Part II. Energy Efficiency by Sectors

Fuels Characteristics and Combustion Principles

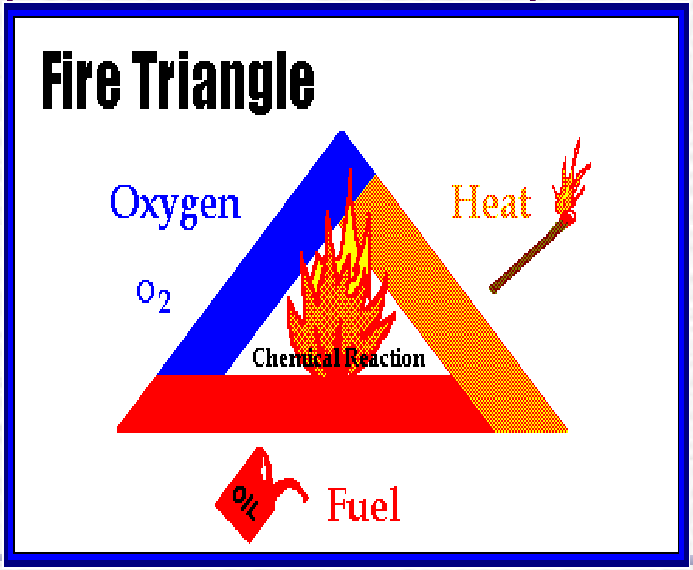
Prepared by: Assoc. Prof. Sengratry KYTHAVONE
Department of Mechanical Engineering, Faculty of Engineering
National University of Laos

What is Combustion?

Combustion is chemistry reaction between fuel and oxygen, and resultant it released heat energy .

Three things must be present at the same time in order to produce fire:

- Enough oxygen to provide combustion,
- Enough heat to raise the material temperature to its ignition temperature,
- Fuel or combustible material which produces high exothermic reaction to propagate heat to not-yet- burnt material nearby.



Fuels

Solid Fuels:
Coal, Fuel Wood, Charcoal, Rice Husk etc.,

Liquid Fuels:
Fuel Oil, Gasoline, Diesel oil, bio fuel etc.,

Gaseous Fuels:
LPG, Natural gas, Biogas, Producer Gas etc.,

Characteristics of a good fuel :

The main characteristics of a good fuel are :

i) Is readily available.

ii) Is cheap.

iii) Is easy to store and transport.

iv) Burns at a moderate rate.

v) Produces a large amount of heat.

vi) Does not leave behind any undesirable substances.

vii) Does not cause pollution.

Important Properties of Fuels

- **Density**
- **Specific gravity**
- **Viscosity**
- **Flash Point**
- **Pour Point**
- **Specific Heat**
- **Calorific Value**
- **Sulphur**
- **Ash Content**
- **Carbon Residue**
- **Water Content**

Fuels

- Properties of Selected Fuels

	CH_4	C_2H_6	C_3H_8	Other HCs	H_2S	Heating Value
			(wt%)			(10^6 J/m^3)
Natural gas (No.1)	87.7	5.6	2.4	1.8	2.7	43.2
Natural gas (No.2)	88.8	6.4	2.7	2.0	0.0004	41.9

(Ultimate analysis)	C	H	N	O	S	Heating value
			(wt%)			(10^6 J kg^{-1})
Gasoline (No.2)	86.4	12.7	0.1	0.1	0.4-0.7	

(Approximate analysis)	Carbon (%)	Volatile matter (%)	Moisture (%)	Ash (%)	Heating value (10^6 J kg^{-1})
Anthracite	77.1	3.8	5.4	13.7	27.8
Bituminous	70.0	20.5	3.3	6.2	33.3
Sub bituminous	45.9	30.5	19.6	4.0	23.6
Lignite	30.8	28.2	34.8	6.2	16.8

Important properties of fuel oil

Properties	Fuel Oils		
	Furnace Oil	LS.H.S.	L.D.O.
Density (Approx. kg/litre at 15^0C)	0.89-0.95	0.88-0.98	0.85-0.87
Flash Point (^{0}C)	66	93	66
Pour Point (^{0}C)	20	72	18
G.C.V. (Kcal/kg)	10,500	10,600	10,700
Sediment, % Wt. Max.	0.25	0.25	0.1
Sulphur Total, % Wt. Max.	Upto 4.0	Upto 0.5	Upto 1.8
Water Content, % Vol. Max.	1.0	1.0	0.25

Chemical Properties

Ultimate Analysis

Typical Ultimate Analyses of Coals

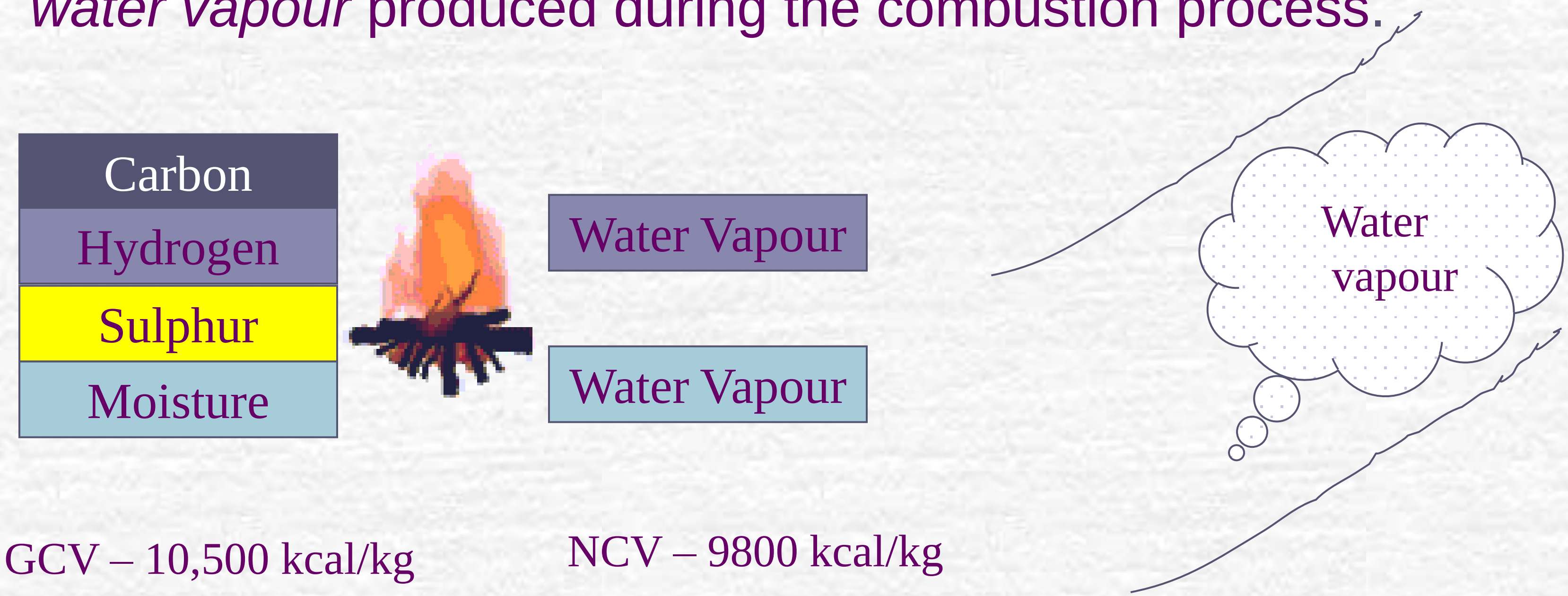
Parameter	Indian Coal, %	Indonesian Coal, %
Moisture	5.98	9.43
Mineral Matter (1.1 x Ash)	38.63	13.99
Carbon	41.11	58.96
Hydrogen	2.76	4.16
Nitrogen	1.22	1.02
Sulphur	0.41	0.56
Oxygen	9.89	11.88

Properties of Agro-Residues

Ultimate Analysis of Typical Agro Residues				
	Deoiled Bran	Paddy Husk	Saw Dust	Coconut Shell
Moisture	7.11	10.79	37.98	13.95
Mineral Matter	19.77	16.73	1.63	3.52
Carbon	36.59	33.95	48.55	44.95
Hydrogen	4.15	5.01	6.99	4.99
Nitrogen	0.82	0.91	0.80	0.56
Sulphur	0.54	0.09	0.10	0.08
Oxygen	31.02	32.52	41.93	31.94
GCV (kcal/kg)	3151	3568	4801	4565

Calorific Value

- The calorific value is the measurement of heat or energy produced, and is measured either as gross calorific value or net calorific value.
- The difference being the *latent heat of condensation of the water vapour* produced during the combustion process.



- The calorific value of a fuel :- is the amount of heat energy produced on complete combustion of 1 kg of a fuel.
- Calorific values of some fuels in kilo Joule per kg

Cow dung cake	6000 - 8000
Wood	17000 - 22000
Coal	25000 - 33000
Petrol	45000
Kerosene	45000
Diesel	45000
Methane	50000
CNG	50000
LPG	55000
Biogas	35000 - 40000
Hydrogen	150000

- Hydrogen has the highest calorific value among all fuels.

Handling of fuel oil

- Storage of Fuel oil
- Removal of Contaminants
- Pumping
- Storage Temperature and Pumping Temperature
- Temperature Control

Physical properties

- Heating Value
- Analysis of Coal
  - ultimate analysis
  - proximate analysis

Combustion

$$C + O_2 \rightarrow CO_2 \quad + \ 8084 \text{ kCals/kg of Carbon}$$

$$2C + O_2 \rightarrow 2\,CO \quad + \ 2430 \text{ kCals/kg of Carbon}$$

$$2H_2 + O_2 \rightarrow 2H_2O \quad + \ 28{,}922 \text{ kCals/kg of Hydrogen}$$

$$S + O_2 \rightarrow SO_2 \quad + \ 2{,}224 \text{ kCals/kg of Sulphur}$$

3 Ts of Combustion

TIME

All combustion requires sufficient Time which depends upon type of Reaction

TEMPERATURE

Temperature must be more than ignition temperature

TURBULENCE

Proper turbulence helps in bringing the fuel and air in intimate contact and gives them enough time to complete reaction.

There are four important factors that control combustion boiler furnace:

1. Air supply- Need adequate air for complete combustion.

➢ The rating (capacity) of a boiler can be increased by supplying additional air (think of the effect of bellows on a small fire).

➢ Too much air can result in excessive stack losses.

2. Mixing of fuel and air- fuel and air molecules must be brought into close proximity in order for combustion to occur.

➢ The larger the fuel "particles" the greater the difficulty in achieving good mixing-

- easiest for gaseous fuels,
- more difficult for liquid fuels and pulverized solids,
- most difficult for stoker coal, bark or large trash clumps.

Factors for combustion

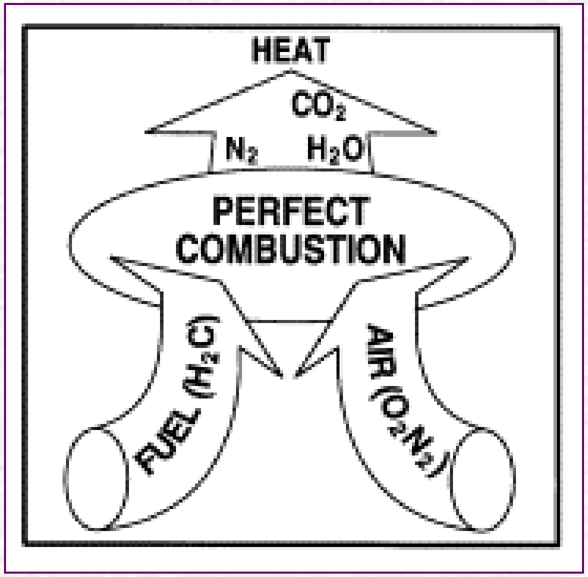
3. Temperature- all combustion reactions proceed exponentially more rapidly with increasing T

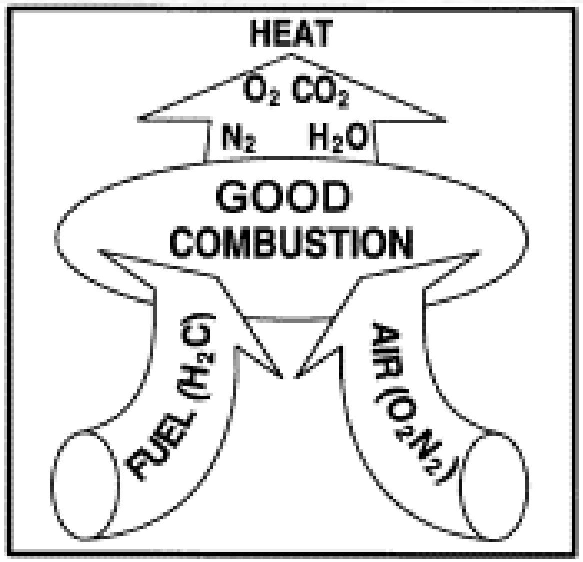
- Temperatures too low:
  - incomplete combustion, waste fuel
  - unburned hydrocarbons and soot emissions greatly increased
- Temperatures too high:
  - equipment failure, metal strength drops off quickly at high T
  - NOx emissions greatly increased.

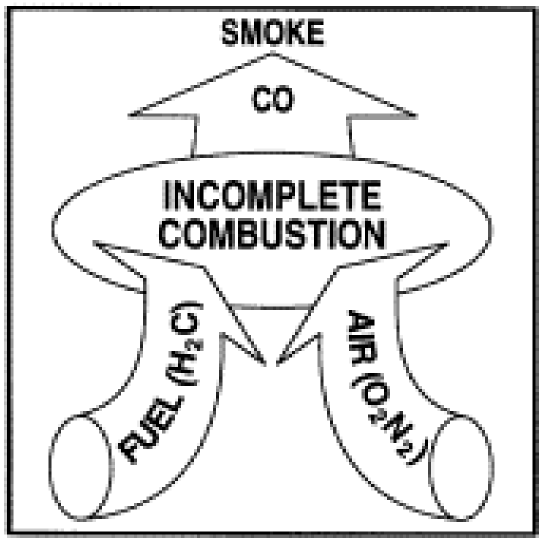
4. Combustion time- fuel "particles" must be given sufficient time (***residence time) in the furnace to*** achieve complete combustion.

- Like fuel/air mixing, the required residence time is least for gases and most for large solid fuels:
  - Gases and fine liquid sprays- 10 - 20 ms burnout
  - Pulverized fuel (coal, sawdust)- 1 s burnout
  - Stoker coal, bark, wood waste, trash- 10’s of minutes

Air for combustion







Stoichiometric Combustion

- The amount of air required for complete combustion of the fuel depends on the elemental constituents of the fuel that is Carbon, Hydrogen, and Sulphur etc. This amount of air is called stoichiometric air

The Specification of furnace oil listed in the table below:

Constituents	% By weight
Carbon	84
Hydrogen	6
Oxygen	7
Nitrogen	1.2
Sulphur	1.4
H_2O`	0.35
Ash	0.05

GCVof fuel: 10,880 kCal/kg

Solution

Step-1: Find the theoretical air requirement

$$[(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)]/100$$

= kg/kg of oil

=[(11.6 x 84) + [{34.8 x (6 – 7/8)} + (4.35 x 1.4)]/100 kg/kg of oil = 14 kg of air/kg of oil

Step-2: Find the %Excess air supplied

Excess air supplied (EA) = $\frac{O_2\%}{21 - O_2\%} \times 100 = \frac{7\%}{21\% - 7\%} \times 100$ = 50%

Step-3: Find the Actual mass of air supplied

Actual mass of air supplied /kg of fuel = [1 + EA/100] x Theoretical Air (AAS)

= [1 + 50/100] x 14

= 1.5 x 14

= 21 kg of air/kg of oil

Formula in the Table for Calculation of Actual Mass of Supplied Air for Combustion

a) Theoretical air required for combustion	=	$[(11.6 x C) + \{34.8 x (H_2 - O_2/8)\} + (4.35 x S)]/100$ kg/kg of fuel. [from fuel analysis]
		Where C, H_2, O_2 and S are the percentage of carbon, hydrogen, oxygen and sulphur present in the fuel.
b) % Excess Air supplied (EA)	=	$\frac{O_2\%}{21 - O_{2\%}} x100$ [from flue gas analysis]
		Normally O_2 measurement is recommended. If O_2 measurement is not available, use CO_2 measurement
		$\frac{7900 x [(CO_2\%)_t - (CO_2\%)_a]}{(CO_2)_a\% \; x [100 - (CO_2\%)_t]}$ [from flue gas analysis]
Where, $(CO_2\%)_t$	=	Theoretical CO_2
$(CO_2\%)_a$	=	Actual CO_2% measured in flue gas
$(CO_2)_t$	=	$\frac{Moles\ of\ C}{Moles\ of\ N_2 + Moles\ of\ C}$
Moles of N_2	=	$\frac{Wt\ of\ N_2\ in\ theoritical\ air}{Mol.wt\ of\ N_2} + \frac{Wt\ of\ N_2\ in\ fuel}{Mol.Wt\ of\ N_2}$
Moles of C	=	$\frac{Wt\ of\ C\ in\ fuel}{Molecular\ Wt\ of\ C}$
c) Actual mass of air supplied/ kg of fuel (AAS)	=	{1 + EA/100} x theoretical air

Conversion formula for proximate analysis to ultimate analysis

$\%C = 0.97C + 0.7\ (VM + 0.1A) - M(0.6 - 0.01M)$

$\%H_2 = 0.036C + 0.086\ (VM - 0.1xA) - 0.0035M^2\ (1 - 0.02M)$

$\%N_2 = 2.10 - 0.020\ VM$

where C = % of fixed carbon
A = % of ash
VM = % of volatile matter
M = % of moisture

Table for calculation amount of air for combustion

No	Factors	Formula	Units	Amount
1	Carbon(C)		% by mass	
2	Hydrogen(H)		% by mass	
3	Oxygen(O_4)		% by mass	
4	Nitrogen		% by mass	
5	Sulphur		% by mass	
6	Water		% by mass	
7	Ash		% by mass	
8	Heating Value GCV of Fuel		kCal/kg	
9	Oxygen required for burning Carbon(O_1)	C x(32/12)	kg/100 kg of Fuel	
10	Oxygen required for burning Hydrogen(O_2)	H x(32/4)	kg/100 kg of Fuel	
11	Oxygen required for burning Sulphur(O_3)	S x(32/32)	kg/100 kg of Fuel	
12	Total Oxygen required (O)	$+O_1 + O_2 + O_3 - O_4$	kg/100 kg of Fuel	
13	Mass of air required(S.A)	O/0.23	kg/100 kg of Fuel	
14	Excess Air(E.A)		%	
15	Actual mass of air	S.A x(1+E.A/100)	kg/100 kg of Fuel	

Opportunities for energy efficiency of combustion

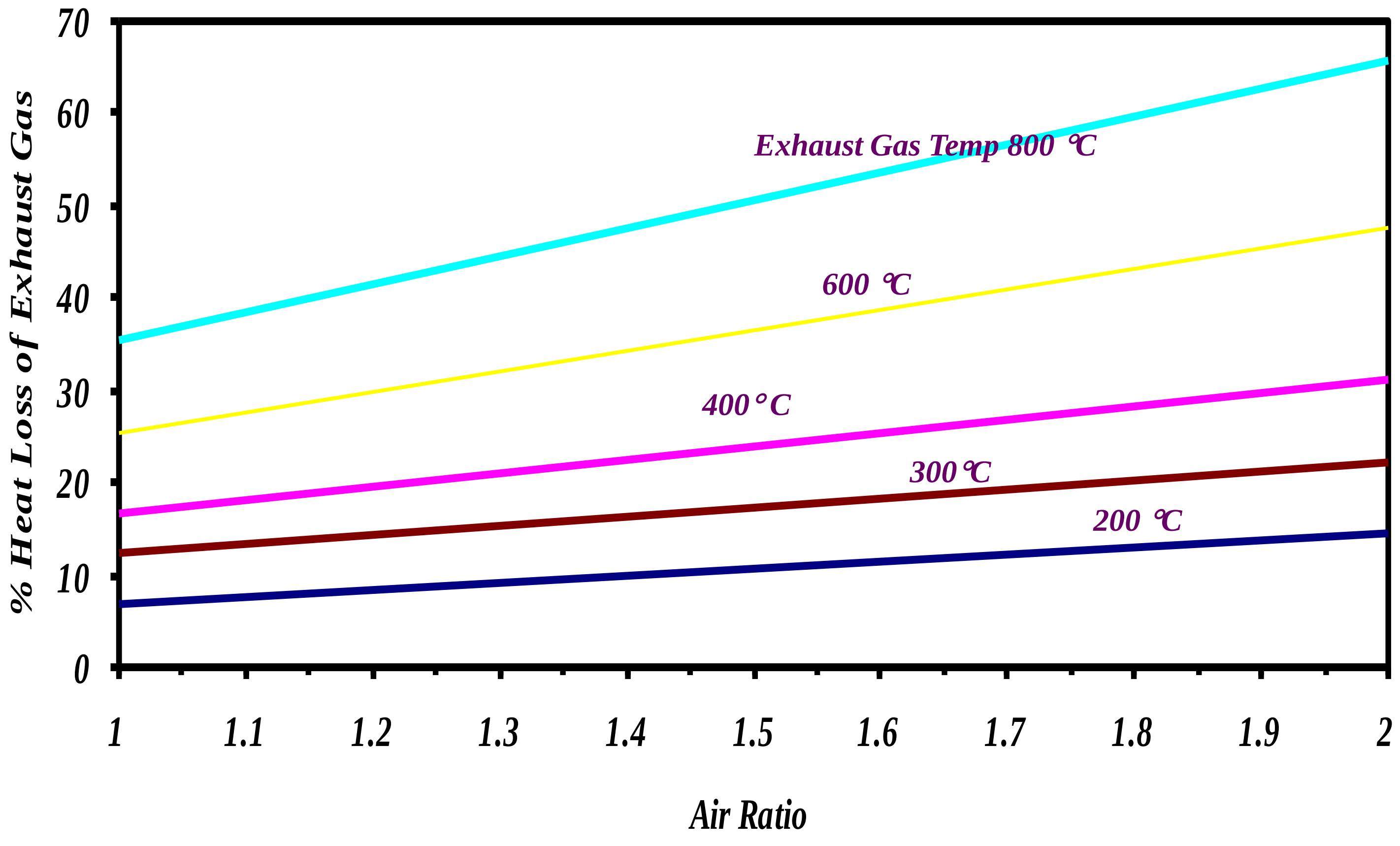
Optimizing Excess Air for Combustion:

- In practice, mixing is never perfect, a certain amount of excess air is needed to complete combustion and ensure that release of the entire heat contained in fuel oil.
- If too much air than what is required for completing combustion were allowed to enter, additional heat would be lost in heating the surplus air to the chimney temperature. This would result in increased stack losses.
- Less air would lead to the incomplete combustion and smoke. Hence, there is an optimum excess air level for each type of fuel.

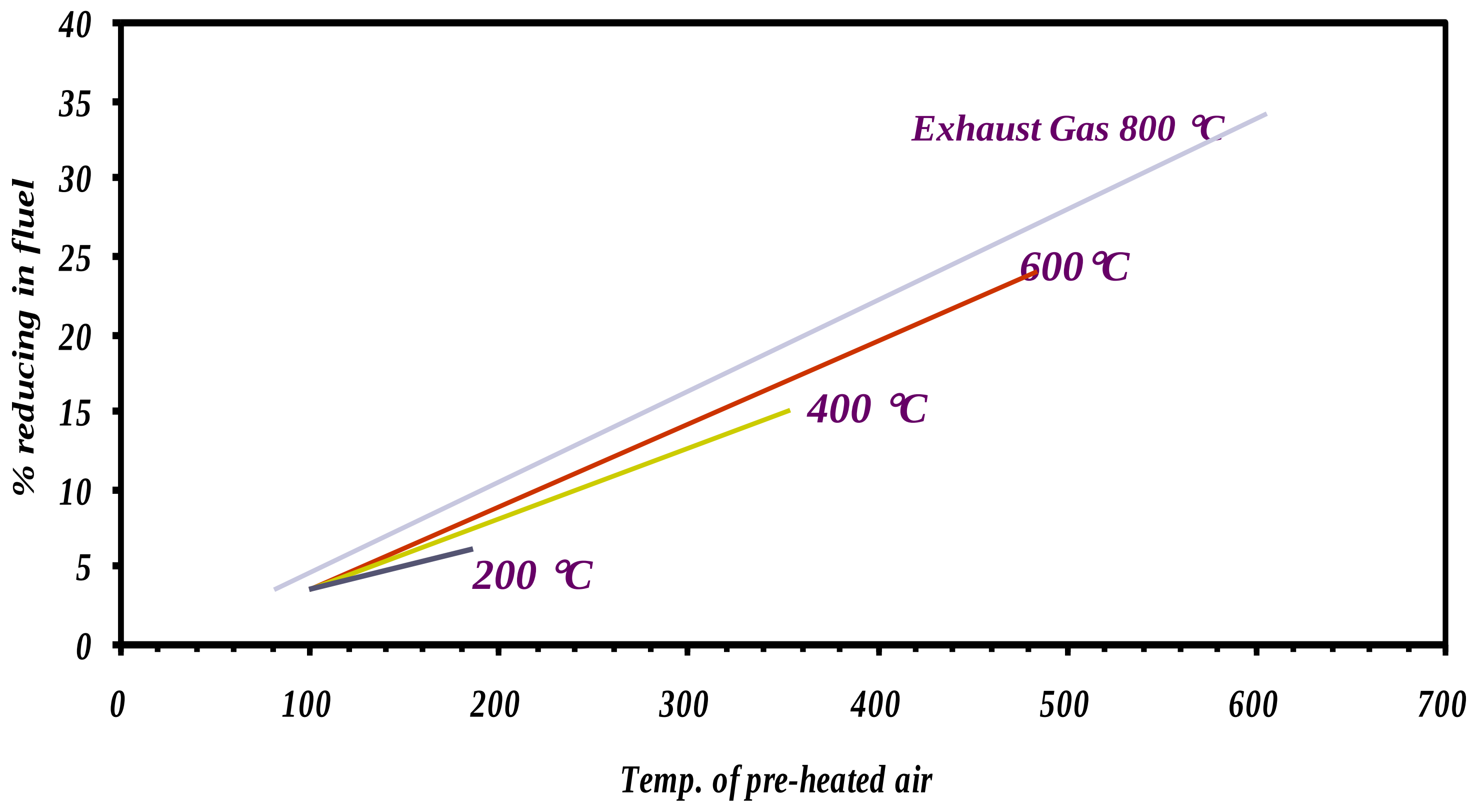
Control of Air and Analysis of Flue Gas

- By measuring carbon dioxide (CO_2) or oxygen (O_2) in flue gases by continuous recording instruments or Orsat apparatus or portable fyrite, the excess air level as well as stack losses can be estimated
- The excess air to be supplied depends on the type of fuel and the firing system.
- For optimum combustion of fuel oil, the CO_2 or O_2 in flue gases should be maintained at 14 -15% in case of CO_2 and 2-3% in case of O_2

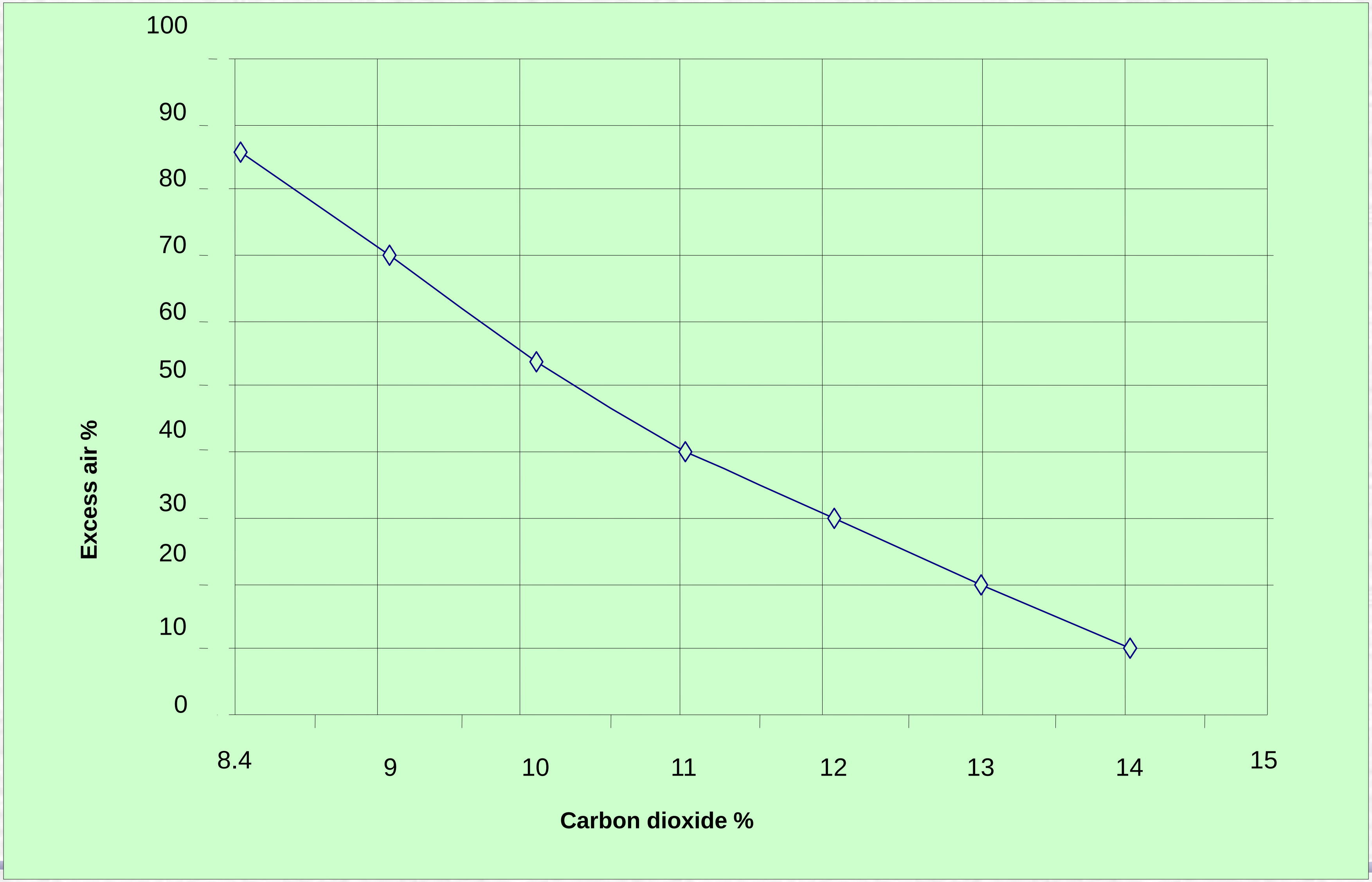
Flue gas heat loss



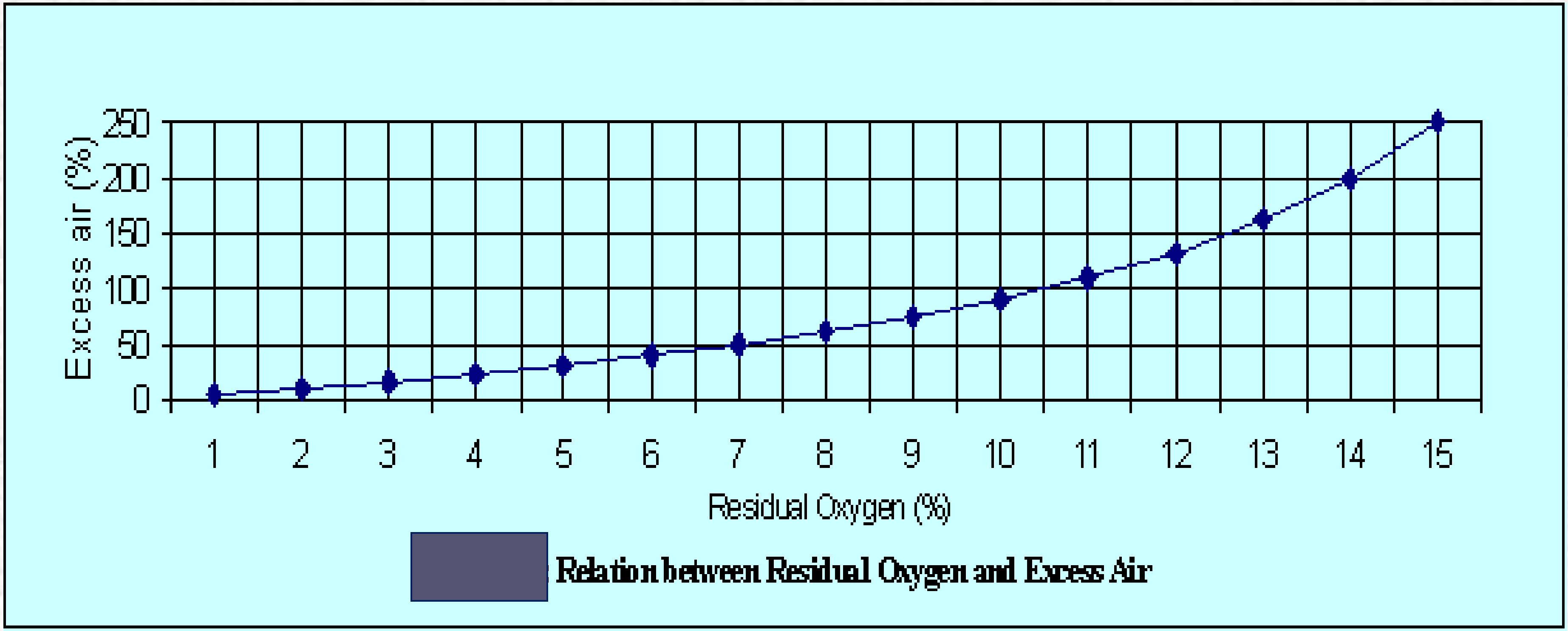
Percentages in fuel reduction VS temp. of preheat air



Relation Between CO_2 and Excess Air for Fuel Oil



Oxygen vs Excess Air



Usual Amount of Excess Air Supplied to Fuel-Burning Equipment

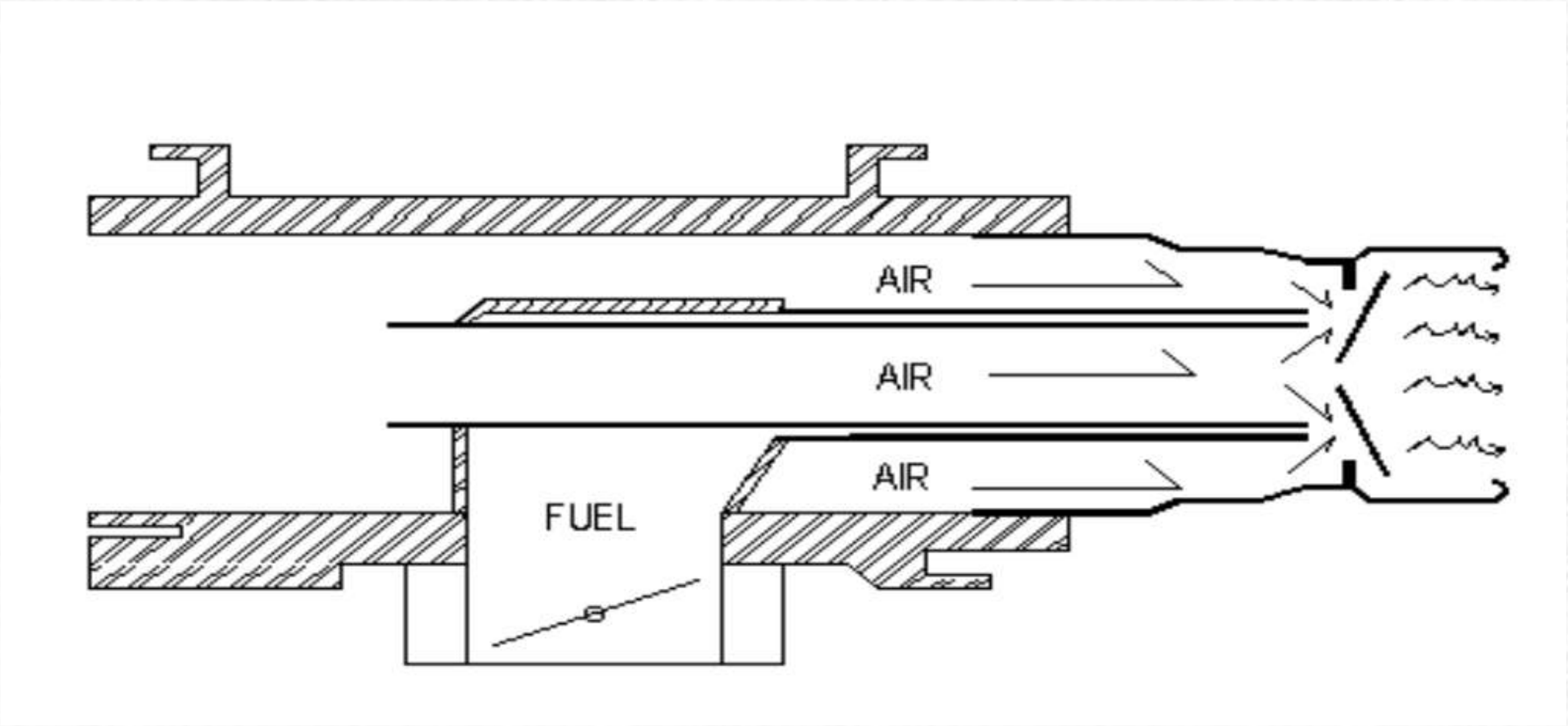
Fuel	Type of Furnace or Burners	Excess Air, % by Weight
Pulverized coal	Completely water-cooled furnace for slag-tap or dry-ash-removal	15–20
	Partially water-cooled furnace for dry-ash-removal	15–40
Crushed coal	Cyclone furnace—pressure or suction	10–15
Coal	Spreader stoker	30–60
	Water-cooled vibrating grate stoker	30–60
	Chain-grate and traveling-grate stokers	15–50
	Underfeed stoker	20–50
Fuel oil	Oil burners, register type	5–10
	Multifuel burners and flat-flame	10–20
Acid sludge	Cone and flat-flame-type burners, steam-atomized	10–15
Natural, coke-oven, and refinery gas	Register-type burners	5–10
	Multifuel burners	7–12
Blast-furnace gas	Intertube nozzle-type burners	15–18
Wood	Dutch oven (10–23% through grates) and Hofft-type	20–25
Bagasse	All furnaces	25–35
Black liquor	Recovery furnaces for kraft and soda-pulping processes	5–7

Courtesy of Babcock and Wilcox Co.

Oil Firing Burners

- The burner is the principal device for the firing of fuel.
- The primary function of burner is to atomize fuel to millions of small droplets so that the surface area of the fuel is increased enabling intimate contact with oxygen in air.
- The finer the fuel droplets are atomized, more readily will the particles come in contact with the oxygen in the air and burn.
- Normally, atomization is carried out by primary air and completion of combustion is ensured by secondary air.
- Burners for fuel oil can be classified on the basis of the technique to prepare the fuel for burning i.e. atomization.

Oil Firing Burners



Turndown Ratio

- Turndown ratio is the relationship between the maximum and minimum fuel input without affecting the excess air level.
- For example, a burner whose maximum input is 250,000 Kcals and minimum rate is 50,000 kcals, has a ‘Turn-Down Ratio’ of 5 to 1
- Since the velocity of air affects the turbulence, it becomes harder and harder to get good fuel and air mixing at higher turndown ratios since the air amount is reduced.
- Towards the highest turndown ratios of any burner, it becomes necessary to increase the excess air amounts to obtain enough turbulence to get proper mixing. <u>The better burner design will be one that is able to properly mix the air and fuel at the lowest possible air flow or excess air</u>

Combustion of Coal

- Excess air required for coal combustion depends on the type of coal firing equipment
- Hand fired boilers use large lumps of coal and hence need very high excess air.
- Stoker fired boilers use sized coal and hence require less excess air. Also in these systems primary air is supplied below the grate and secondary air is supplied over the grate to ensure complete combustion.
- Fluidized bed combustion in which turbulence is created leads to intimate mixing of air and fuel resulting in further reduction of excess air.
- The pulverized fuel firing in which powdered coal is fired has the minimum excess air due to high surface area of coal ensuring complete combustion.

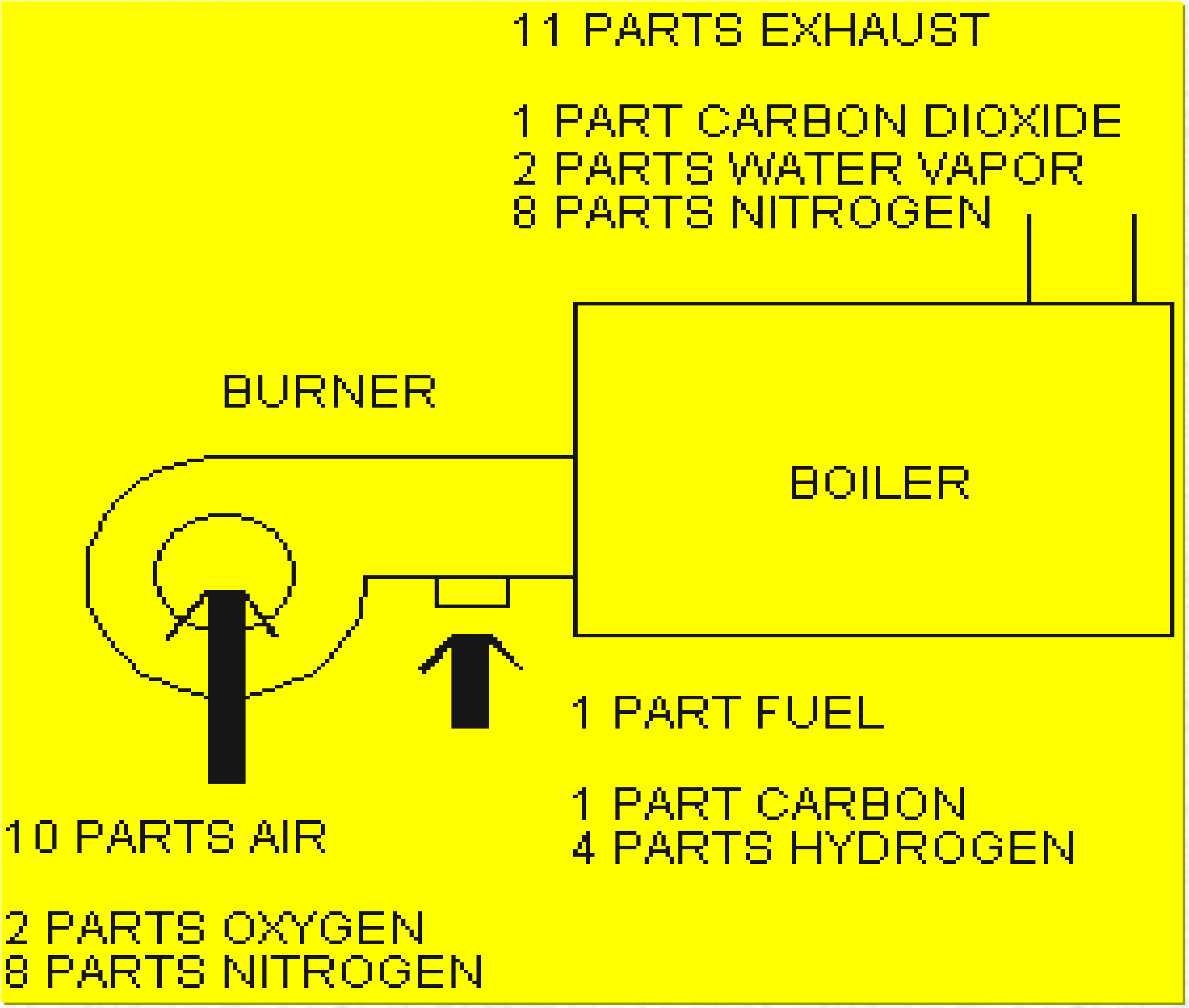
Clinker Formation

- Clinker is a mass of rough, hard, slag-like material formed during combustion of coal due to low fusion temperature of ash present in coal.
- Presence of silica, calcium oxide, magnesium oxides etc. in ash lead to a low fusion temperature.
- Typically Indian coals contain ash fusion temperature as low as $1100^{o}C$.
- Once clinker is formed, it has a tendency to grow. Clinker will stick to a hot surface rather than a cold one and to a rough surface rather than a smooth one.

Combustion of Gas

- The stoichiometric ratio for natural gas (and most gaseous fuels) is normally indicated by volume.
- The air to natural gas (stoichiometric) ratio by volume for complete combustion vary between 9.5:1 to 10:1
- Natural gas is essentially pure methane, CH4. Its combustion can be represented as follows:
  - $CH_4 + 2O_2 = CO_2 + 2H_2O$
- So for every 16 kgs of methane that are consumed, 44 kgs of carbon dioxide are produced.

Natural Gas Combustion



Draft

- Natural Draft
  - It is the draft produced by a chimney alone. It is caused by the difference in weight between the column of hot gas inside the chimney and column of outside air of the same height and cross section
- Balanced Draft
  - Forced-draft (F-D) fan (blower) pushes air into the furnace and an induced-draft (I-D) fan draws gases into the chimney thereby providing draft to remove the gases from the boiler
- Induced Draft
  - An induced-draft fan draws enough draft for flow into the furnace, causing the products of combustion to discharge to atmosphere
- Forced Draft
  - The Forced draft system uses a fan to deliver the air to the furnace, forcing combustion products to flow through the unit and up the stack

Combustion Control

- On/Off Control
  - The simplest control, ON/OFF control means that either the burner is firing at full rate or it is OFF. This type of control is limited to small boilers
- High/Low/Off Control
  - The burner operates at slower firing rate and then switches to full firing as needed. Burner can also revert to low firing position at reduced load. This control is fitted to medium sized boilers
- Modulating Control
  - The modulating control operates on the principle of matching the steam pressure demand by altering the firing rate over the entire operating range of the boiler

Air Pollutants from Combustion

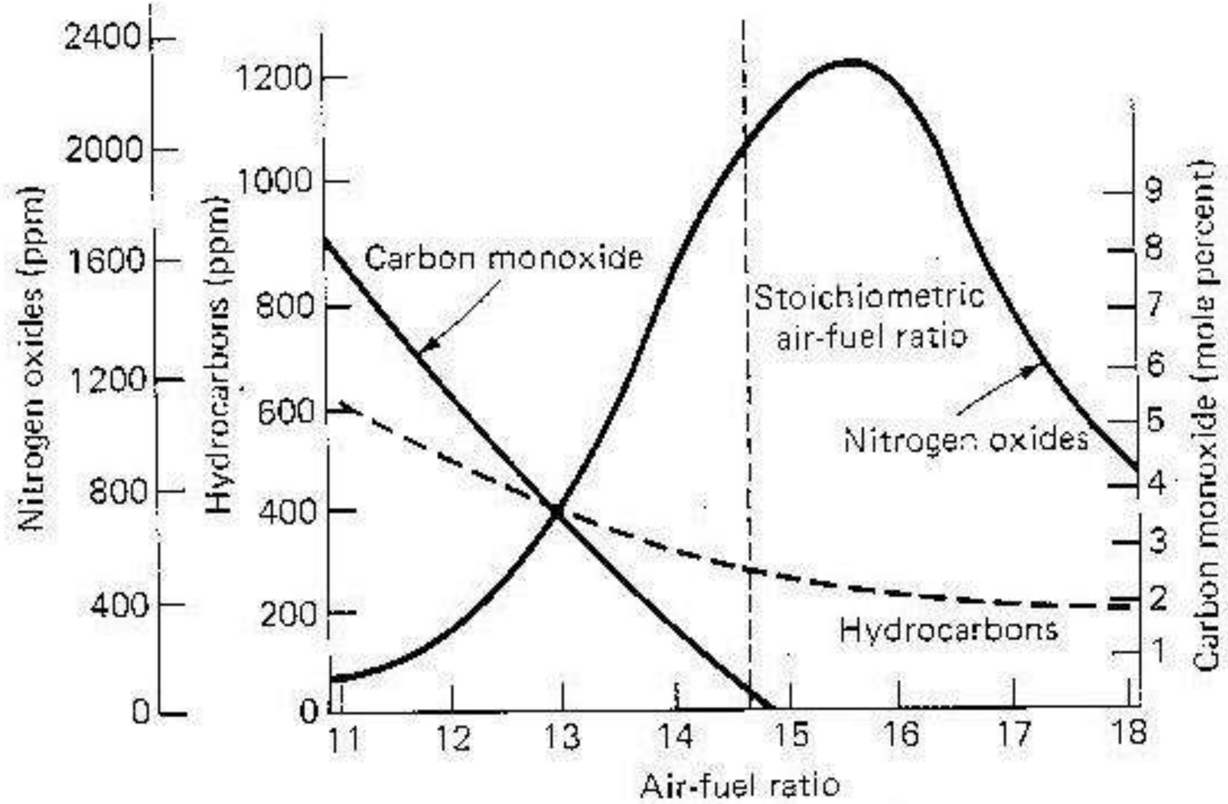


Figure 3.6. Exhaust hydrocarbons, carbon monoxide, and nitric oxide as a function of air–fuel ratio.

Source: Seinfeld, J. Atmospheric Chemistry and Physics of Air Pollution.

Harmful effects on the environment due to burning of fuels :

i) Fuels like wood, coal, petroleum release unburnt carbon particles which cause respiratory diseases like asthma.

ii) Incomplete combustion of fuels release carbon monoxide gas which is a very poisonous gas which can cause death.

iii) Burning of most fuels release carbon dioxide gas which causes rise in the temperature of the atmosphere. This is called global warming. It causes melting of polar ice, rise in sea level and flooding of coastal areas.

iv) Burning of coal and petroleum release oxides of sulphur and nitrogen which dissolve in rain water and forms acid rain. It is harmful for crops, soil and damages buildings.