



# Fuels and its Combustion in Boiler

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**steag**

# Objectives and other details of modules

**Duration** – 75 minutes

## **Training aids**

Power point Presentations

Reading Material

## **Objective**

*At the end of the session participants will be able to:*

- **Illustrate coal properties and its effect**
- **Determine of heat value,**
- **Undertake coal analysis and describe its relationship to coal combustion**
- **Describe the process of coal combustion in boiler**
- **Explain the sytromatric and excess air and its influence combustion**
- **Apply methods for controlling oxygen for achieving optimal coal combustion**

- Coal and its origin**
- Coal Components and its Importance**
- Coal Properties and its Importance**
- Ash Behavior at high temperature**
- Fuel Oil Characteristics**
- Stoichiometry and its application in Boiler**
- Excess Air - Calculation, Importance and Measurement**
- Combustion Equipments – Burners & NOx**

## Fossil Fuels: Coal – Its Origin

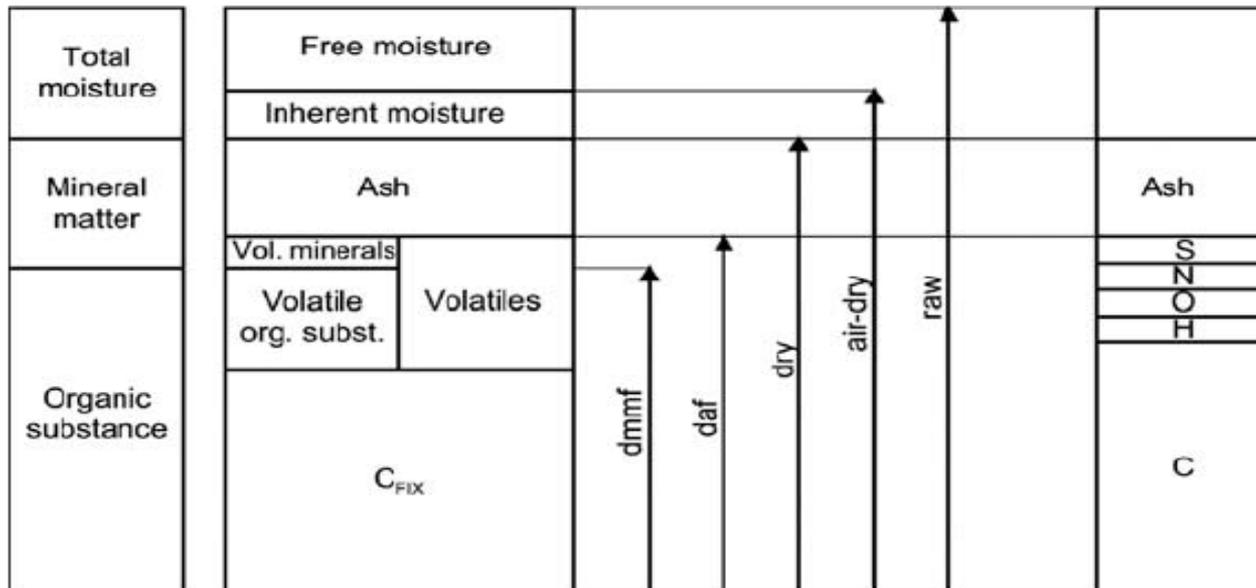
- Coal, Oil and natural gas are called fossil fuels because they are remains of plant and animal life preserved in sedimentary rocks.
- Brown and hard coal - process of partial decomposition under air-deficient condition of plant matter
- The older segments gradually sunk to greater depth - greater pressure and heat resulting into dewatering and compaction.
- Under anaerobic condition the Organic matter underwent a metamorphic process called coalification.
- Further greater depths, higher pressure and rising temperatures - thermal metamorphosis - peat to soft brown coal and eventually to hard brown coal.

## Fossil Fuels: Coal – Its Origin contd.

- In earlier stages of decomposition during coalification the formation of  $H_2O$ ,  $CO_2$  and  $N_2$  predominated. In advanced stages  $CH_4$  was mainly produced.
- Further, due to rising pressure and temperature the moisture and volatile content reduced drastically.
- Thus, as a result of this process, the fraction of solid carbon increased and volatile matter and moisture reduced.
- Hence, the coal stratum which formed earlier have better carbon fraction and lower volatiles & moisture contents. The reverse is true with newer coal stratums.

# Coal Composition and its Importance

- Coal is the mixture of organic material and mineral matter. The organic matter is responsible for the energy content of the fuel while it is the mineral matter that presents significant challenges in the design and operation of power plant.



- daf – Dry Ash Free, dmmf – Dry mineral matter free

# Typical Coal Mineral Components

Mineral	Formula
Clay minerals	
Kaolinite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$
Illite	$\text{K}_2\text{O} \cdot 3(\text{Al, Fe})_2\text{O}_3 \cdot 16\text{SiO} \cdot 4\text{H}_2\text{O}$
Carbonates	
Calcite	$\text{CaCO}_3$
Dolomite	$\text{CaMg}(\text{CO}_3)_2$
Siderite	$\text{FeCO}_3$
$\text{SiO}_2$ group	
Quartz	$\text{SiO}_2$
Chalcedony	$\text{Si} \cdot \text{O}_2$
Sulphides	
Pyrite	$\text{FeS}_2$
Marcasite	$\text{FeS}_2$
Accessory minerals	
Feldspar	$(\text{K, Na})\text{AlSi}_3\text{O}_3$
Apatite	$\text{Ca}_5\text{F}(\text{PO}_4)_3$
Hematite	$\text{Fe}_2\text{O}_3$
Rock salt	$\text{NaCl}$
Rutile	$\text{TiO}_2$

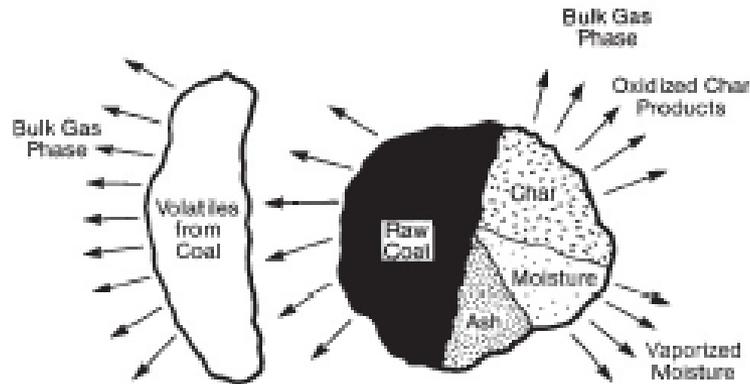
## ▪ Proximate analysis of Coal

The Proximate analysis of coal is an empirical procedure for analysis of coal with following composition:

- a. **Moisture (M)**: The loss of weight when coal is heated in oven at 105 DegC.
- b. **Volatile Combustible Matter (VCM)**: The loss in weight when the coal sample is heated in covered crucible for about 7 minutes at 950 Deg C – wt. of moisture. The VCM contains of complex organic compounds consisting C, H, O, N and S.
- c. **Ash (A)**: The wt. of residue obtained when the sample of coal is subjected to complete combustion in a muffle furnace at 700 – 750 deg C.
- d. **Fixed Carbon**:  $100 - (M + VCM + A)$

The proximate analysis of coal can be done readily and provides with approximate information required for day-to-day planning.

# Coal Combustion Stages



As coal particle enters the furnace its surface temperature increases due to radiative and convective heat transfer. Due to increase of temperature the remaining moisture vaporizes and the char devolatilizes. The volatile products ignites and burns almost immediately (0.1 secs) which further increases the temperature of particle. The char reaction (i.e. carbon burning) prolongs for 1-2 secs depending upon the char reactivity. In general char reactivity lessens with increasing coal rank.

## **Volatile Matter**

- Maintains flame stability and accelerates char burn-out.
- Coals with minimal volatile matter like anthracite are difficult to ignite.
- The heat value of volatile matter depends upon the quality of components. High rank coals have considerable amount of hydrocarbons and high heat value. Whereas, with low rank coals these are predominantly CO and moisture which have lower heat values.
- High VM coal loses its VM on prolonged storage.
- Lower mill outlet temperature to avoid mill fires.

## **Moisture**

- Char burn-outs are depressed by moisture due to reduction in flame temperature.
- The latent heat of vaporization can not be recovered from this.
- Difficulty in coal conveying and grinding.
- The higher rank coals have lesser moisture than lower rank coals.
- Increases the porosity of char particle - penetration of oxygen and hence burning

## **Mineral matter**

- The mineral matter or resulting ash is inert and dilutes coal heating value.
- Based on its composition they slagging and fouling of heating surfaces interfering heat transfer.

## ▪ Ultimate Analysis of Coal

The ultimate analysis of coal gives the composition as percentage by weight of various elements viz. C, H, N, O, S and Ash.

Hydrogen – Hydrogen in moisture + Hydrogen in volatile matter

Carbon – Fixed carbon + Carbon in volatile matter

The ultimate analysis of coal along with the elemental analysis of ash and other information gives all necessary information to the designer for design of various components of Power Plant.

e.g. With help of this heating values of coal can be arrived at and corresponding coal consumption pattern can be understood, which helps in design of Boiler, coal mills, feeders, Coal Handling Plant.

# Coal Characteristic Properties – Heating Value

## ▪ Heating Value of Coal

- The **heating value** (or **energy value** or **calorific value**) of a fuel, is the amount of heat released during the combustion of a specified amount of it.
- The energy value is a characteristic for each substance.
- Measured in units of energy per unit of the substance - kJ/kg, kJ/mol, kcal/kg, Btu/lb.
- Commonly determined by use of a bomb calorimeter.

- Two important heat values of coal - higher heat value (HHV) and Lower heat value (LHV).

## ▪ Higher Heating Value

- (**HHV**) (or *gross energy* or *upper heating value* or *gross calorific value* (**GCV**) or *higher calorific value* (**HCV**)) is determined by bringing all the products of combustion back to the original pre-combustion temperature, and in particular condensing any vapor produced.

## Coal Characteristic Properties – Heating Value

- HHV assumption - all the water component is in liquid state at the end of combustion and heat below 150°C can be put to use.
- Latent heat of vaporization of water in the combustion products also as usable energy.

### ▪ Lower Heating Value

- **LHV** (*net calorific value (NCV)* or *lower calorific value (LCV)*) is determined by subtracting the heat of vaporization of the water vapor from the higher heating value.
- This treats any H<sub>2</sub>O formed as a vapor.
- The energy required to vaporize the water therefore is not released as heat.

## Coal Characteristic Properties contd.

### ▪ **Grindability of Coal**

- An indication of the relative ease with which coal may be pulverised in comparison with coals chosen as reference.
- The hardgrove method by ASTM utilizing Hardgrove machine has been accepted as a Standard. Each hardgrove machine is calibrated by use of standard reference samples of coal with HGI of approximately 40, 60, 80 and 110. The numbers are based on an original soft coal chosen as standard coal sample whose HGI value is 100. The harder the coal the lower the index number.
- The HGI number affects design of coal carrying components viz. Conveyors, Feeders, Coal Mill, Coal Pipe etc.

### ▪ **Swelling Index of Coal –**

- Measure of increase in coal volume when heated in air, with the exclusion of air. This helps in evaluating the coal for combustion.

- The other important aspects of coal are **Bulk Density** and **Particle Size Distribution**.

## Typical Ash Components

### Ash component

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Silica oxide	$\text{SiO}_2$
Aluminium oxide	$\text{Al}_2\text{O}_3$
Iron oxide	$\text{Fe}_2\text{O}_3$
Calcium oxide	$\text{CaO}$
Magnesium oxide	$\text{MgO}$
Sulphur trioxide	$\text{SO}_3$
Phosphoric acid	$\text{P}_2\text{O}_5$
Potassium and sodium oxides	$\text{K}_2\text{O} + \text{Na}_2\text{O}$

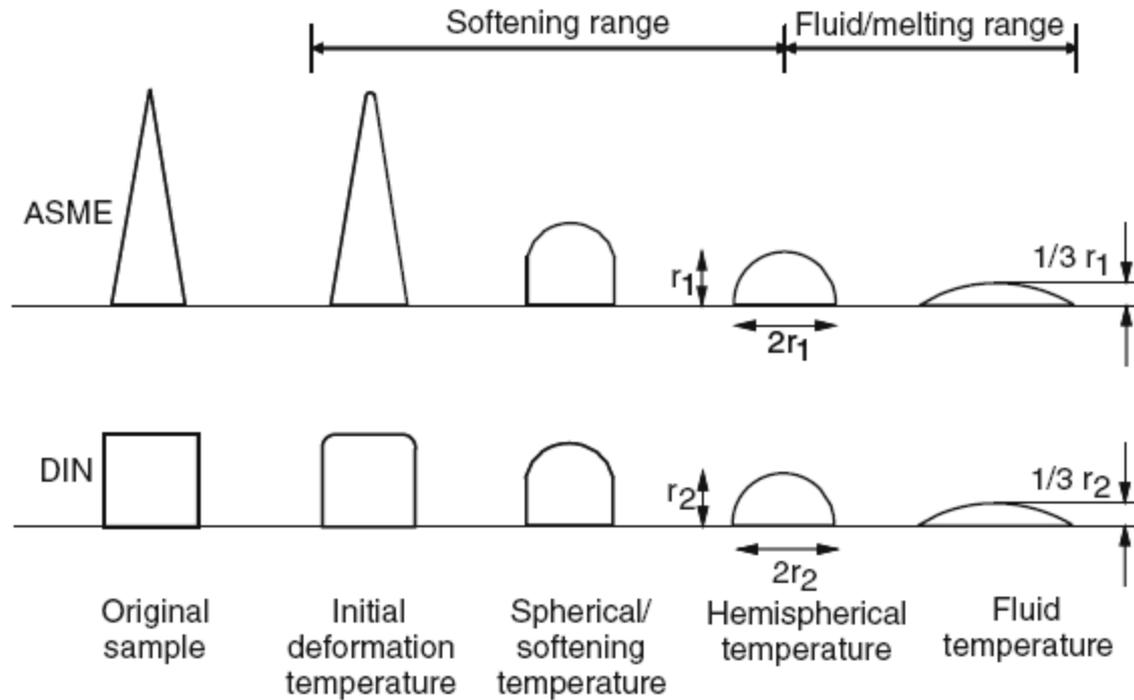
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## Ash Fusion Behavior and its importance

### Ash Fusion Behavior:

- **Initial Deformation Temperature (IDT):** When the first signs of change in form are visible.
  
  - **Spherical or Softening Temperature (ST):** When the sample has deformed to a spherical shape where the height of the sample is equal to the width at the base ( $H=W$ ).
  
  - **Hemispherical Temperature (HT):** When the sample body has changed to hemispherical shape where the height of the sample is equal to one half of the width at the base ( $H=1/2 W$ ).
  
  - **Fluid Temperature (FT):** When the sample body has melted down to a flat layer with a maximum height of about one third of its height at hemispherical temperature.
- 
- Characteristic behavior of ash from different coal sources.
  - They play critical role in ash slagging, fouling and clinkering behavior in Boiler.
  - limiting value to maximum temperature that should be reached in the Boiler furnace. Role in design of soot blowing system.

# Ash Fusion Behavior – Pictorial view



# Fuel Oil Characteristics – HFO Characteristics

## Heavy Fuel Oil Characteristics – IS 1953, Grade HV

Sl. No.	Parameter	Value
1	Total Sulfur content	4.5% (Max.)
2	Gross Calorific value (kcal/kg)	of the order of 11,000
3	Flash Point (Min.)	66 Deg.C
4	Water content by Volume (Max.)	1.00%
5	Sediment by weight (Max.)	0.25%
6	Asphaltene content by weight (Max.)	2.50%
7	Kinematic Viscosity in 370 (Max.) Centistokes	
	at 50 Deg.C	180
	At 98.9 Deg.C	20 - 30
8	Ash Content by weight (Max.)	0.10%
9	Acidity (in inorganic)	Nil
10	Pour Point (Max.)	24 Deg.C (Max.)
11	Vanadium content	25 ppm
12	Specific heat (KCal/KG. Deg.C)	0.5

# Fuel Oil Characteristics – LDO Characteristics

## Light Diesel Oil Characteristics – IS 1460

Sl. No.	Parameter	Value
1	Pour Point (Max.)	12 Deg.C & 18 Deg.C for Summer and Winter respectively
2	Kinematic viscosity in centistokes at 38 Deg.C	2.5 to 15.7
3	Water content, percent by volume (Max.)	0.25
4	Sediment percent by mass (MAX.)	0.1
5	Total Sulfur percent by mass (Max.)	1.8
6	Ash percent by mass (Max.)	0.02
7	Carbon residue (Rans bottom) percent by wt. (Max.)	1.5
8	Acidity in organic	Nil
9	Flash point (Min.) (Pensky Martens) closed cup	66 Deg.C
10	Acidity, total, mg of KOH/g (Max.)	Nil
11	Copper strip corrosion for 3 hours at 100 Deg.C	Not worse than No.2

# Stoichiometry and Excess Air

## ▪ Stoichiometry -

- A branch of chemistry that deals with the relative quantities of reactants and products in chemical reactions.
- For Boiler, the stoichiometry is used to assess the quantity of required air to completely burn the combustibles (Coal/ Oil).
- The combustibles in coal are picked-up from the Ultimate analysis of the coal.
  - Dynamics of Boiler - the theoretical air may result into insufficient burning of coal in various pockets.
  - The coal properties from different sources have different compositions.
  - Thus, an excess air is always maintained over this theoretical/ stiochiometric air to ensure proper combustion.
  - The excess air is measured by excess oxygen in the Flue Gas at Air Preheater inlet and outlet. It is always advisable to maintain the optimum level of excess oxygen in the furnace.
  - Higher excess air than optimum - more Dry Flue Gas loss, Boiler cooling, reduced steam generation, more penalty on auxiliary power consumption, higher erosion in furnace and ducts, increased opacity etc.

## Excess Air – Representation and Interpretation

- The lower excess air than optimum - increased carbon monoxide in the Flue gas, unburnt carbon in fly ash, Second pass combustion etc.
- The excess air is measured by Fuel-Air equivalence ratio. This is defined as

$$\phi = \frac{\text{fuel-to-oxidizer ratio}}{(\text{fuel-to-oxidizer ratio})_{st}} = \frac{m_{fuel}/m_{ox}}{(m_{fuel}/m_{ox})_{st}} = \frac{n_{fuel}/n_{ox}}{(n_{fuel}/n_{ox})_{st}}$$

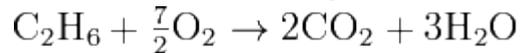
- The ratios greater than one - excess fuel in the fuel–oxidizer mixture (rich mixture).
- The ratios less than one - a deficiency of fuel or equivalently excess oxidizer in the mixture (lean mixture).
- In the boiler controls the excess air/ oxygen is maintained by FD Fans.
- The excess oxygen as measured is compared against the set values, the error if any acts on the blade pitch of the fan to modulate discharge flow of FD fans.

## Excess Air Calculation – An example

### Example

Mixture of one mole of ethane and one mole of oxygen:

Stoichiometric Equation



From the above equation,

Actual molar fuel-air ratio is

$$\frac{n_{\text{C}_2\text{H}_6}}{n_{\text{O}_2}} = \frac{1}{1} = 1$$

Stoichiometric molar fuel-air ratio is

$$(\text{fuel-to-oxidizer ratio based on number of moles})_{st} = \left( \frac{n_{\text{C}_2\text{H}_6}}{n_{\text{O}_2}} \right)_{st} = \frac{1}{3.5} = 0.286$$

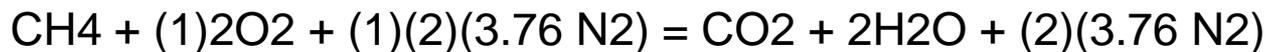
Thus fuel air equivalence ratio is

$$\phi = \frac{n_{\text{C}_2\text{H}_6}/n_{\text{O}_2}}{(n_{\text{C}_2\text{H}_6}/n_{\text{O}_2})_{st}} = \frac{1}{0.286} = 3.5$$

## Excess Air - Excess Oxygen Relationship

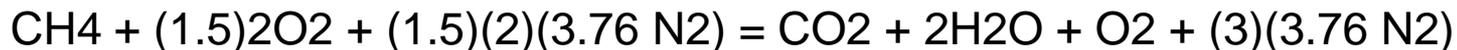
### Excess Air-Oxygen Relationship

The balanced chemical equation for the combustion of methane under stoichiometric condition i.e. 100% theoretical air is:



*(Since air contains 21% O<sub>2</sub> and 79% N<sub>2</sub> by volume, i.e. for one mole of oxygen in air, 3.76 (79/21) moles of N<sub>2</sub> is present.)*

Let us consider 50% excess air is given, the chemical equation for this becomes,



% by volume of oxygen on wet basis (assuming all water vapor is present) in the combustion product,

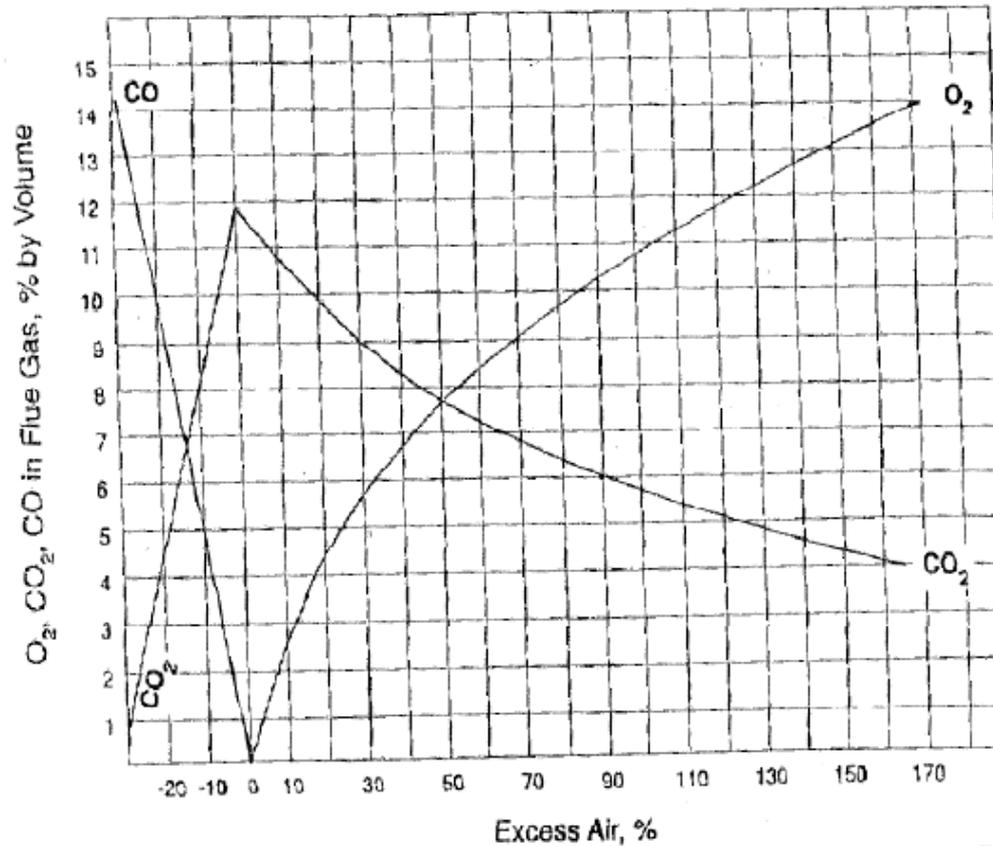
$$= 1/(1 + 2 + 1 + 11.28) * 100 = 6.54\% \text{ (on wet basis)}$$

% by volume of oxygen on dry basis (assuming all water vapor is condensed) in the combustion product,

$$= 1/(1 + 1 + 11.28) * 100 = 7.53\% \text{ (on dry basis)}$$

# Excess Air and Combustion Products – The Empirical Relationship

Figure  $O_2$ ,  $CO_2$ ,  $CO$  versus Excess Air



## Measurements

- **Excess Oxygen only:** For sub-stoichiometric burning the extent of incomplete burning can not be measured.
- **Carbon Dioxide only:** It can not indicate to which side of stoichiometric, combustion is taking place
- **Carbon monoxide only:** For super stoichiometric burning, extent of excess air can not be assessed.
- **Oxygen and Carbon dioxide:** It covers entire range of combustion, but the extent of incomplete combustion can not be measured.
- **Oxygen and Carbon monoxide:** It covers entire range of combustion, and also the extent of incomplete combustion can be measured ***and hence is most favorable combination.***

## Coal Combustion Equipments – Coal Burners

A coal burner shall be rated on following aspects:

1. Flame stability – The burner should introduce PA and coal to the secondary air in a manner that the flame stability is maintained over a range of firing rate.
  2. Emission control of Nox, CO and unburnt carbon
  3. No continuous requirement of burner adjustments
  4. Minor maintenance
  5. Safety
- 
- Fuel-air mixing is the key design aspect to meet the above requirements. Air Fuel mixing can be affected by various means viz. deflectors, bluff bodies and swirl generators.
  - The low NOX emission and CO/ unburnt carbon control are competing features. For proper flame stability intense fuel air mixing is required. This requires higher burner throat velocities. Higher the burner throat velocity, higher the fuel flow rate and hence higher the flame temperature. This results into higher Nox formation.
  - Thus, to contain this the conventional burners have witnessed various modifications over a period of time.

## Coal Burners contd.

- Prior to Nox emission regulations introduced, the primary focus of combustion system development was to permit the design of compact and cost effective boilers.
- As a result the burner systems developed focus on maximizing heat input per unit volume to enable smaller furnace volumes using rapid mixing burners.
- They generated very high temperatures with a side effect of very high NOx emissions.

These include:

- **Conventional Circular Burner:** One of the earliest forms of swirl stabilized burners. It is composed of a central nozzle, equipped with an impeller at tip for radial dispersion, to which PA and PC are supplied. Secondary air is admitted through registers consisting of interlinked circularly distributed doors. The register opening is modulated to provide swirl.
- **The Cell Type Burner:** These burners included two or three circular burners stacked vertically in single unit. While very effective in fuel burning, they have very high Nox emissions.
- **S-type Burner:** The S-type burner has central nozzle similar to the circular burner but with improved SA admission technique through sliding disks near burner barrel and adjustable spin vanes in burner barrel. The air measuring pitot tube before spin vanes measure the SA flow and helps in local adjustments for perfect swirl.

# Coal Burners contd.

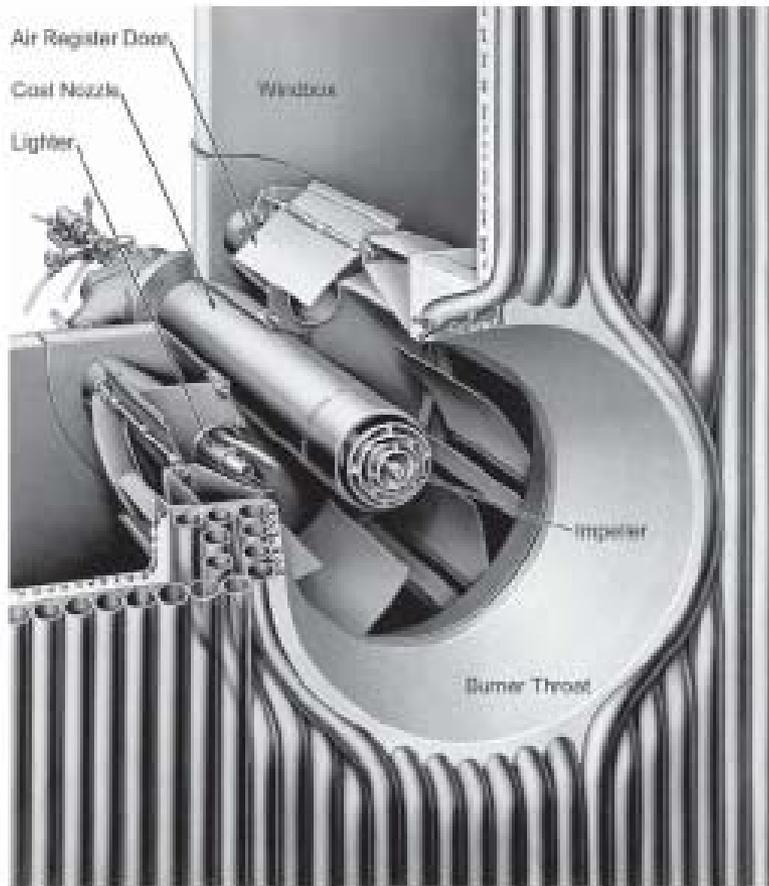
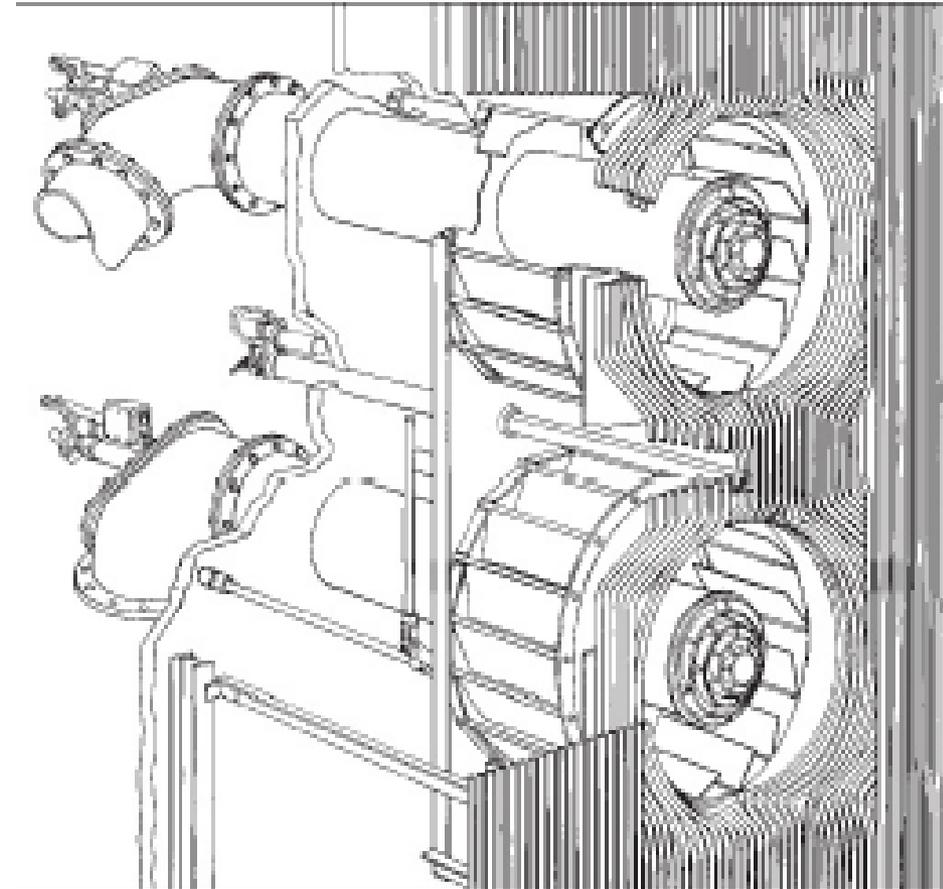


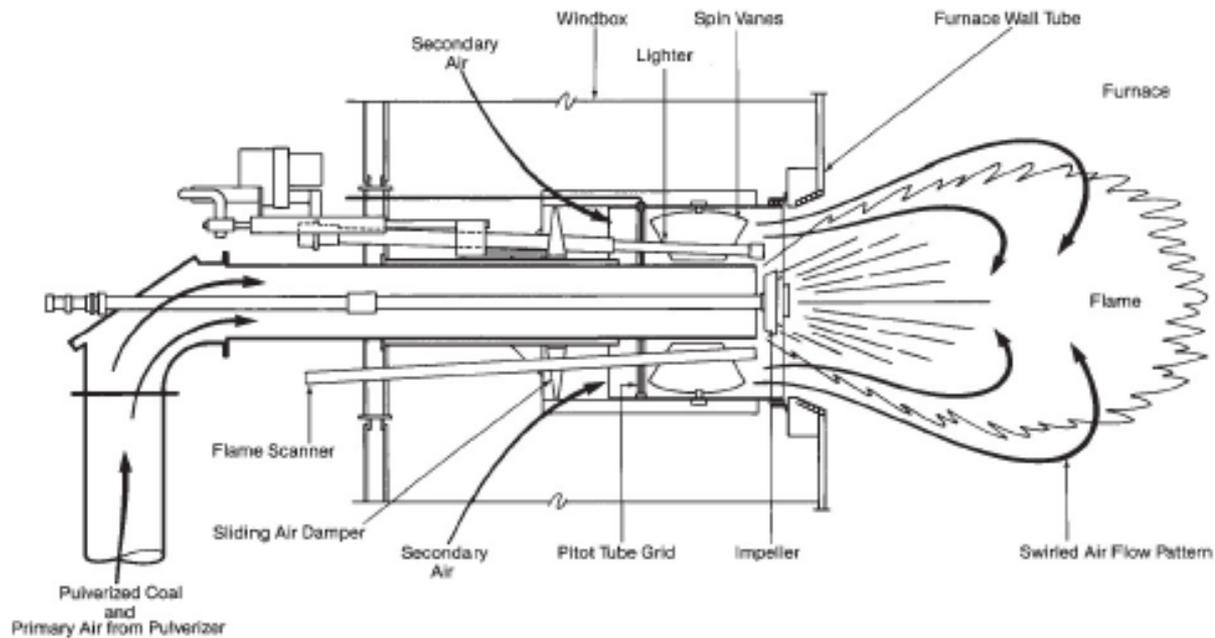
Fig. 6. Conventional circular burner with impeller



Conventional Circular Burner

Cell Type Burner

# Coal Burners contd.



S-Type Burner

## The notorious NOX

- There are seven Oxides of Nitrogen known: Nitrous oxide ( $N_2O$ ), Nitric Oxide ( $NO$ ), Nitrogen dioxide ( $NO_2$ ), Dinitrogen dioxide ( $N_2O_2$ )/ trioxide ( $N_2O_3$ )/ tetraoxide ( $N_2O_4$ )/ pentaoxide ( $N_2O_5$ ).
- Out of them NOX refers to combined emission of Nitric oxide and nitrogen dioxide.
- Nitric oxide in atmosphere is oxidized to nitrogen dioxide. The chemical reaction between the volatile organic compounds and  $NO_2$  in presence of strong sunlight produces ground level ozone which ultimately leads to photochemical smog.
- Further, NOX reacts with water vapor in atmosphere to form nitric acid.
- The NOX formed during conventional PC fired boiler comes from fuel NOX (majority) and thermal NOX (minority).
- Fuel NOX is formed by oxidation of fuel bound nitrogen. The fuel bound nitrogen comes from volatile matter as well as char.

## The notorious NOX

- The volatile matter bound nitrogen has very high conversion efficiency to NOX conversion during devolatilization due to quick release, high flame temperature during process and high oxygen availability.
- Char bound nitrogen has low conversion efficacy due to low oxygen availability during char burnout.
- The remaining is primarily Thermal NOX, which is formed due to conversion of Nitrogen in air to NOX at very high temperature.
- The NOX control hence aims at controlling the conditions which promote NOX formation that is oxygen control and flame temperature reduction.
- The most effective way is to permit a fraction of the air only to mix with coal during devolatilization. The remaining is then mixed downstream in the flame to complete combustion. However, overall air-fuel mixing is reduced to some extent resulting uncombustibles in flue gas.

## The notorious NOX

### ▪ Air Staging –

➤ The second method of reducing oxygen availability is to remove a part of combustion air from the burner and introduce it at some other location, This is done through **Over fired dampers**.

➤ Besides increased unburnt in combustibles, it poses problems of increased corrosion of Boiler tubes. Due to air staging the fuel rich condition exists in furnace zone. Thus, SO<sub>2</sub> % by volume in FG increases and hence sulfonation chances. They also tend to reduce flame temperature and hence thermal NOX formation.

### ▪ Reburning or Fuel staging –

➤ it intends to destroy NOX after it has formed by introduction of fuel in stages.

➤ The bulk of fuel is injected in the furnace near stoichiometric condition and the balance with limited air in reducing condition.

➤ The reducing condition form hydrocarbon radicals which strip the oxygen from NOX thereby reducing NOX emissions. These are costlier and more complicated than other designs.

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