
Combustion_Fundamentals

Biomass_Combustion

CONTENTS

- Solid Fuels
- Thermo-chemical Reactions
- Effect of raising temp. described
- Comparison of coal & wood as fuel
- Excess air, Efficiency and Turn-down
- Proximate & Ultimate Analysis, HHV
- Chemical composition
- Furnace Design Calculations

Solid fuels

Fossil fuels:

- Coal (moisture, volatiles, fixed carbon, ash)
($\text{CH}_{0.8}$)
- Coke (devolatilized coal or petroleum)

Biofuels:

- Wood (moisture, volatiles, fixed carbon, ash)
- Charcoal (devolatilized wood)
- Key difference among fuels: the quantity of CO_2 formed per unit of energy released. Natural gas releases $\sim 42\%$ less CO_2 than coal

Chemical equilibrium constant are calculated for following 6 equations. Eq. No.3 & 4 is called as Water Gas Reaction. Eq. No.5 is called Methane Formation Reaction. Eq. No.6 is called as Shift Reaction

Chemical Equations	ΔH_0	ΔS_0	Equation No.
$C + O_2 = CO_2$	-94,200	206	1
$2C + O_2 = 2CO$	-53,300	45.54	2
$C + H_2O = CO + H_2$	+31,230	33.41	3
$C + 2H_2O = CO_2 + H_2$	+21,560	-7.89	4
$CO + 3H_2 = CH_4 + H_2O$	-49,300	6.51	5
$CO + H_2O = CO_2 + H_2$	-9,670	-10.07	6

Combustion-

PROCESS DESCRIPTION-1

- Combustion refers to rapid oxidation. The feedstock is placed into a combustion chamber, where it is exposed to high heat. This completes the drying of the feedstock.
- Once all of the water has been evaporated, the feedstock can become hot enough for pyrolysis to occur. (In plant matter, this is 440°F-620°F for hemicellulose and 480°F-930°F for lignin.)

PROCESS DESCRIPTION-2

- Pyrolysis refers to the chemical breakdown of the feedstock, and the primary reactions such as volatile compounds like carbon monoxide, carbon dioxide, methane and tar.
- The release of volatile gases inhibits further combustion because they prevent necessary oxygen from reaching the feedstock.

PROCESS DESCRIPTION-3

- When completely pyrolyzed, what remains of the feedstock is known as char. Given sufficient oxygen, oxidation of both the char and the volatile gases will occur.
- The oxidation of the gases is referred to as flaming combustion, and only carbon dioxide and water will remain if the process is given enough heat, turbulence and residence time.

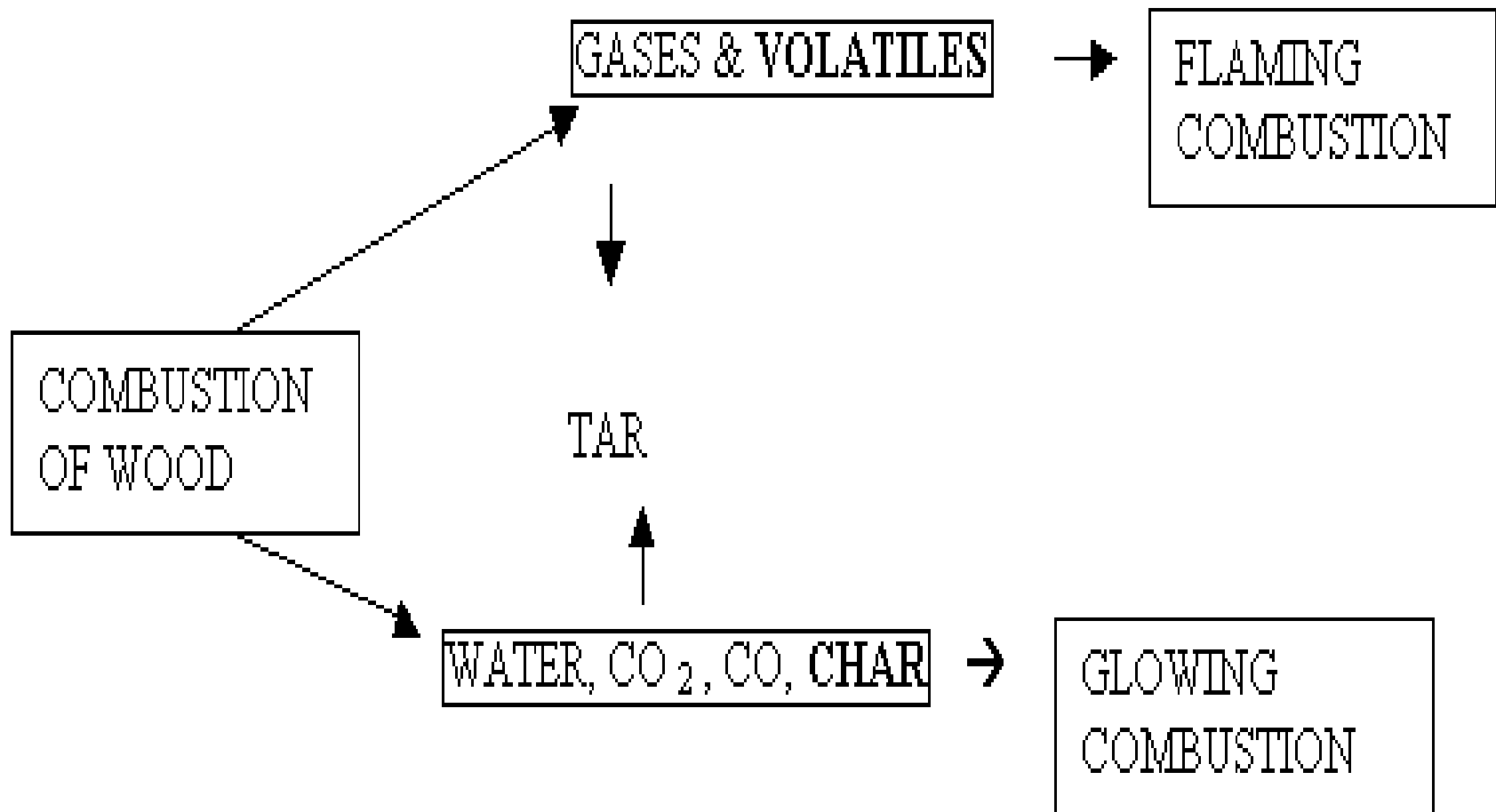


Fig: General pathways for pyrolysis and combustion of Wood

PROCESS DESCRIPTION-4

- Otherwise, this incomplete conversion will yield intermediate chemical compounds like carbon monoxide, polycyclic aromatic hydrocarbons and chlorinated hydrocarbons, all of which are pollutants.
- Likewise, the oxidation of the char is referred to as glowing combustion, and its completeness is also a function of heat, mixing and time

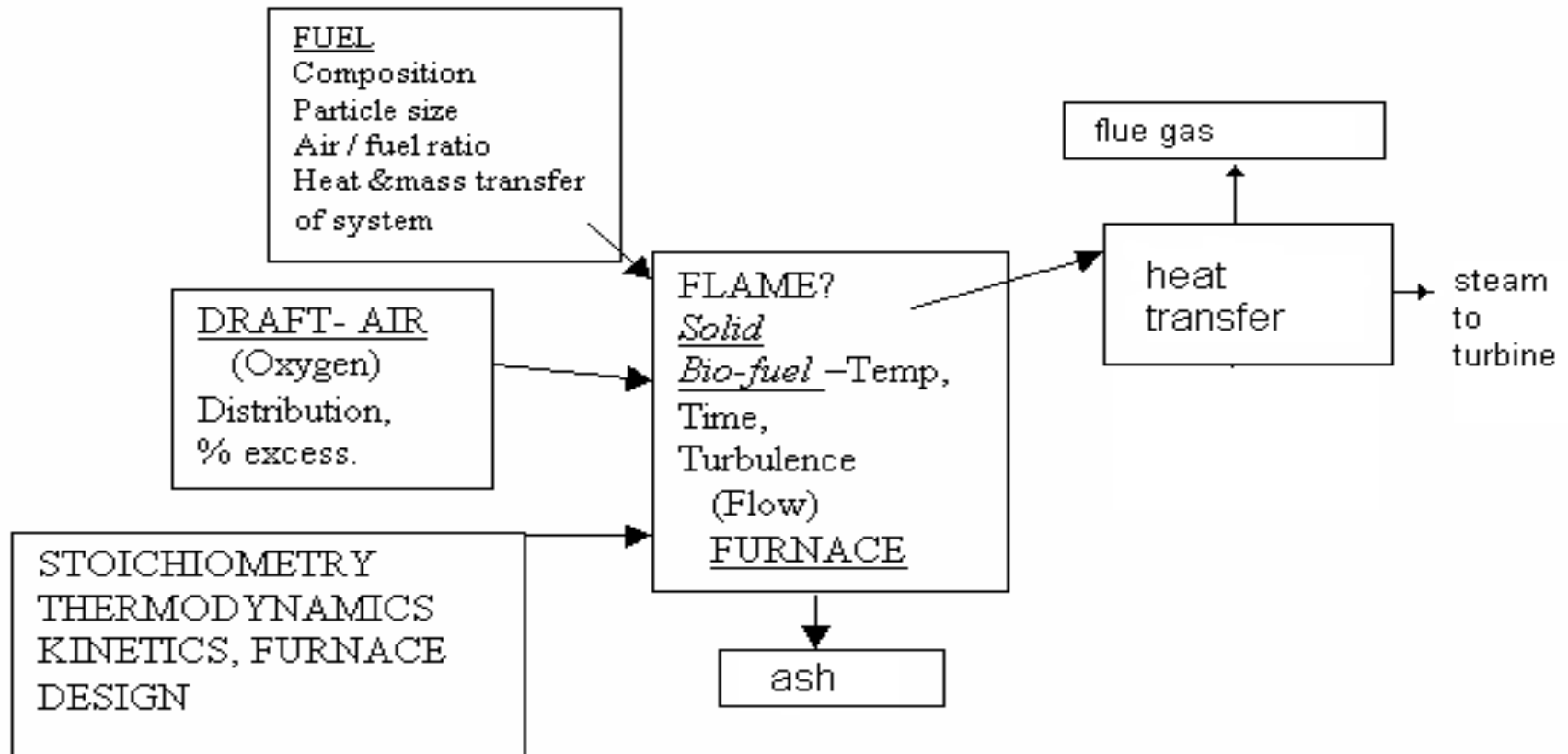
PROCESS DESCRIPTION-5

- So long as every surface of the char comes into contact with oxygen, it will react and become carbon monoxide and carbon dioxide.
- (Ideally, the carbon monoxide will be oxidized during flaming combustion and become carbon dioxide.)
- Combustion gives off heat. A common strategy is to co-fire biomass with fuels like coal.

PROCESS DESCRIPTION-6

- There are marginal efficiency losses from co-firing biomass, and can provide a waste handling solution for industry. Similar to the substitution of gasoline with ethanol, the inclusion of biomass in coal-firing operations can reduce emissions by displacing coal.

Combustion: A chemical process _ Oxidation of reduced forms of carbon and hydrogen by free radical processes. Chemical properties of the bio-fuels determine the higher heating value of the fuel and the pathways of combustion.



COMBUSTION OF BIOFUEL IN BOILER TO GENERATE STEAM

COMPARISON OF COAL AND WOOD AS FUEL FOR COMBUSTION:

COAL

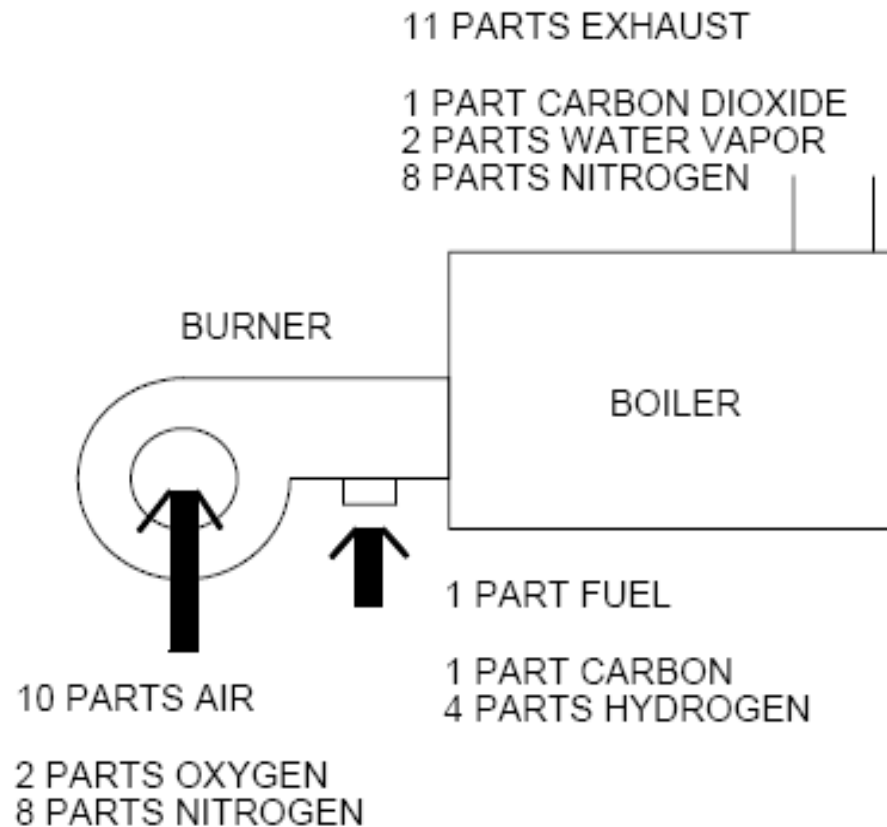
- Solid fuel, high ash content,
- used for Raising HP steam,
- Power production with Rankine cycle
- Gas Turbine cycles, Brayton cycle
- Can be used for producing process steam for direct heating
- Large scale availability near mines and ports
- Assured Technology for handling, storage and Processing well established
- Sulfur content and ash content are problems

WOOD

- Solid fuel, less ash, more volatile, reactive,
- used for Raising HP steam,
- Power production with Rankine cycle,
- Gas Turbine cycles more difficult
- Can be used for producing process steam for direct heating
- Assured availability is only on small scale—
Variable
- Large scale processing. storage and energy conversion technology not established in India
- Moisture content, low bulk density, Location specific availability are problems

The chemistry of combustion:

Natural gas is primarily composed of methane, CH_4 . When mixed with the proper amount of air and heated to the combustion temperature, it burns. **Figure 1** shows the process with the amount of air and fuel required for perfect combustion.



Excess Air, Efficiency and Turndown

- **Excess Air:** The extra amount of air added to the burner above that which is required to completely burn the fuel.
- **Turndown:** The ratio of the burner's maximum BTUH firing capability to the burner's minimum BTUH firing capability.
- As the excess air is increased, the stack temperature rises and the boiler's efficiency drops.

PROXIMATE & ULTIMATE ANALYSIS

- For expressing the complete composition of any solid fuel:
- the organic composition,
- proximate analysis and
- ultimate or elemental analysis are used.
- Typical values of chemical composition of some biomass are shown in Table 1.
- Table 2. shows average composition, ultimate analysis and bulk density of hardwood.
- Table 3. and 4. are data of typical compositions of solid fuels.

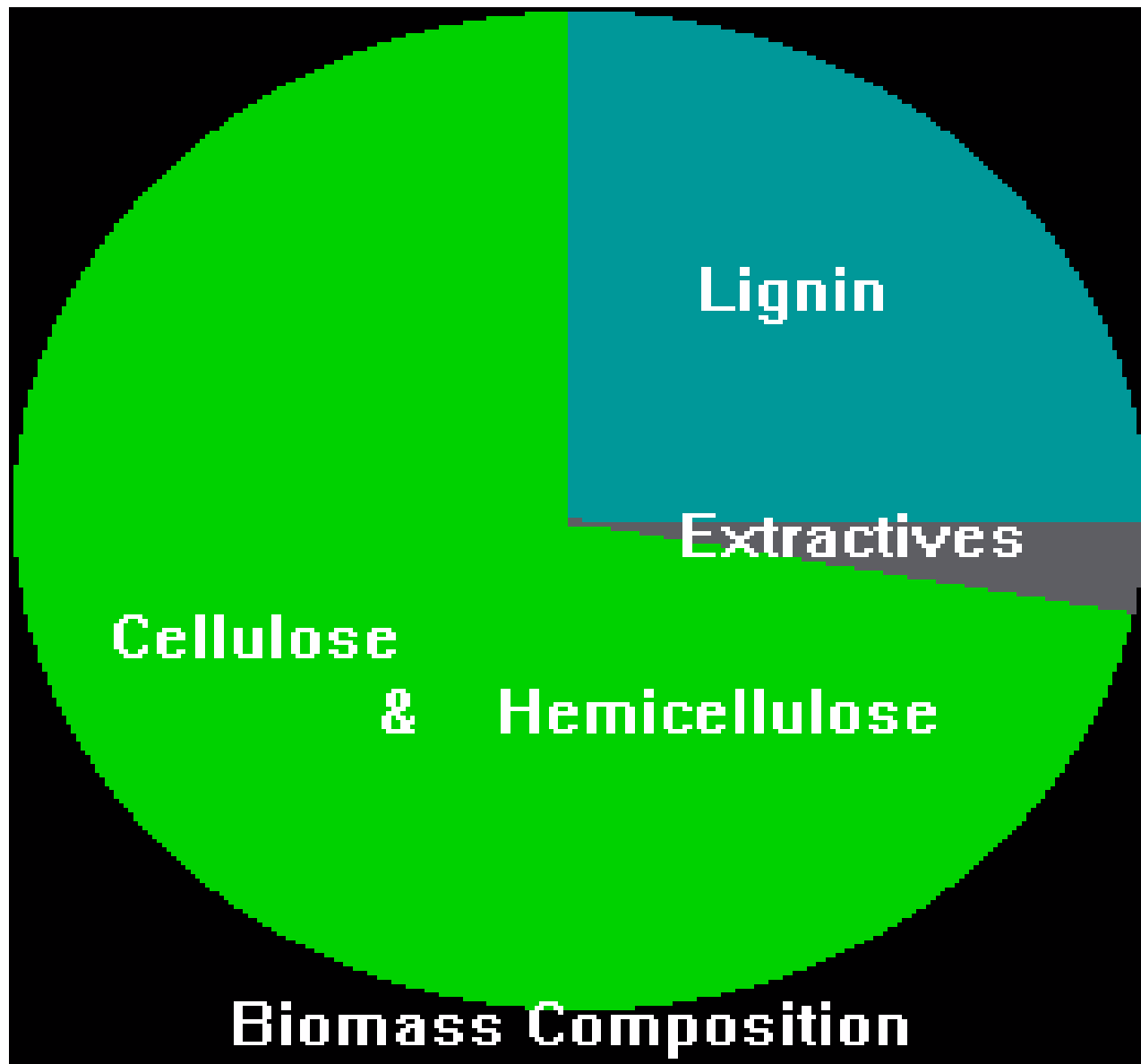


Table: 1.

Chemical composition of some biomass material

Species	Total ash%	Lignin%	Hemi-cellulose%	Cellulose %
Bagasse	2.2	18.4	28.0	33.1
Rice Straw	16.1	11.9	24.1	30.2
Wheat Straw	6.0	16.0	28.1	39.7

Table 2. Av. Comp. & properties of hardwood:

GroupWise Composition, air dried	%
Cellulose	45-55
Lignin	25-35
Hemi-cellulose	4-6
Fats, waxes, and resins	0.5-2
Water	10-15

Ultimate Analysis and other properties, dry basis

Carbon %	50
Hydrogen %	6
Oxygen, %	43.5
Ash, %	0.5
Density, kg/m ²	650
Calorific value, kcal/kg	4,600

TABLE 3. TYPICAL COMPOSITIONS OF SOLID FUELS

Types	Proximate Analysis				Ultimate Analysis					HH V, dry basis, kcal/ kg
	Moisture	Volatile	Fixed carbon	Ash	C	H	O	N	S	
Wood Oak (dry)	-----	85.6	13.0	1.4	58.2	6.0	43.3	0.1	-	4622
Pine (dry)	-----	87.0	12.8	0.7	52.2	7.0	40.2	0.2	-	5338
Peat	56.8	26.0	11.2	6.0	23.1	9.6	59.6	1.3	0.4	4625
Lignite	34.8	28.2	30.8	6.2	42.4	6.7	43.3	0.7	0.7	6110
Coal (Range Of property)	3-20	16- 40	40- 80	3.0 -40	60- 50	3.0-- 6	3.0- 6	1- 1.5	0.3- 4.3	4000 to 8000
Bagasse	-----	80.5	17.0	2.5	48	6.0	43.2	0.3	0.1	4430
Coke	0.8	1.4	87.1	10.7	85	0.8	1.2	1.3	1.0	7105
Char coal	12.0	1.9	83.1	3.0	84	2.3	10.7	--	--	7130

Table 4.	Douglas Fir wood	Western Hemlock	Bagasse	Rice Husk	Pittsburgh Bitum. coal
All on oven dry basis					
Proximate- Wt % Volatiles	85.8	83.8	83.8	64.5	33.9
Fixed Carbon	13.4	14.0	12.7	12.9	55.8
Ash	0.8	2.22	3.5	22.6	10.3
Ultimate- Wt% Hydrogen	6.3	5.8	5.8	4.4	5.0
Carbon	52.3	50.4	48.8	38.3	75.5
Oxygen	40.5	41.4	41.7	33.9	4.9
Nitrogen	0.1	0.1	0.2	0.8	1.2
Sulphur	--	0.1	--	--	3.1
Ash	0.8	2.22	3.5	22.6	10.3
HHV, MJ/kg	21.05	20.05	19.32	13.81	31.74

To determine the quantity of air required for complete combustion

- To determine the air, the ultimate analysis is useful.
- $C + O_2 = CO_2 + 97644 \text{ cal /mole } [15 \text{ }^\circ\text{C}]$
- $H_2 + O_2 = H_2O + 69000 \text{ cal / mole } [15 \text{ }^\circ\text{C}]$
- Excess air % = $(40 \cdot MC_g) / (1 - MC_g)$ where MC_g is moisture content on total wt basis (green). For typical biomass fuels at 50 % moisture content, for grate firing system about 40% excess air may be required.
- For suspension fired and fluidized bed combustion, air required may be 100 % excess
- Distribution of air and whether it is pre-heated is also important

Higher Heating Value

- Calorific value of a fuel is the total heat produced when a unit mass of a fuel is completely burnt with pure oxygen. It is also called heating value of the fuel. When the c.v. is determined, water formed is considered as in vapour state, net c. v. is got.
- Gross calorific value or higher heating value of a fuel containing C, H and O is given by the expression:
- $C_g = [C \times 8137 + (H - O/8) \times 34500] / 100$ where C, H and O are in % and C_g is in calories.
- Net calorific value is the difference between GCV and latent heat of condensation of water vapor present in the products

Combustion of wood / biomass

- Biomass fuel enters a combustor in a wet (50% moist), dirty, light in weight, heterogeneous in particle size, and quite reactive condition.
- Moisture content lowers the combustion efficiency and affects the economics of the fuel utilization.
- Biomass fuels are highly reactive, volatile, oxygenated fuels of moderate heating value.

Changes during heating to combustion temperature

- Due to the effect of heating fuel decomposes as the exothermic oxidation proceeds.
- Drying, pyrolysis of solid particle, release of volatiles and formation of char are followed by pre-combustion gas phase reactions and char oxidation reactions.

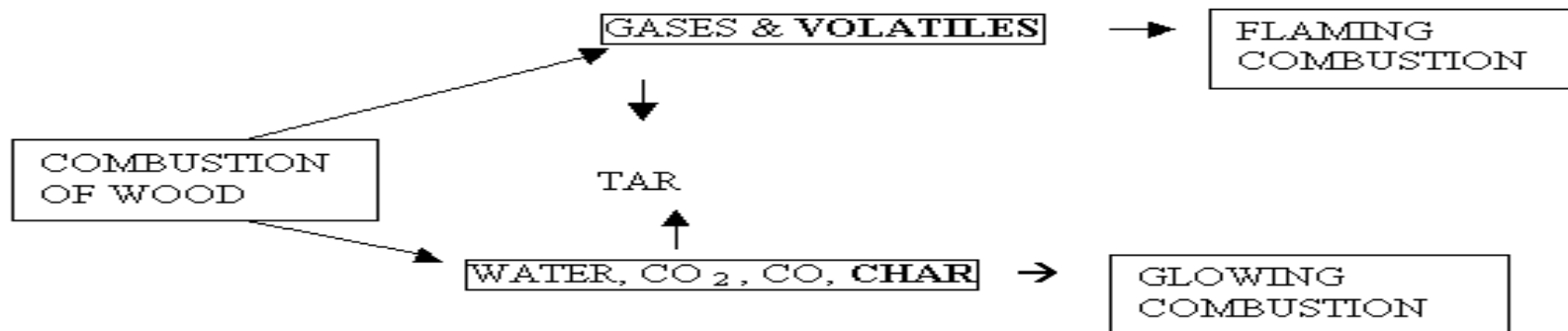


Fig: General pathways for pyrolysis and combustion of Wood

COMPOSITION PARAMETERS AFFECTING COMBUSTION-1

- Net energy density available in combustion of biomass varies from about 10 MJ/kg (green wood) to about 40 MJ/kg (Oils/fats). Water requires 2.3 MJ/(kg of water) to evaporate. Moisture content (MC) influences efficiency more than any variable.

COMPOSITION PARAMETERS AFFECTING COMBUSTION-2

- A system which gives a thermal efficiency of about 80% while firing a fuel of MC 15%, gives reduced efficiencies of 65% when the fuel MC is 50 % or more.
- Cellulose embedded in a matrix of hemi-cellulose and lignin is the main constituent of woody biomass. Compared to coal, biomass has less mineral content and wood gives less ash than agro-residue.

Conditions for efficient Combustion-1

- Sufficient air to provide oxygen needed for complete burning of the fuel. Higher than stoichiometric amount of air is supplied.
- Free and intimate contact between fuel and oxygen by distribution of air supply.
- Secondary air to burn the volatile mass leaving the fuel bed completely before it leaves the combustion zone.

Conditions for efficient Combustion-2

- Volatile matter leaving the fuel bed should not cool below combustion temperature by dilution with the flue gas. Flow path should assure this.
- Volume of the furnace should be arranged so as to provide for expansion of gases at high temperature and complete burning of volatile matter before flowing away.

Induced draft and Forced draft

- The Δp required to make the air flow through the fuel bed and to the flue gas discharge height is called draft of air in a furnace.
- The draft is produced [i] naturally by means of a chimney [ii] mechanically by a fan.
- Mechanical draft can be_ induced draft [fan is used to suck the gases away from the furnace] _ a forced draft _force the air required for combustion through the grate.

Principles of furnace design calculations:

Thermal load of fire grate area:

- It is the amount of heat generated in kilo-calories by the complete combustion of a solid fuel on one sq. m. of grate area/hour.
- Thermal load of fire grate area , $QA = W.Cn / A$ kcal/m².hr

Thermal load of volume of furnace:

- It is the amount of heat generated in kilo-calories by the complete combustion of a solid fuel, in one cu. m. of furnace volume/h.
- Thermal load of vol. of furnace, $QV = W Cn / V$ kcal/m³.hr

Thermal efficiency of furnace:

Thermal efficiency of furnace is the ratio of actual heat delivered by furnace to the available heat in the fuel

- *Thermal efficiency* of furnace, $\eta_F =$
(Heat generated – Heat losses) /
(Net calorific value
of fuel)

$$= (M.h) / (W C_n)$$

Example 1. Combustion of Municipal Solid Waste (MSW):

- The ultimate analysis of MSW is given below.
- C- 30% H- 4% O- 22% H₂O – 24% and ash--metal, etc-20%;
- Compute the actual air required and the flue gases produced per kg. of MSW if 50% excess air is supplied for complete combustion.

Notations for furnace design calculations

- Q_A = Thermal load of fire grate area, kcal/m².hr
- Q_V = Thermal load of volume of furnace, kcal/m³.hr
- W = Fuel burned kg / hr,
- C_n = Net calorific value of fuel, kcal / kg
- A = furnace grate area, m²
- V = volume of furnace space, m³
- h = enthalpy of flue gas kilocalories/ m³
- M = Flow rate of flue gas, m³/hr

Rice husk based power plant-1

- A power plant of 6 MW power operated in Raipur district of M.P. [in 1999] It uses 7 tonnes of rice husk an hour to produce high pressure steam (at 480 o C) _used to produce electricity.
- To burn the husk, the plant uses fluidized bed combustion type boiler supplied by Thermax.

Rice husk based power plant-2

- The plant is owned by Indo- Lahari Power Limited. The estimated capital cost for a megawatt of power produced is 35 million rupees as against 40 million rupees for a coal based power plant.
- In Raipur area one tonne of rice husk costs about rupees 550 per tonne as compared to rupees 1400 per tonne of coal.

Combustion Theory

Stoichiometry, Calculations of Equivalent-ratio,
AFR, products of complete combustion,
Concentrations,

Equivalence ratio

The equivalence ratio of a fuel-air mixture is defined as

$$\phi = \frac{(m_{fuel} / m_{air})}{(m_{fuel} / m_{air})_{st}} = \frac{(V_{fuel} / V_{air})}{(V_{fuel} / V_{air})_{st}}, \quad (1.1)$$

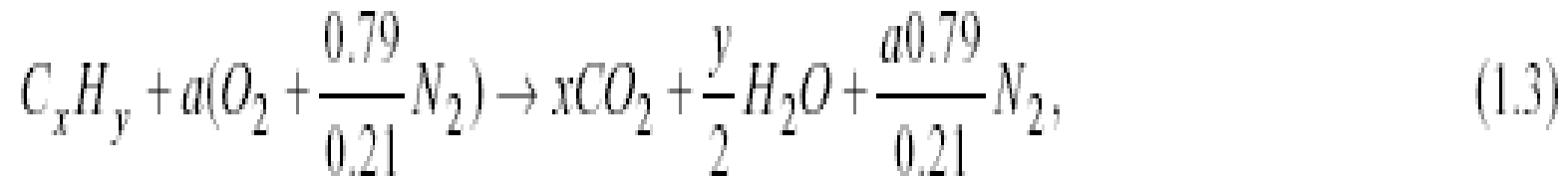
expressed in terms of the mass (m) or volume (V) of fuel and air present in the mixture. The subscript st refers to stoichiometric conditions. The equivalence ratio is related to the Air to Fuel Ratio (AFR) by

$$AFR = \frac{1}{\phi} AFR_{st}. \quad (1.2)$$

Pure fuel corresponds to $AFR=0$ and $\phi=\infty$, while pure air to $AFR=\infty$ and $\phi=0$. In some cases, it is customary to work in terms of the AFR (or $1/\phi$) (e.g. in gas turbines) and in others to work with ϕ (e.g. in SI engines and in flame propagation studies as in the 3A5 Experiment).

Calculation of AFR_{st}

The stoichiometric quantity of oxidizer is just that amount that is necessary to completely burn a quantity of fuel. The stoichiometric AFR is calculated by balancing C, H, and O atoms in the combustion reaction. Complete combustion of a general hydrocarbon with atmospheric air is written as



Each kmol of atmospheric air has 0.79kmol of N_2 and 0.21kmol of O_2 . C, H, and N atom balance have already been enforced in Eq. (1.3). By counting O atoms, it is easy to see that

$$a = x + y/4. \quad (1.4)$$

The stoichiometric AFR (by mass) is then given by

$$AFR_{st} = \frac{a(MW_{O_2} + 0.79/0.21MW_{N_2})}{MW_{fuel}}, \quad (1.5)$$

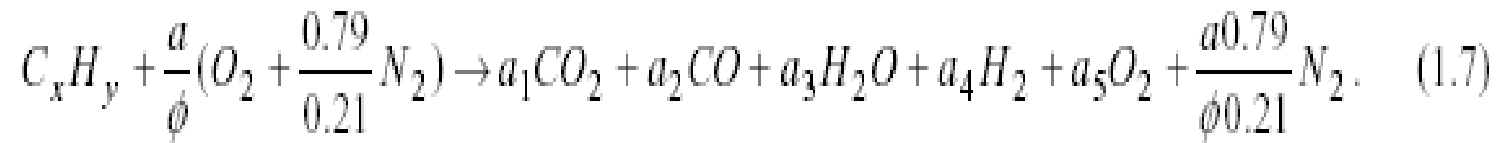
with a given by Eq. (1.4). The volumetric AFR_{st} is given by

$$AFR_{st,vol} = \frac{a(1 + 0.79/0.21)}{1}. \quad (1.6)$$

For example, for CH_4 , $x=1$ and $y=4$, hence $a=2$, and the volumetric $AFR_{st,vol}$ is 9.524, while the mass AFR_{st} is 17.167. If there is no explicit distinction as to whether the AFR refers to mass or volume (molar) ratio, we usually take it as a mass ratio. The same approach can be used to find the stoichiometric ratio of any fuel to any air. For example, the fuel may contain oxygen or nitrogen (e.g. various coals of the generic formula $\text{C}_p\text{H}_q\text{O}_r\text{N}_s$), while the O_2/N_2 ratio in the “air” used in combustion may be different from that in atmospheric air, for example due to oxygen enrichment to achieve high temperatures.

Products of complete combustion

The reaction of *lean* ($\phi < 1$), stoichiometric ($\phi = 1$) or *rich* ($\phi > 1$) mixtures with atmospheric air can be written in the general form:



One could add other species in the r.h.s. (e.g. O, H, OH etc), if required. Equation (1.7) is the starting point in evaluating the composition of the product mixture. It is different from Eq. (1.3) in that we have not assumed yet complete combustion.

- For $\phi = 1$ and complete combustion, Eq. (1.7) reduces to Eq. (1.3).
- If $\phi < 1$ and complete combustion occurs, $a_2 = a_4 = 0$ (all fuel is oxidized to CO_2 and H_2O) and then atomic balances of C, H, and O give that $a_1 = x$, $a_3 = y/2$, and $a_5 = a(1 - \phi)/\phi$. The quantity $(1 - \phi)/\phi$ is referred to in the literature as the “*excess air*”.
- If $\phi > 1$, it is not possible to calculate the final product composition simply by atom conservation because CO and H_2 are also present (we get more unknowns than equations). Equilibrium considerations will resolve this in Lecture 3.

Mole fractions and mass fractions

The factor that appears before the chemical symbol in the combustion equation (1.3) or (1.7) is the number of kmols of that particular species. The total number of kmols may be different in the products than in the reactants. The ratio of the number of kmols, n_i , of a particular species i to the total number of kmols n_{tot} in the mixture is the *mole fraction* or *volume fraction*:

$$X_i = \frac{n_i}{n_{tot}}. \quad (1.8)$$

The *mass fraction* Y_i is defined as the mass of i divided by the total mass. Using the obvious

$$\sum_{i=1}^N X_i = \sum_{i=1}^N Y_i = 1, \quad (1.9)$$

where N is the total number of species in our mixture, the following can be easily derived for Y_i and the mean molecular weight \overline{MW} :

$$Y_i = X_i \frac{MW_i}{\overline{MW}}, \quad (1.10)$$

$$\overline{MW} = \sum_{i=1}^N X_i MW_i = \left(\sum_{i=1}^N \frac{Y_i}{MW_i} \right)^{-1}. \quad (1.11)$$

Note that the combustion equation (1.3 or 1.7) gives us mole fractions, which can then be used to give mass fractions through the individual and the mean molecular weights.

Concentrations

The *concentration* of species i is defined as the number of kmols of the species per unit volume. The usual notation used for concentrations is C_i or the chemical symbol of the species in square brackets, e.g. $[\text{CH}_4]$ for methane. From this definition and Eq. (1.8),

$$C_i = \frac{n_i}{V} = \frac{X_i n_{tot}}{V}, \quad (1.12)$$

and using the equation of state $PV = n_{tot} R^0 T$ (R^0 is the universal gas constant), we get:

$$C_i = \frac{X_i n_{tot}}{n_{tot} R^0 T / P} = X_i \frac{P}{R^0 T} \quad (1.13)$$

This relates the concentration to the mole fraction. Note that the total pressure P and the temperature T of the mixture have now appeared (i.e. for given mass or mole fractions, the concentrations are functions of pressure and temperature). Applying Eq. (1.10) to Eq. (1.13), we relate the concentration to the mass fraction:

$$C_i = \frac{Y_i \overline{MW}}{MW_i} \frac{P}{R^0 T} = \frac{Y_i \rho}{MW_i}. \quad (1.14)$$

$$C_i = \frac{Y_i \overline{MW}}{MW_i} \frac{P}{R^0 T} = \frac{Y_i \rho}{MW_i} \quad (1.14)$$

The mixture density ρ appearing in Eq. (1.14) can be related to the mixture constituent densities by

$$\rho = \frac{\overline{PMW}}{R^0 T} = \sum_{i=1}^N \frac{P X_i MW_i}{R^0 T} = \sum_{i=1}^N X_i \rho_i \quad (1.15)$$

where ρ_i is the density of each species calculated at the total pressure. The first equality in Eq. (1.15) constitutes the definition of the mixture density, while the last can be used to get the mean density from Tables that give the individual species densities at a given temperature and pressure. As a (good) first approximation in combustion problems, the mixture molecular weight (and hence density) may be taken as that of air due to the abundance of N_2 , especially for lean mixtures (Ex. 1-1).

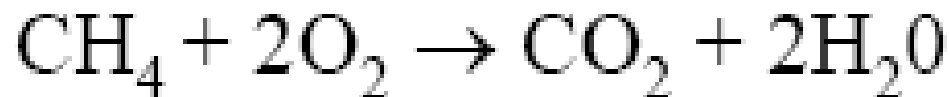
Usually, the chemical reaction rate is expressed in terms of concentrations, while the conservation laws for mass, momentum, and energy that are used in combustion problems are expressed in terms of mass fractions. On the other hand, it is the volume fractions that are measured (e.g. by exhaust gas analysers) or set (e.g. by flow meters) in practice. The above relations are useful for performing transformations between the various quantities.

Real combustion & Emissions

in biomass & solid fossil fuel
combustion and Gasification

What happens in combustion?

- Fuel + oxidizer -> Products + light + heat
- Combustion, in its simplest form, e.g: methane



A clean reaction, except for the issue of carbon dioxide and the global climate

This idealized reaction takes place in an 'atmosphere' (oxygen) free of impurities

How much CO₂ is produced when 1 ton of wood (C₆H₁₂O₆) is burned?

Balance the equation:



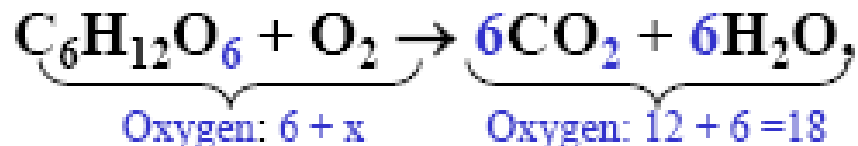
First the **carbon**:



Then the **hydrogen**:



Last, the **oxygen** (because you can change the oxygen without altering other elements):



So, $6 + x = 18 \rightarrow x = 12$, or 6 O₂ The balanced equation is:



What about the grams per mole of wood (molecular weight):

$$\text{C}_6\text{H}_{12}\text{O}_6 = (6 \times 12) + (12 \times 1) + (6 \times 16) = 180 \text{ grams/mole}$$

How much CO₂ is produced when 1 metric ton of wood is burned, continued ...

From the equation we can find out how much CO₂ we get per metric ton of wood.

So, from $C_6H_{12}O_6 \rightarrow 6CO_2 + 6H_2O$, we see that:

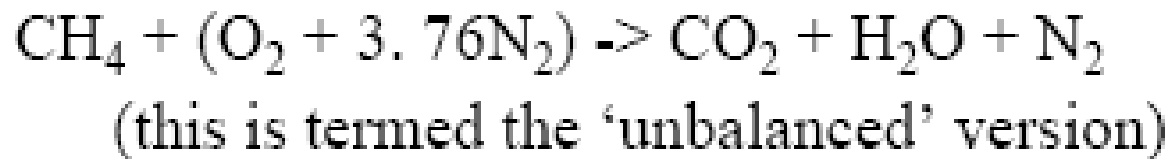
$$\frac{180\text{g } C_6H_{12}O_6}{\underbrace{264\text{g } CO_2}} = \frac{10^6\text{g } C_6H_{12}O_6}{X\text{g}CO_2}$$

(12+(2x16)) = 44 grams per mole of CO₂

$$x = \frac{264\text{g} \times 10^6\text{g}}{180\text{g}} = 1.47 \times 10^6\text{g} = 1.47 \text{ tons of } CO_2$$

Simple combustion equation, but put it in air

- Example: methane reacts with air

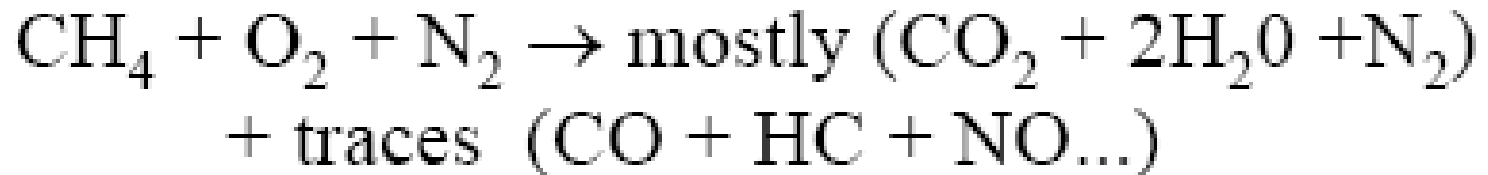


(balanced, stoichiometric: exactly the correct amount of oxidizer to convert all C to CO_2 , and all H to H_2O)

- Note: Air is 78% nitrogen, 21% oxygen, + other stuff

Real Combustion

- If combustion occurs without complete oxidation instead, we get:



- This can occur when:
 - temperature too low,
 - insufficient O,
 - combustion too rapid,
 - poor mixing of fuel and air, etc. ...

Real, Real (fully nasty), Combustion

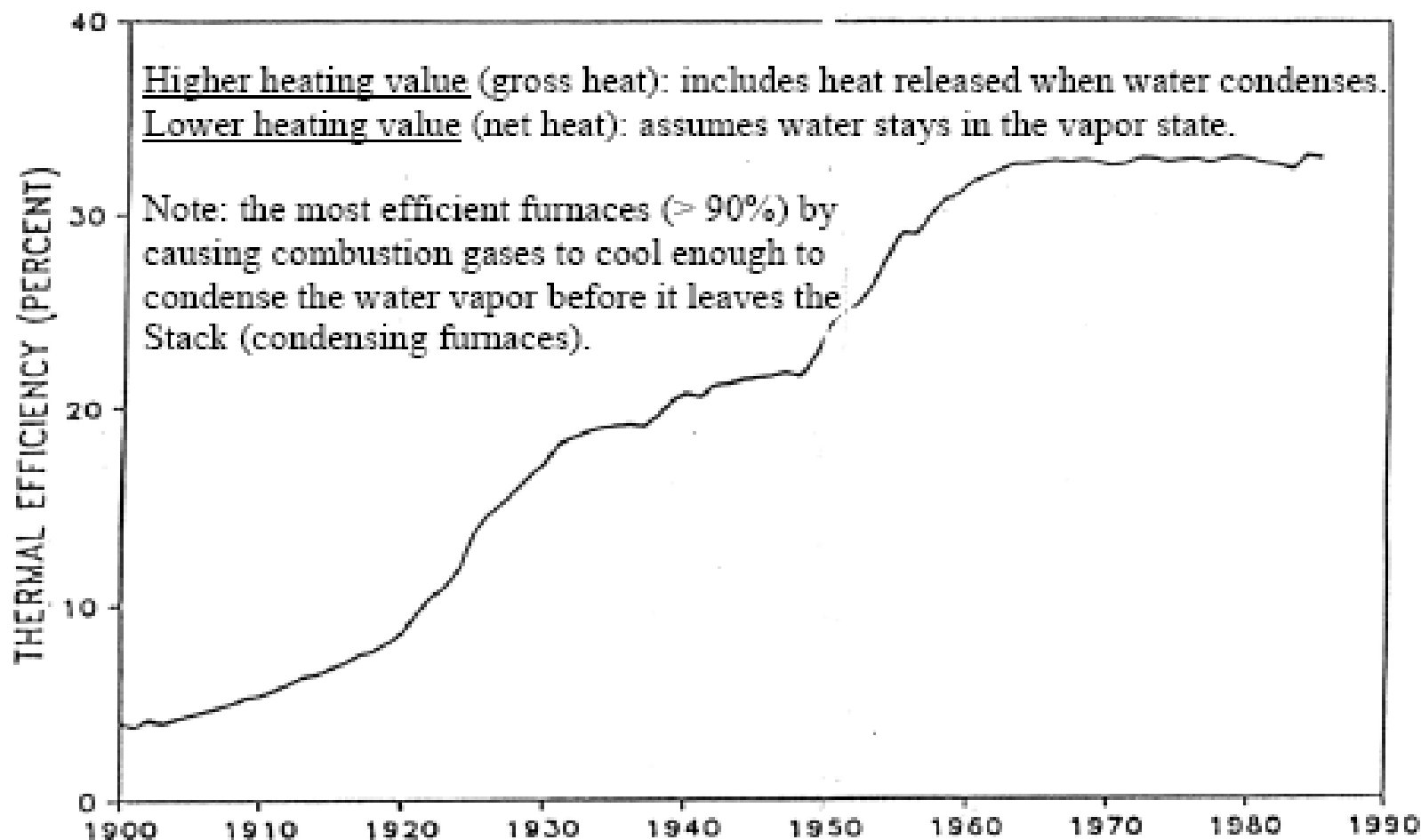
- At higher temperatures, N reacts with O:
$$\text{air}(\text{N}_2 + \text{O}_2) + \text{heat} \rightarrow \text{NO}_x \text{ (thermal)}$$
- So much for pure fuels, now add impurities:
enter N, S, metals and ash (non-combustibles)

What we really get:

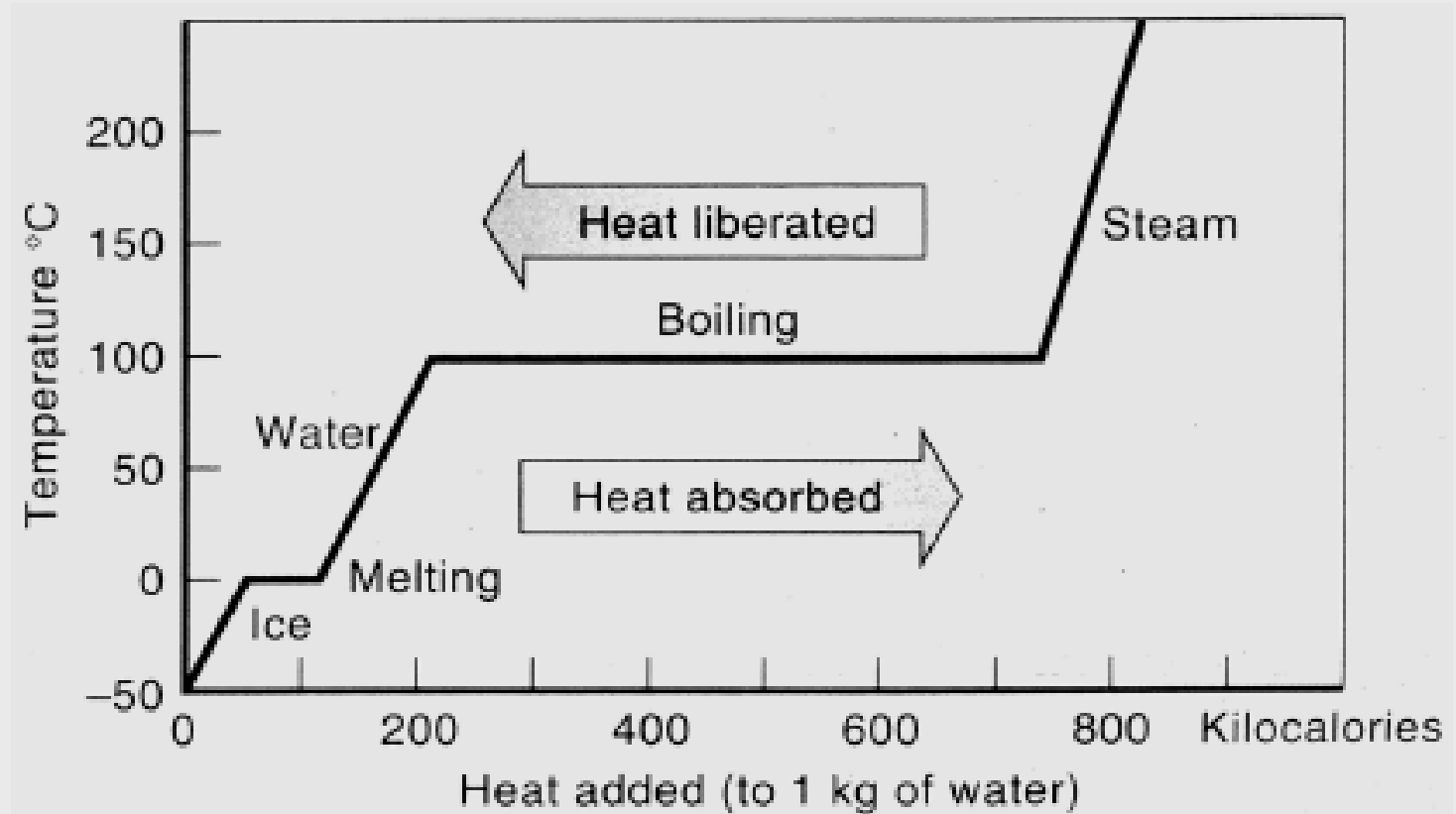
- Fuel (C, H, N, S, ash) + air ($\text{N}_2 + \text{O}_2$) \rightarrow
(CO_2 , H_2O , CO, NO_x , SO_x , VOCs, particulates) +
ash
 - Volatile Organic Compounds: VOCs

Historical trend in the average efficiency of electricity generation in central-station thermal power plants in the U.S.

(efficiency in percent, higher heating value (HHV) basis)



Heat Needed to Convert 1 kg of ice to steam:



2.1 kJ/°C to heat ice

4.18 kJ/°C to heat water

2257 kJ/kg needed to vaporize

333 kJ/kg needed to melt ice

2.0 kJ/°C to heat the vapor

HHV versus LHV

Higher heating value: includes energy of state changes

Lower heating value: without state changes included.

The energy released by burning methane (CH_4) is 890 kJ/mol, including the energy of condensation of the water vapor.

The energy is 810 kJ/mol without the condensation, or the LHV

Calculate the same way :

Balance the equation



Since 1 mol of CO_2 has 12 g of carbon, the HHV intensity is :

$$\text{HHV carbon intensity} = \frac{12\text{gC}}{890 \text{ kJ}} = 0.0135 \text{ gC} / \text{kJ} = 13.5 \text{ gC} / \text{MJ}$$

$$\text{LHV carbon intensity} = \frac{12\text{gC}}{810 \text{ kJ}} = 0.015 \text{ gC} / \text{kJ} = 15 \text{ gC} / \text{MJ}$$

Summary: Combustion Products

- Air, N_2 , O_2 , Ar
- Products of complete combustion: CO_2 , H_2O
- Products of incomplete combustion: trace hydrocarbons, unburned hydrocarbons, CO , H_2 , aldehydes, soot
- Fuel impurities: SO_2 , SO , metals, metal oxides, ash (silica, sand)
- Nitrogen compounds: N source is the air or the fuel, e.g.

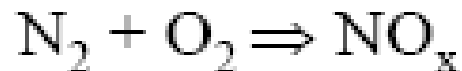
NO , NO_2 , N_2O , HONO, NH_2

Emissions

- Mole fraction (% , ppm, ppb)
- mass/energy in (pollutant/MMBtu, Kg/KJ)
- mass/distance (g/mile) [vehicle standards]
- mass/volume = $\mu\text{g}/\text{m}^3$
- reference emissions to corrected oxygen content in exhaust to prevent apparent emission reductions by dilution
 - Remember, the solution to pollution is ... dilution.

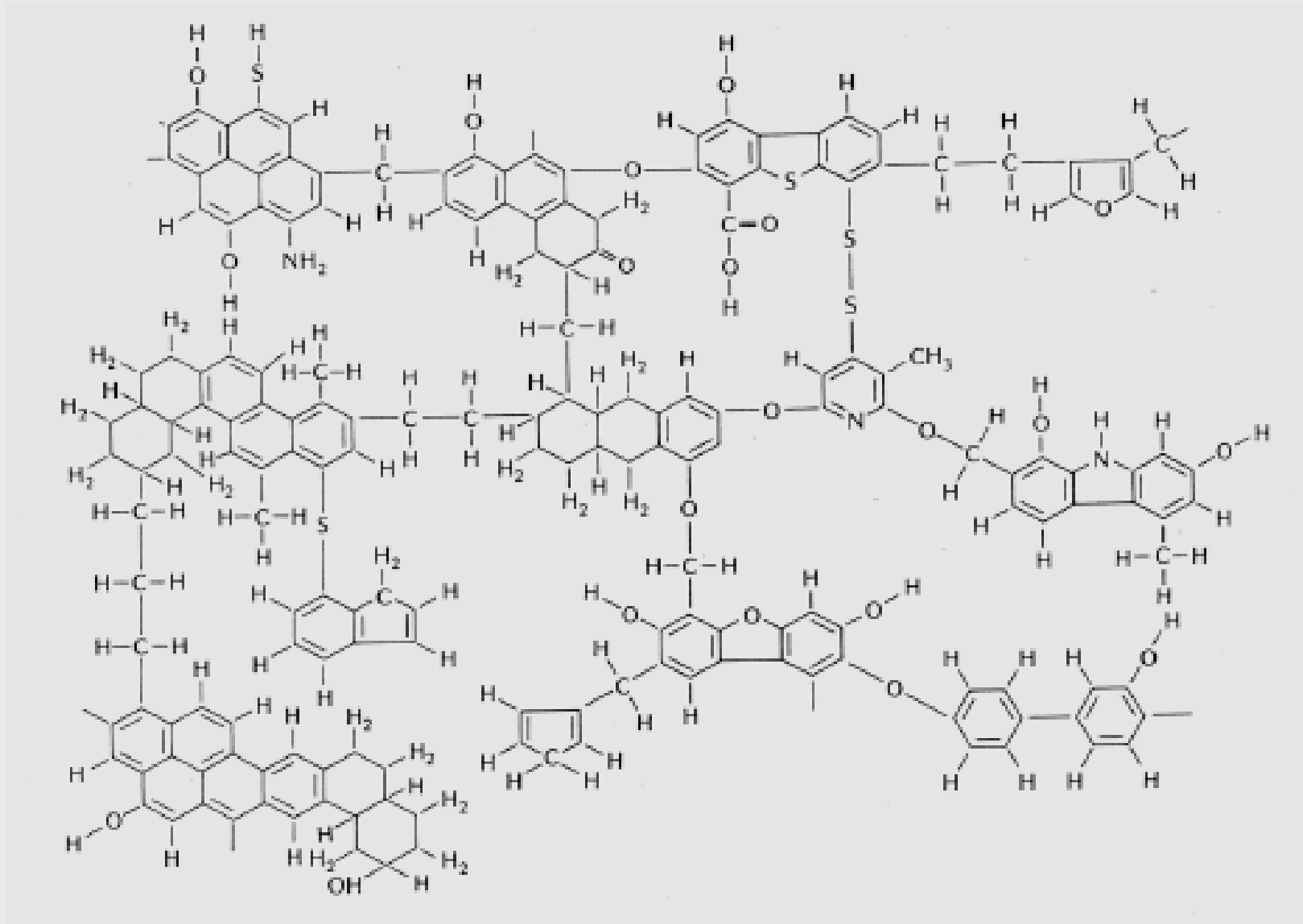
Fossil fuel combustion (chemistry)

- Coal = Carbon (C) + impurities (e.g., sulfur)
- Oil = Mixture of hydrocarbons (C_xH_y) + imp.
- Natural Gas = methane (CH_4) + carbon dioxide (CO_2) + imp.
- Combustion = oxidation, exothermic



- Ratio of x:y determines ratio of $CO_2:H_2O$
- CH_4 has lowest x:y and thus lowest CO_2 per energy
- Carbon has the highest ratio

Chemical Structure of Coal



Gas and Liquid Fuels

- Natural gas: CH_4 , C_2H_6 , N_2 , CO_2
- Propane (C_3), Butane (C_4), LPG (mixture)
- Synthetic gases (from biomass, coal products)
- Petroleum derived fuels ($\sim\text{CH}_2$);
 - Gasoline (C_4 to C_{10} , avg: C_8)
 - Diesel (C_{12})
 - Turbine fuels, kerosene (C_{10})
 - Heavy fuel oils
- Shale oil derived liquids
- Alcohols, ethers (have oxygen in the fuel)
- Hydrogen

Products

- Depend on fuel, mixing, and temperature
- At temperatures < 1250 K
 - fuel + oxidizer \rightarrow $O_2 + CO_2 + H_2O + N_2$
- At combustion temperatures (~ 1400 - 2200 K)
 - many stable species dissociate
 - molecular events and elementary reactions important
 - $CO_2 \rightleftharpoons CO + 1/2 O_2$
 - $H_2O \rightleftharpoons H_2 + 1/2 O_2$
 - Actual product concentrations depend on balance among reactions that lead to formation & consumption of intermediate species (and the kinetics)

Reaction mechanisms

contain several hundred elementary reactions plus thermodynamic data that allow one to calculate the major products and all the trace products for a given mixture of methane and oxidizer (O_2 or air) at specified conditions of temperature and pressure

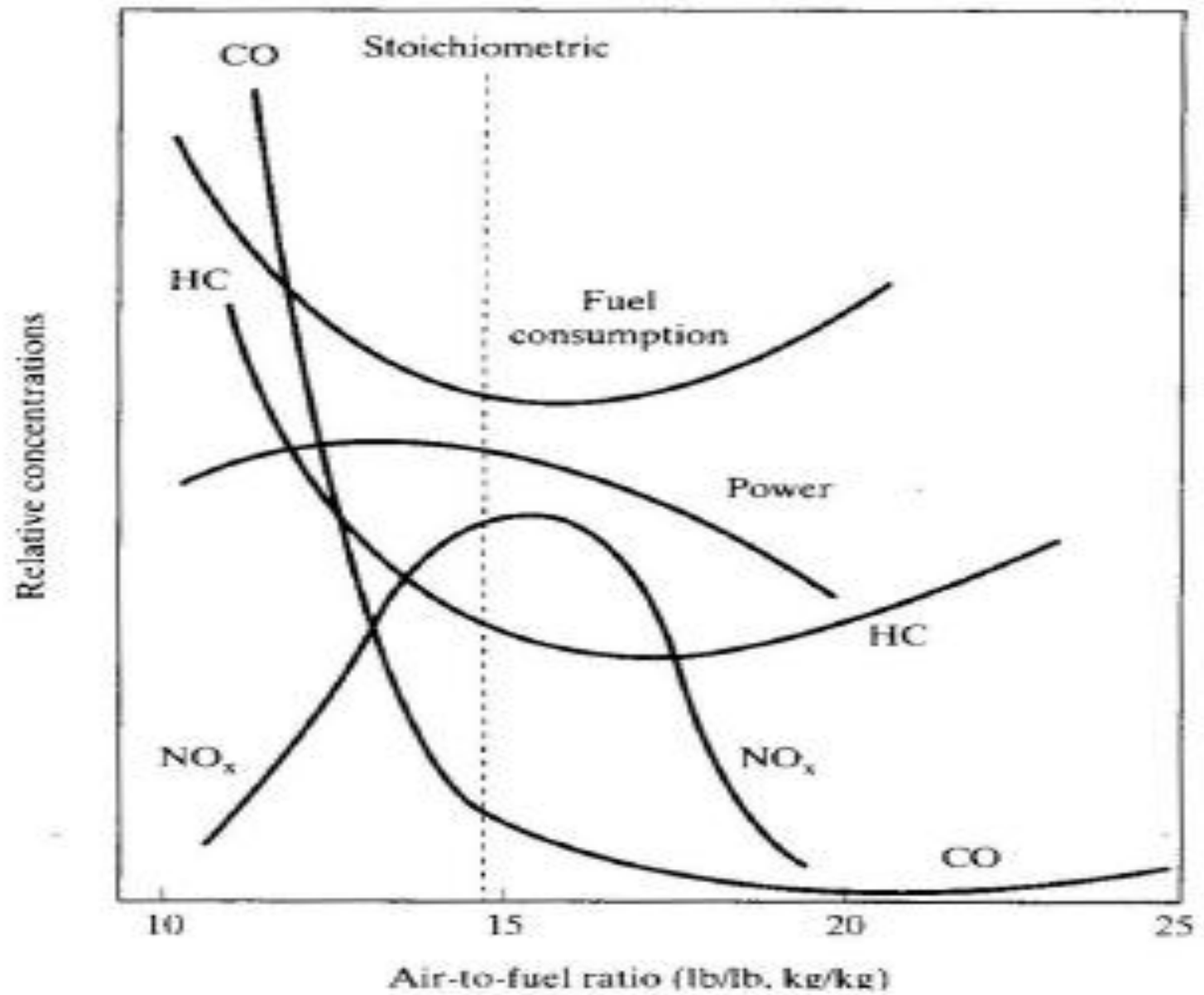


FIGURE 7.22 Effect of air-to-fuel ratio on emissions, power, and fuel economy.

All reactions accompanied by absorption or release of energy

- Ideal system: adiabatic (ideal) combustion
 - no heat loss or energy transfer out of the system
 - constant pressure process, steady state, exothermic
 - Energy expressed as enthalpy

$$\text{Energy} = E = U + \text{KE} + \text{PE}$$

But for gases changes of state require another term, too:

$$\text{Enthalpy} = H = U + pV$$

internal energy + pressure volume work

$$H_{\text{reactants}} = H_{\text{products}} \text{ for an adiabatic system}$$

ΔH for constant pressure reaction = heat absorbed

$$H_{\text{reactants}} = H_{\text{products}}$$

- $H = h_f + \int C_p dT$
= heat of formation + (specific heat) x (temp)

Other terms

- Mass fuel/mass air
- Mass air/ mass fuel = AFR (air fuel ratio)
 - typically about 14, 15 for HC
- Percent excess air = $100 \{(1/\phi) - 1\}$
 - 0% excess air = stoichiometric

Combustion equipment for solid biomass

For wood:

- **Inclined step grate furnace**
- **Spreader Stoker**

For solid biomass particulates- (agro-residues):

- **Cyclonic, Suspension Fired Combustion System**
- **Fluidised Bed Combustion System**

Inclined step grate furnace

- In the inclined grate system, fuel is fed to the top of the grate. In this system, heating and drying can occur very near to the fuel feed shoot. Solid phase pyrolysis can occur as the fuel is sliding down the grate. Char oxidation can occur at the base of the grate and on the dumping grate. Gas phase reactions can be controlled by over-fire air distribution and separated completely from solid phase reactions.

Spreader Stoker

- In the spreader stoker, fuel particles are fed into the firebox and flung, mechanically or pneumatically across the grate. Some heating and drying and possibly some pyrolysis occurs while the particle is in suspension.
- For the most part however, solid phase pyrolysis and char oxidation occur on the grate.

Spreader Stoker...

- Pre-combustion gas phase reactions occur between the grate and the zone where secondary air is introduced.
- Gas phase oxidation occurs either throughout the firebox or in the vicinity of the zone where secondary air is introduced if the under-grate air is limited to sub-stoichiometric quantities.

Cyclonic, Suspension Fired Combustion System

Horizontal Cyclone Furnace:

- A horizontal cyclone furnace consists of a horizontal or slightly inclined cylinder lined with firebricks into which air is ejected tangentially at a velocity of 6000-7000 m/min so that the flame in the furnace revolves at a rpm of 1200 to 1800
- The fuel introduced at the cyclone tip is entrained by the revolving mass and is thrown against the cyclone walls where it burns.
- The flue gases that escape at high velocities through the aperture at the other end of the cyclone are substantially free from fly ash.

Cyclonic, Suspension Fired Combustion...

- The heat release rate of $(2-5) \times 10^6$ kcal/m²-hr can be achieved for pulverized coal in a cyclone furnace.
- The rotary motion imparted to the flame results in an intensive mixing of the flame mass and the fuel particles are subjected to the action of centrifugal force. This increases the residence time of the fuel in the furnace and combustion is complete.

Fluidised Bed Combustion System-1

- In fluidized bed combustion, bio-fuel is dispersed and burned in a fluidized bed of inert particles. Temperature of the bed is maintained in the range of 750 to 1000 °C so that combustion of the fuel is completed but particle sintering is prevented. The gaseous products leave the bed at its operating temperature, removing about 50% of the heat generated.

Fluidised Bed Combustion- 2

- The remainder of the heat is available for direct transmission to heat transfer surfaces immersed within the bed; in boiler applications these comprise a set of steam raising tubes.
- The heat transfer to immersed surfaces is uniformly high in comparison with the variation of radiation heat transfer through a conventional combustion chamber.
- Consequently less heat transfer surface is required for a given output and a boiler system occupies a smaller volume.

BIOMASS TO BIOENERGY

