ m$^3$, Total volume of flue gas = 10.238 m$^3$

% of Carbon Dioxide = $1/10.238 \times 100 = 9.767$

**Stoichiometric ratio**

If the minimum air is used following the stoichiometry of the combustion reaction then the air is called the stoichiometric air. The ratio of actual air to stoichiometric air is called stoichiometric ratio. For example, soichiometric air for burning of methane is
\[ \text{Stoichiometric ratio} = \frac{\text{Actual air}}{\text{Stoichiometric air}} \]

\[ \text{Excess air} = \frac{\text{Actual air} - \text{Stoichiometric air}}{\text{Stoichiometric air}} \]

\[ \text{Excess air} = (\text{Stoichiometric ratio} - 1) \times 100 \% \]

**Example 3:** Calculate the percentage excess air for methane burning. The flow rate of methane and air are 25 and 290 m³/h respectively.

Stoichiometric air for methane burning is 9.524 m³/m³

Assuming the flow rate of methane = 25 m³/h

The flow rate of air = 290 m³/h

Air required = 25 × 9.524 = 238.1 m³/h

Then \[ \text{Stoichiometric ratio} = \frac{290}{238.1} = 1.22 \]

Excess air = (1.22 – 1) × 100 % = 22 %
References
