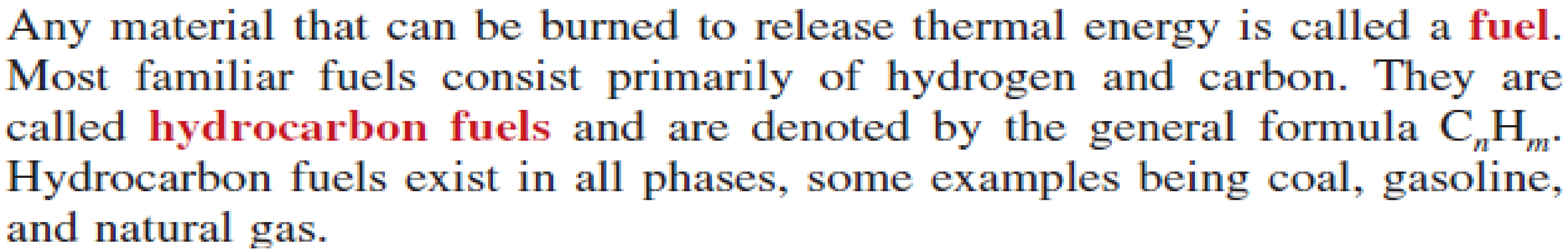
POWER PLANT ENGINEERING

MANSOOR ALI ZAHEER
Assistant Professor
Mechanical Engineering Department
University of Sargodha

What is fuel?



Any material that can be burned to release thermal energy is called a **fuel**. Most familiar fuels consist primarily of hydrogen and carbon. They are called **hydrocarbon fuels** and are denoted by the general formula C_nH_m. Hydrocarbon fuels exist in all phases, some examples being coal, gasoline, and natural gas.

Classification of fuels

Fuel

- **Solid**
  - Hard Coal
  - Brown coal
  - Waste/garbage
  - Wood
  - Tree bark
  - Peat
  - Process residuals
- **Paste-like (semi-liquid**
  - Tar
  - Food stuff leftovers
  - Asphalt
  - Fat
  - Sludge
  - Petroleum coke
  - Residual oil
- **Liquid**
  - Light fuel oil
  - Heavy fuel oil
  - Coal and/or water mixtures
  - Sulfite liquor
  - Sulfate liquor
  - Chemical waste liquor
  - Solvent leftovers
  - Organic elements
  - Water/aqueous salt solvents
- **Gaseous**
  - Natural gas
  - Blast furnace gas
  - Refinery gas
  - Coke gas
  - Process waste gas
  - Exhaust steam
  - Solvent steam

Definition: "Lower heating value" and "higher heating value"

Heating Value, J/kg of fuel, is the amount of heat of combustion released when 1 kg of the fuel burns with oxygen and the reaction products are cooled back to the reactant temperature (usually assumed 25 °C). It may be determined on as-received, dry, or dry-and-ash-free basis

Upper or **Higher heating value**, **HHV**: includes the energy released by water vapor in the product assuming that all of the water in the products are condensed to liquid.

Lower heating value, **LHV**: corresponds to the case where none of the water is assumed to condense.

Properties of fossil fuels and combustion calculations

The HHV and LHV can be related as:

$$\mathbf{LHV = HHV - (9m_{h2} + m_w)h_{fg}}$$

where

m_w = initial mass of water vapor per unit mass of fuel burnt, as-recieved basis

m_{H2} = mass of original hydrogen per unit mass of fuel, as-recieved basis

h_{fg} = latent heat of vaporization of water vapor at its partial pressure in the combustion products, J/kg H_2O.

Fossil Fuels

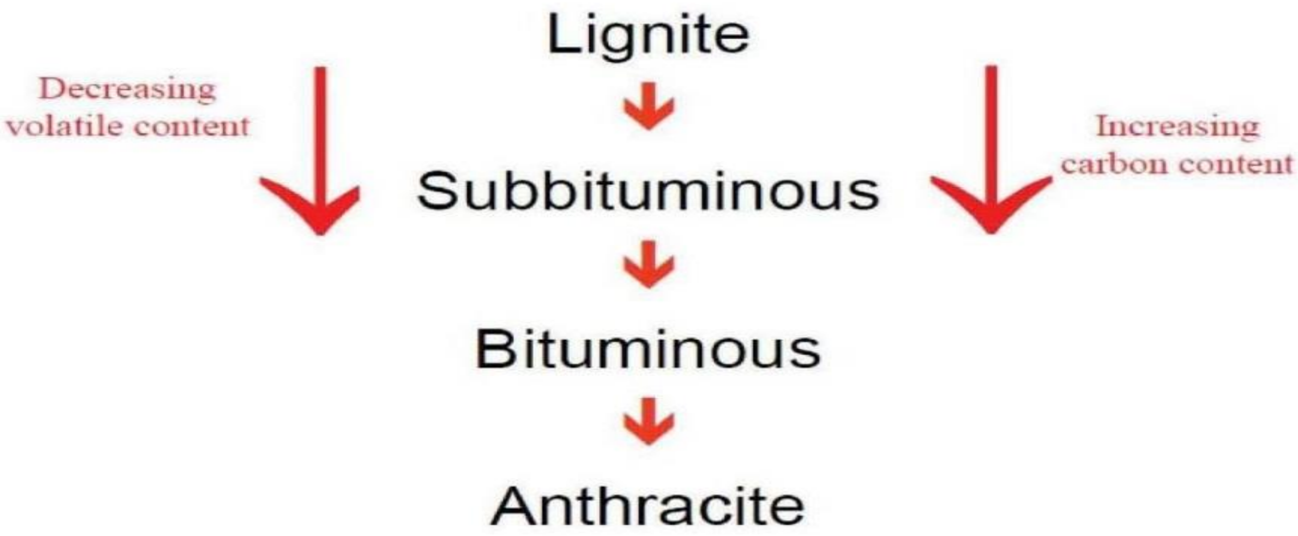
Coal

Coal

- is the most abundant and utilized fossil fuel in power generation
- it accounts for 40% of the world's total electricity production
- is the most polluting fuel which accounts for 20% of the total CO2 produced
- is a highly inhomogeneous material, of widely varying composition

Classification of Coal

Coal types according to rank



Lignite

↓

Subbituminous

↓

Bituminous

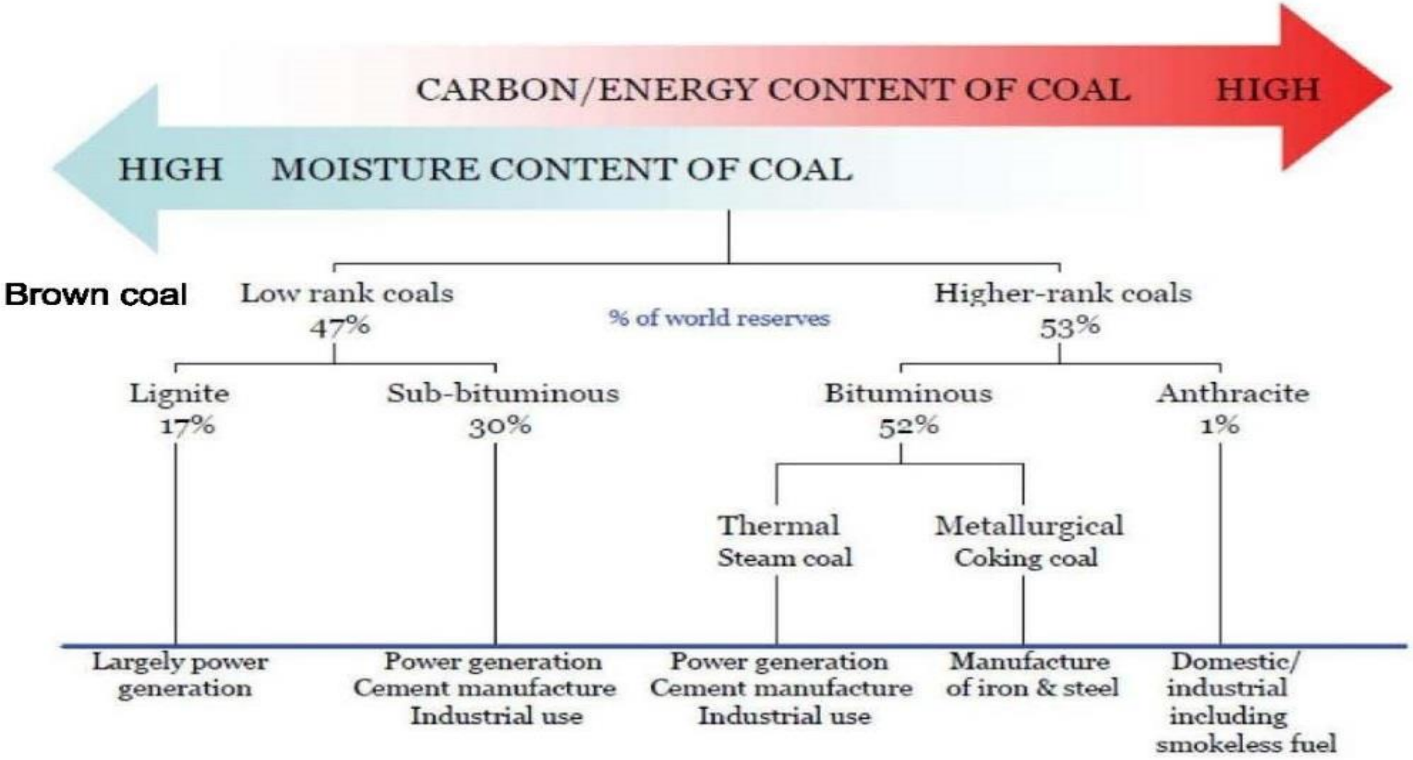
↓

Anthracite

Decreasing volatile content

Increasing carbon content

Properties of fossil fuels and combustion calculations



CARBON/ENERGY CONTENT OF COAL HIGH

HIGH MOISTURE CONTENT OF COAL

Brown coal

Low rank coals
47%

% of world reserves

Higher-rank coals
53%

Lignite
17%

Sub-bituminous
30%

Bituminous
52%

Anthracite
1%

Thermal
Steam coal

Metallurgical
Coking coal

Largely power generation

Power generation
Cement manufacture
Industrial use

Power generation
Cement manufacture
Industrial use

Manufacture of iron & steel

Domestic/ industrial including smokeless fuel

Coal analysis

The basis of an analysis helps to specify the conditions under which the coal is tested

- ***as-mined basis:*** coal sample are freshly taken from the mine
- ***as-fired basis:*** may have resided in a coal pile for months, and be analyzed just before burning
- ***as-received basis:*** examined immediately after transport from the mine
- ***dry, ash-free*****, or** *dry and ash-free* ***basis:*** in the absence of water and/or non-combustible mineral matter

The two main coal analysis are:

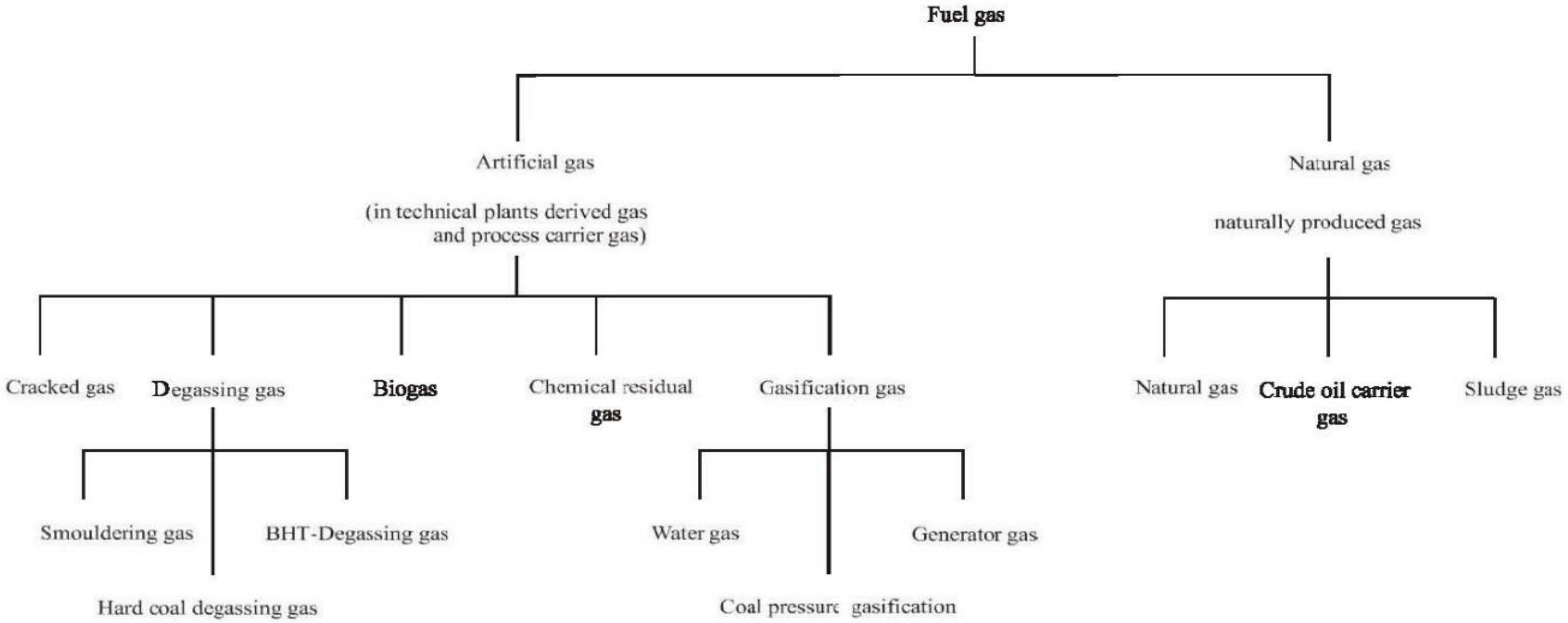
- Proximate analysis: determines mass percentage of
  - fixed carbon
  - volatile matter
  - moisture
  - ash
- Ultimate analsis: determines mass percentage of
  - carbon
  - hydrogen
  - nitrogen
  - oxygen
  - sulfur
  - Ash

Liquid Fuels

- Liquid fuels are primarily derived from crude oil through cracking and fractional distillation.
    - *Cracking* is a process by which long-chain hydrocarbons are broken up into smaller molecules.
    - *Fractional distillation* separates high-boiling-point hydrocarbons from those with lower boiling points.

Gaseous Fuels

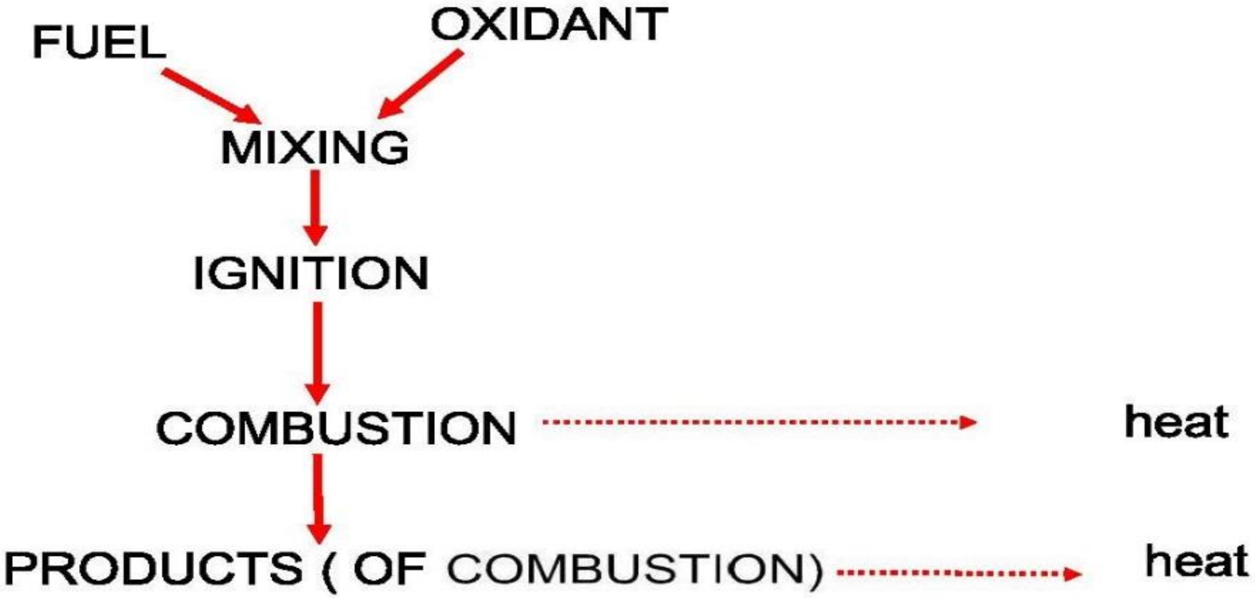
Natural gas is the most common gaseous fuel used in power plants. It mainly consists of methane (CH_4), ethane (C_2H_6) and nitrogen



- Fuel gas
  - Artificial gas (in technical plants derived gas and process carrier gas)
    - Cracked gas
    - Degassing gas
      - Smouldering gas
      - Hard coal degassing gas
      - BHT-Degassing gas
    - **Biogas**
    - Chemical residual **gas**
    - Gasification gas
      - Water gas
      - Coal pressure gasification
      - Generator gas
  - Natural gas naturally produced gas
    - Natural gas
    - **Crude oil carrier gas**
    - Sludge gas

Combustion of Fuels

- **Combustion** is a "chemical reaction between fuel and oxidizer involving significant release of energy as heat".
- **Fuel** is any substance that releases energy when oxidized.
- **Oxidizer** is any oxygen-containing substance (e.g. air) that reacts with fuel.



FUEL

OXIDANT

MIXING

IGNITION

COMBUSTION heat

PRODUCTS (OF COMBUSTION) heat

Composition of Standard Dry Air

- Air is a mixture of gases including oxygen (O_2), nitrogen(N_2), argon (Ar), carbon dioxide (CO_2), water vapour (H_20)….
- For combustion dry air is taken to be composed of 21% O_2 and 79% N_2 by volume (mole fraction).
- by mass air is 23.2% O2 and 76.8% N2

Hence, $$\frac{n_{N_2}}{n_{O_2}} = \frac{n_{N_2}}{n_{tot}} \cdot \frac{n_{tot}}{n_{O_2}} = \frac{y_{N_2}}{y_{O_2}} = \frac{0.79}{0.21} = 3.76$$

Hence, for every mole of O_2 there are 3.76 moles of N_2

And by mass from a similar analsis: for every kg of O2 there are 3.3 times kg of N2

.

Enthalpy of Formation

The enthalpy of formation is defined as the specific enthalpy change that occurs when a chemical compound is formed isothermally from its constituents. In a steady-flow process, the enthalpy of formation is equal to the quantity of heat absorbed or released during a chemical reaction.

$$\dot{Q} = \Delta H_o = \dot{m}_p h_p - \dot{m}_r h_r = \Delta H_p - \Delta H_r$$

$$= \sum_p (n_i \Delta h_i) - \sum_r (n_i \Delta h_i)$$

$H_p < H_r$, $Q < 0$ exothermic reaction

$H_p > H_r$, $Q > 0$ endothermic reactio

where

Δh_i = specific enthalpy of any product or reactant and
n_i = number of moles of the respective product or reactant of the chemical reaction.

The calcualtion of Δh_i will vary with calculation of the specific entalpy at any specified conditions. Thus, the values at the standard temperature and pressure are given for calculations.

Adiabatic Flame Temperature

The ***adiabatic flame** temperature **(combustion** temperature)* is the maximum theoretical combustion temperature when a complete chemical reaction occurs adiabatically, i.e. when no heat loss to the environment and no dissociation of effect (molecular decomposition). Highest possible temperature that can be achieved during combustion

Actual flame temperature is much cooler than this, due to

- heat transfer from the flame to the surrounding by convection and radiation
- Incomplete combustion, e.g. due to insufficient/inadequate mixing of the fuel with air or due to too short a residence time in the combustion chamber
- dissociation of $CO_2 \longrightarrow CO + 0.5O_2$ and $H_2O \longrightarrow H_2 + 0.5O_2$

EXAMPLE 1 **Balancing the Combustion Equation**

One kmol of octane (C_8H_{18}) is burned with air that contains 20 kmol of O_2, as shown in Fig. . Assuming the products contain only CO_2, H_2O, O_2, and N_2, determine the mole number of each gas in the products and the air–fuel ratio for this combustion process.

SOLUTION The amount of fuel and the amount of oxygen in the air are given. The amount of the products and the AF are to be determined.

Assumptions The combustion products contain CO_2, H_2O, O_2, and N_2 only.

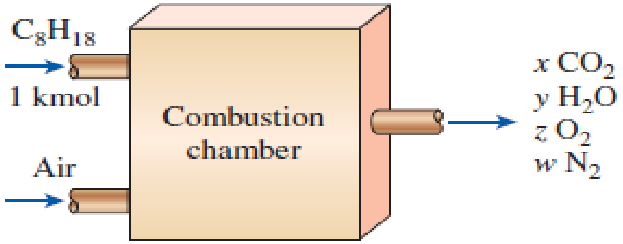
Properties The molar mass of air is $M_{air} = 28.97$ kg/kmol $\cong 29.0$ kg/kmol (Table A–1).

Analysis The chemical equation for this combustion process can be written as

$$C_8H_{18} + 20(O_2 + 3.76N_2) \rightarrow xCO_2 + yH_2O + zO_2 + wN_2$$

where the terms in the parentheses represent the composition of dry air that contains 1 kmol of O_2 and *x*, *y*, *z*, and *w* represent the unknown mole numbers of the gases in the products. These unknowns are determined by applying the mass balance to each of the elements—that is, by requiring that the total mass or mole number of each element in the reactants be equal to that in the products:

$$\begin{aligned}
&\text{C:} & 8 &= x & &\rightarrow & x &= 8\\
&\text{H:} & 18 &= 2y & &\rightarrow & y &= 9\\
&\text{O:} & 20 \times 2 &= 2x + y + 2z & &\rightarrow & z &= 7.5\\
&\text{N}_2\text{:} & (20)(3.76) &= w & &\rightarrow & w &= 75.2
\end{aligned}$$



FIGURE

Schematic for Example 1.

Substituting yields

$$C_8H_{18} + 20(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 7.5O_2 + 75.2N_2$$

Note that the coefficient 20 in the balanced equation above represents the number of moles of *oxygen*, not the number of moles of air. The latter is obtained by adding 20 × 3.76 = 75.2 moles of nitrogen to the 20 moles of oxygen, giving a total of 95.2 moles of air. The air–fuel ratio (AF) is determined from Eq. 15–3 by taking the ratio of the mass of the air and the mass of the fuel,

$$\begin{aligned} \mathrm{AF} &= \frac{m_{\mathrm{air}}}{m_{\mathrm{fuel}}} = \frac{(NM)_{\mathrm{air}}}{(NM)_{\mathrm{C}} + (NM)_{\mathrm{H_2}}} \\ &= \frac{(20 \times 4.76\ \mathrm{kmol})(29\ \mathrm{kg/kmol})}{(8\ \mathrm{kmol})(12\ \mathrm{kg/kmol}) + (9\ \mathrm{kmol})(2\ \mathrm{kg/kmol})} \\ &= \mathbf{24.2\ kg\ air/kg\ fuel} \end{aligned}$$

That is, 24.2 kg of air is used to burn each kilogram of fuel during this combustion process.

EXAMPLE 2 Combustion of Coal with Theoretical Air

Coal from Pennsylvania which has an ultimate analysis (by mass) as 84.36 percent C, 1.89 percent H_2, 4.40 percent O_2, 0.63 percent N_2, 0.89 percent S, and 7.83 percent ash (non-combustibles) is burned with theoretical amount of air . Disregarding the ash content, determine the mole fractions of the products and the apparent molar mass of the product gases. Also determine the air-fuel ratio required for this combustion process.

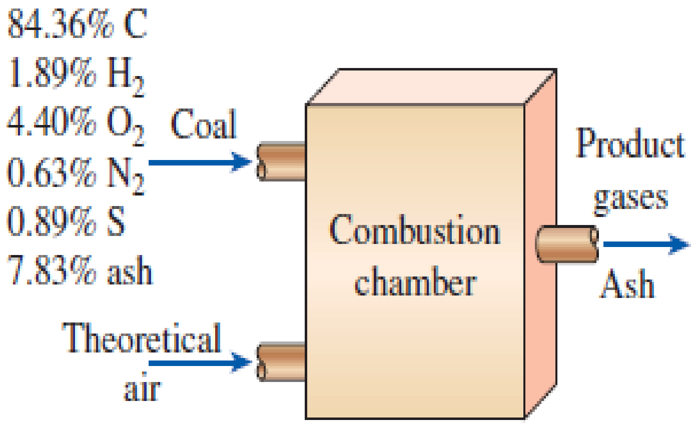


FIGURE
Schematic for Example 2.

SOLUTION Coal with known mass analysis is burned with theoretical amount of air. The mole fractions of the product gases, their apparent molar mass, and the air-fuel ratio are to be determined.

Assumptions **1** Combustion is stoichiometric and thus complete. **2** Combustion products contain CO_2, H_2O, SO_2, and N_2 only (ash disregarded). **3** Combustion gases are ideal gases.

Analysis The molar masses of C, H_2, O_2, S, and air are 12, 2, 32, 32, and 29 kg/kmol, respectively (Table A-1). We now consider 100 kg of coal for simplicity. Noting that the mass percentages in this case correspond to the masses of the constituents, the mole numbers of the constituent of the coal are determined to be

$$N_C = \frac{m_C}{M_C} = \frac{84.36\text{ kg}}{12\text{ kg/kmol}} = 7.030\text{ kmol}$$

$$N_{H_2} = \frac{m_{H_2}}{M_{H_2}} = \frac{1.89\text{ kg}}{2\text{ kg/kmol}} = 0.9450\text{ kmol}$$

$$N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{4.40\text{ kg}}{32\text{ kg/kmol}} = 0.1375\text{ kmol}$$

$$N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{0.63\text{ kg}}{28\text{ kg/kmol}} = 0.0225\text{ kmol}$$

$$N_S = \frac{m_S}{M_S} = \frac{0.89\text{ kg}}{32\text{ kg/kmol}} = 0.0278\text{ kmol}$$

Ash consists of the non-combustible matter in coal. Therefore, the mass of ash content that enters the combustion chamber is equal to the mass content that leaves. Disregarding this non-reacting component for simplicity, the combustion equation may be written as

$$7.03C + 0.945H_2 + 0.1375O_2 + 0.0225N_2 + 0.0278S + a_{th}(O_2 + 3.76N_2) \longrightarrow xCO_2 + yH_2O + zSO_2 + wN_2$$

Performing mass balances for the constituents gives

C balance: $x = 7.03$

H_2 balance: $y = 0.945$

S balance: $z = 0.0278$

O_2 balance: $0.1375 + a_{th} = x + 0.5y + z \longrightarrow a_{th} = 7.393$

N_2 balance: $w = 0.0225 + 3.76a_{th} = 0.0225 + 3.76 \times 7.393 = 27.82$

Substituting, the balanced combustion equation without the ash becomes

$$7.03C + 0.945H_2 + 0.1375O_2 + 0.0225N_2 + 0.0278S + 7.393(O_2 + 3.76N_2) \longrightarrow 7.03CO_2 + 0.945H_2O + 0.0278SO_2 + 27.82N_2$$

The mole fractions of the product gases are determined as follows:

$$N_{\text{prod}} = 7.03 + 0.945 + 0.0278 + 27.82 = 35.82 \text{ kmol}$$

$$y_{CO_2} = \frac{N_{CO_2}}{N_{\text{prod}}} = \frac{7.03 \text{ kmol}}{35.82 \text{ kmol}} = \mathbf{0.1963}$$

$$y_{H_2O} = \frac{N_{H_2O}}{N_{\text{prod}}} = \frac{0.945 \text{ kmol}}{35.82 \text{ kmol}} = \mathbf{0.02638}$$

$$y_{SO_2} = \frac{N_{SO_2}}{N_{\text{prod}}} = \frac{0.0278 \text{ kmol}}{35.82 \text{ kmol}} = \mathbf{0.000776}$$

$$y_{N_2} = \frac{N_{N_2}}{N_{\text{prod}}} = \frac{27.82 \text{ kmol}}{35.82 \text{ kmol}} = \mathbf{0.7767}$$

Then, the apparent molar mass of product gases becomes

$$M_{\text{prod}} = \frac{m_{\text{prod}}}{N_{\text{prod}}} = \frac{(7.03 \times 44 + 0.945 \times 18 + 0.0278 \times 64 + 27.82 \times 28)\text{kg}}{35.82 \text{ kmol}}$$
$$= \mathbf{30.9 \ kg/kmol}$$

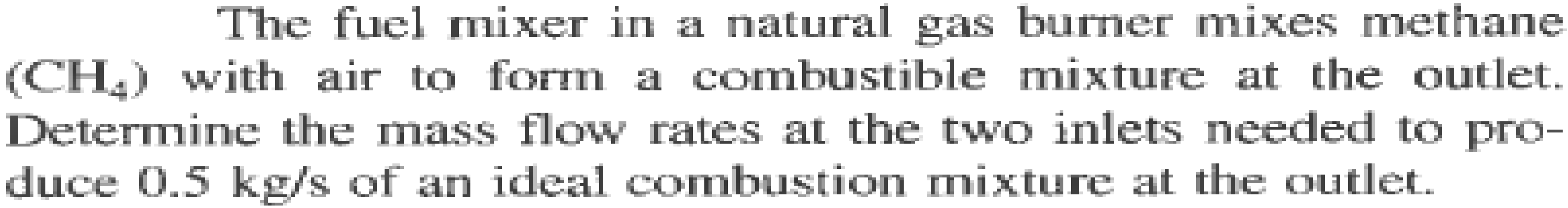
Finally, the air-fuel mass ratio is determined from its definition to be

$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{(7.393 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{100 \text{ kg}} = \mathbf{10.2 \ kg \ air/kg \ fuel}$$

That is, 10.2 kg of air is supplied for each kg of coal in the furnace.

Discussion We could also solve this problem by considering just 1 kg of coal, and still obtain the same results. But we would have to deal with very small fractions in calculations in this case.

Class Problem



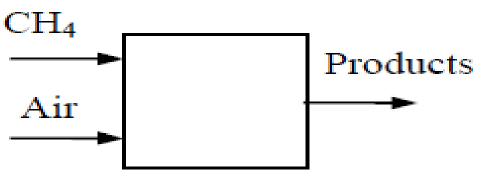
The fuel mixer in a natural gas burner mixes methane (CH_4) with air to form a combustible mixture at the outlet. Determine the mass flow rates at the two inlets needed to produce 0.5 kg/s of an ideal combustion mixture at the outlet.

Methane is burned with air. The mass flow rates at the two inlets are to be determined.

Properties The molar masses of CH_4, O_2, N_2, CO_2, and H_2O are 16, 32, 28, 44, and 18 kg/kmol, respectively (Table A-1).

Analysis The stoichiometric combustion equation of CH_4 is

$$\mathrm{CH_4} + a_{\mathrm{th}}\left[\mathrm{O_2} + 3.76\mathrm{N_2}\right] \longrightarrow \mathrm{CO_2} + 2\mathrm{H_2O} + 3.76a_{\mathrm{th}}\mathrm{N_2}$$



O_2 balance: $a_{\mathrm{th}} = 1 + 1 \longrightarrow a_{\mathrm{th}} = 2$

Substituting, $\mathrm{CH_4} + 2\left[\mathrm{O_2} + 3.76\mathrm{N_2}\right] \longrightarrow \mathrm{CO_2} + 2\mathrm{H_2O} + 7.52\mathrm{N_2}$

The masses of the reactants are

$$m_{\mathrm{CH4}} = N_{\mathrm{CH4}} M_{\mathrm{CH4}} = (1\ \mathrm{kmol})(16\ \mathrm{kg/kmol}) = 16\ \mathrm{kg}$$
$$m_{\mathrm{O2}} = N_{\mathrm{O2}} M_{\mathrm{O2}} = (2\ \mathrm{kmol})(32\ \mathrm{kg/kmol}) = 64\ \mathrm{kg}$$
$$m_{\mathrm{N2}} = N_{\mathrm{N2}} M_{\mathrm{N2}} = (2 \times 3.76\ \mathrm{kmol})(28\ \mathrm{kg/kmol}) = 211\ \mathrm{kg}$$

The total mass is

$$m_{\mathrm{total}} = m_{\mathrm{CH4}} + m_{\mathrm{O2}} + N_{\mathrm{N2}} = 16 + 64 + 211 = 291\ \mathrm{kg}$$

Then the mass fractions are

$$\mathrm{mf}_{\mathrm{CH4}} = \frac{m_{\mathrm{CH4}}}{m_{\mathrm{total}}} = \frac{16\ \mathrm{kg}}{291\ \mathrm{kg}} = 0.05498$$
$$\mathrm{mf}_{\mathrm{O2}} = \frac{m_{\mathrm{O2}}}{m_{\mathrm{total}}} = \frac{64\ \mathrm{kg}}{291\ \mathrm{kg}} = 0.2199$$
$$\mathrm{mf}_{\mathrm{N2}} = \frac{m_{\mathrm{N2}}}{m_{\mathrm{total}}} = \frac{211\ \mathrm{kg}}{291\ \mathrm{kg}} = 0.7251$$

For a mixture flow of 0.5 kg/s, the mass flow rates of the reactants are

$$\dot{m}_{\mathrm{CH4}} = \mathrm{mf}_{\mathrm{CH4}}\dot{m} = (0.05498)(0.5\ \mathrm{kg/s}) = \mathbf{0.02749\ kg/s}$$
$$\dot{m}_{\mathrm{air}} = \dot{m} - \dot{m}_{\mathrm{CH4}} = 0.5 - 0.02749 = \mathbf{0.4725\ kg/s}$$