




Konsep Fundamental TEKNOLOGI PEMBAKARAN -1

COMBUSTION TECHNOLOGY & THERMAL ANALYSIS

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Instructor's Background



- BEng. (1995): Universitas Diponegoro
- Meng. (2000): Institut Teknologi Bandung
- PhD. (2006): Universiti Teknologi Malaysia
- Specialization:
 - Catalyst Design for Energy Conversion
 - Process Design for Energy Conversion
 - Combustion Engineering
 - Computational Fluid Dynamic (CFD)

SYLLABUS

- 1. Dasar-dasar Teknik Pembakaran (150')
- 2. Konsep Fundamental Kimia Sistem Pembakaran (2x150')
- 3. Konsep Perpindahan Panas dalam Sistem pembakaran (150')
- 4. Flame Impingement (150')
- 5. Perancangan Sistem Burner (2x150')
- 6. Troubleshooting Sistem Pembakaran (150')
- 7. Bahan Bakar untuk Proses Pembakaran (2x150')
- 8. Permodelan Proses Pembakaran (2x150')
- 9. Pengendalian Proses Pembakaran (150')
- 10. Keselamatan Proses Dalam Sistem Pembakaran (2x150')
- 11. Sistem Flare di Teknologi Pembakaran (150')

Introduction

- Combustion is the controlled release of heat from the chemical reaction between a fuel and an oxidizer.
- The fuels in the refining, petrochemical, and power generation industries are almost exclusively hydrocarbons (C_xH_y).
- Hydrocarbons comprise only hydrogen (H) and carbon (C) in their molecular structure.
- Natural gas and fuel oil are examples of hydrocarbon fuels

Definitions of Natural Gas, Gas Reservoir, Gas Drilling, and Gas Production

- **What is Natural Gas?**
 - The gas obtained from natural underground reservoirs either as free gas or gas associated with crude oil
 - Contains large amounts of methane (CH₄) along with decreasing amounts of other hydrocarbon
 - Impurities such as H₂S, N₂, and CO₂ are often found with the gas
 - generally comes saturated with water vapor.

Why are Oil and Gas so Useful?

- **Oil is liquid.** Meaning that oil may be transported and delivered through pipe
- The primary use of **natural gas is as a fuel**, it is also a source of hydrocarbons for petrochemical feedstocks and a major source of elemental sulfur
- Natural gas presents many **environmental advantages** over petroleum and coal
- **Carbon dioxide**, a greenhouse gas linked to global warming, is produced from oil and coal at a rate of about 1.4 to 1.75 times higher than from natural gas

Typical gas Compositions

	Canada (Alberta)	Western Colorado	Southwest Kansas	Bach Ho Field ^a Vietnam	Miskar Field Tunisia	Rio Arriba County, New Mexico	Cliffside Field, Amarillo, Texas
Helium	0.0	0.0	0.45	0.00	0.00	0.0	1.8
Nitrogen	3.2	26.10	14.65	0.21	16.903	0.68	25.6
Carbon dioxide	1.7	42.66	0.0	0.06	13.588	0.82	0.0
Hydrogen sulfide	3.3	0.0	0.0	0.00	0.092	0.0	0.0
Methane	77.1	29.98	72.89	70.85	63.901	96.91	65.8
Ethane	6.6	0.55	6.27	13.41	3.349	1.33	3.8
Propane	3.1	0.28	3.74	7.5	0.960	0.19	1.7
Butanes	2.0	0.21	1.38	4.02	0.544	0.05	0.8
Pentanes and heavier	3.0	0.25	0.62	2.64	0.630	0.02	0.5

^a Tabular mol% data is on a wet basis (1.3 mol% water)

Source: U.S. Bureau of Mines (1972) and Jones et al. (1999).

Typical gas Composition in Indonesia

Component	Terengganu (Malaysia) ¹⁾	Natuna (Indonesia) ²⁾	Terrell County (Texas USA) ³⁾	Arun (Indonesia) ⁴⁾
Methane (CH ₄)	80.93	28.0 ^a	45.7	75
Ethane (C ₂ H ₆)	5.54	-	0.2	5.5
Propane (C ₃ H ₈)	2.96	-	-	3.4 ^b
Butane (C ₄ H ₁₀)	1.40	-	-	-
>=C ₅₊	-	-	-	0.8
Nitrogen (N ₂)	0.10	0.5	0.2	0.3
Carbon dioxide (CO ₂)	8.48	71.0	53.9	15
Hydrogen Sulfida (H ₂ S)	-	0.5	-	0.01

^a CH₄ + low C₂₊ hydrocarbons

^b C₃, C₄ hydrocarbons

¹⁾ Gordon et al. (2001)

²⁾ Suhartanto *et al.* (2001)

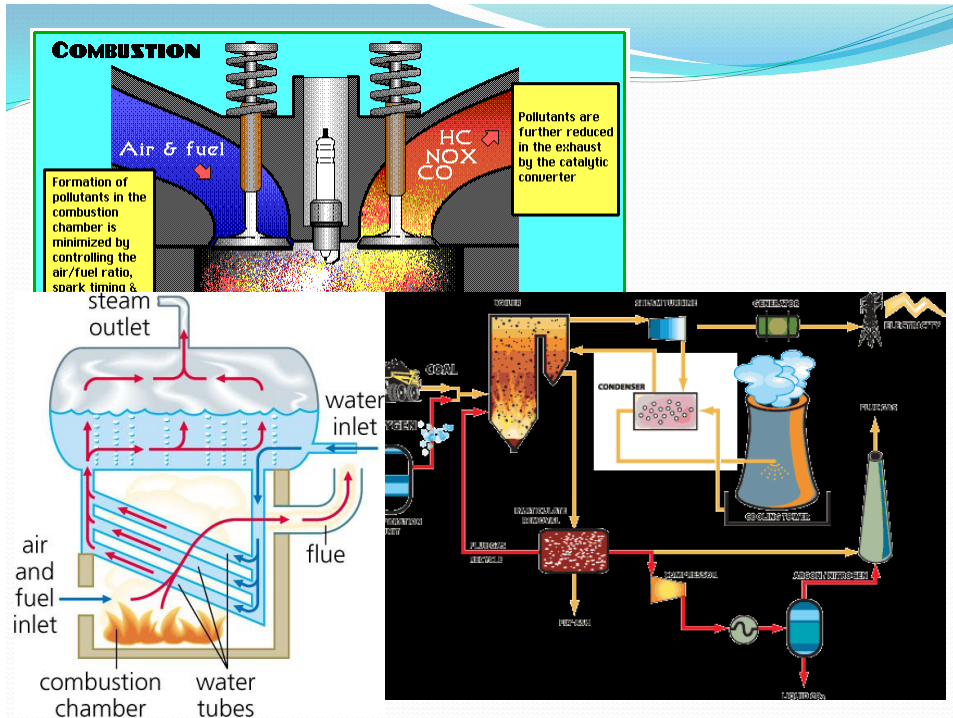
³⁾ Bitter (1997)

⁴⁾ Centi *et al.* (2001)

COMBUSTION EQUIPMENT AND HEAT TRANSFER

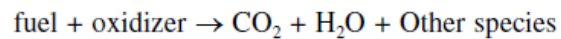
- In the process industries, combustion powers **gas turbines, process heaters, reactors, and boilers**.
- The burner **combusts fuel** and generates products of combustion and heat.
- A firebox contains the **flame** envelope.
- The fire **heats water** in the tubes to boiling.
- The steam rises to a steam drum that separates the liquid and vapor phases, returning water to the tubes and passing steam.
- The steam may be further heated in a **superheater**.
- Superheaters raise the temperature of the steam above the boiling point, using either radiant and/or convective heat transfer mechanisms.

- **Most large boilers** have water in the tubes and fire outside
- — called water-tube boilers.
- **Fire-tube boilers** put the fire and hot gases in tubes surrounded by water.
- **Reactors** such as cracking furnaces and reforming furnaces are more extreme versions of process heaters.
- Here, the process fluid undergoes chemical transformations to a different substance. For example, in an ethylene cracking furnace, liquid or gas feedstock transforms to ethylene (C_2H_4), an intermediate in the production of polyethylene and other plastics.
- There are many specialized types of reactors using combustion as the heat source.

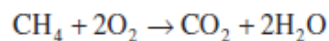


NET COMBUSTION CHEMISTRY OF HYDROCARBONS

- Consider the combustion of methane (CH_4) and air. CH_4 is the major component of natural gas. The combustion of CH_4 produces carbon dioxide (CO_2) and water vapor (H_2O).

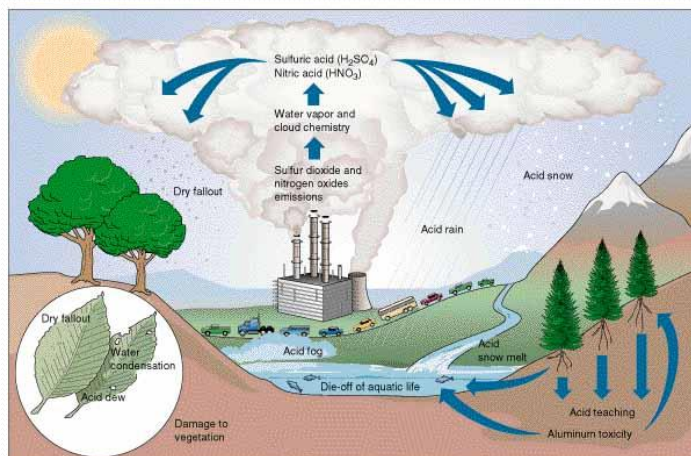
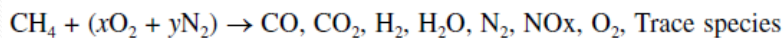


- Stoichiometric Equation:



- In a stoichiometric equation, the subscripted numbers define the proportions of elements in a molecule:
 - the methane molecule comprises four hydrogen atoms for every carbon atom,
 - and that an oxygen molecule comprises two oxygen atoms
- A mole comprises 6.02×10^{23} molecules \rightarrow Avogadro's number

- A global combustion reaction using CH₄ as the fuel can be written as:



CONSERVATION OF MASS

- Stoichiometric equations are always balanced equations
- Combustion reactions conserve mass; that is, the mass of the reactants must equal the mass of the products
- Stoichiometrically, 1 mole of CH₄ reacts with 2 moles of O₂ to produce 1 CO₂ and 2 moles of H₂O
- mass is conserved, but not in moles

TABLE 2.2 Molar Ratios for Some Combustion Reactions and Products

Reaction	Moles Reactants	Moles Products
$\text{H}_2 + 0.5 \text{O}_2 \rightarrow \text{H}_2\text{O}$	1.5	1.0
$\text{CO} + 0.5 \text{O}_2 \rightarrow \text{CO}_2$	1.5	1.0
$\text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}$	3.0	3.0
$\text{C}_2\text{H}_2 + 3 \text{O}_2 \rightarrow 2 \text{CO}_2 + \text{H}_2\text{O}$	2.5	3.0
$\text{C}_3\text{H}_8 + 5 \text{O}_2 \rightarrow 3 \text{CO}_2 + 4 \text{H}_2\text{O}$	6.0	7.0
$\text{C}_4\text{H}_{10} + 6.5 \text{O}_2 \rightarrow 4 \text{CO}_2 + 5 \text{H}_2\text{O}$	8.5	9.0

Note: Most combustion reactions do not conserve moles.

TABLE 2.3 Molecular Weights and Stoichiometric Coefficients for Common Gaseous Fuels

Common Name	Formula	Molecular Weight	O ₂ (moles)	CO ₂ (moles)	H ₂ O (moles)
Hydrogen	H ₂	2.02	0.5	0.0	1.0
Carbon monoxide	CO	28.01	0.5	1.0	0.0
Methane	CH ₄	16.05	2.0	1.0	2.0
Ethane	C ₂ H ₆	30.08	5.0	2.0	3.0
Ethene, ethylene	C ₂ H ₄	28.06	4.0	2.0	2.0
Acetylene, ethyne	C ₂ H ₂	26.04	3.0	2.0	1.0
Propane	C ₃ H ₈	44.11	7.0	3.0	4.0
Propene, propylene	C ₃ H ₆	42.09	6.0	3.0	3.0
Butane	C ₄ H ₁₀	58.14	7.0	4.0	5.0
Butene, butylene	C ₄ H ₈	56.12	8.0	4.0	4.0
Generic hydrocarbon	C _x H _y	12.01 x + 1.01 y	x + y/2	x	y/2

Ideal Gas Law

- The ideal gas law applies for typical combustion reactions and relates the pressure, volume, and number of moles

$$PV = nRT$$

where P = Pressure of the gas, psia
 V = Volume of the gas, ft³
 n = Number of moles
 R = Gas constant = 10.73 psia-ft³/lbmol-°R
 T = Absolute temperature, °R

- Another useful form of the ideal gas law:

$$PM = \rho RT$$

where ρ = Density of the gas, lb/ft³
 M = Molecular weight of the gas, lb/lbmol

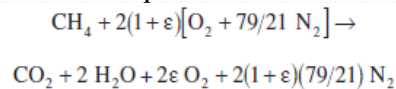
STOICHIOMETRIC RATIO AND EXCESS AIR

- The stoichiometric coefficient for **oxygen** → the theoretical oxygen required for combustion.
- The **theoretical air** comprising this amount of oxygen, it is necessary to define a mole of air as: **0.21 lbmol O₂ + 0.79 lbmol N₂**.

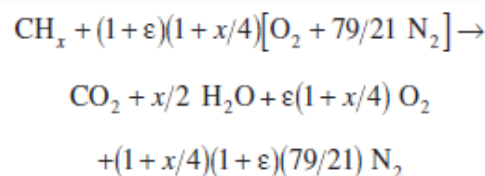
- Therefore:



- In industrial practice, perfect mixing cannot be achieved. It is actually more cost-effective to ensure complete combustion with the addition of excess air.
- Excess air is that amount beyond theoretical added to ensure complete combustion of the fuel.
- To account for excess air, the above Equation is modified with ϵ , the fraction of excess air:



- Two important chemical features of complete combustion → no carbon monoxide (CO) and no some unreacted oxygen appear in the combustion products
- To account for any hydrocarbon fuel, the Equation is modified by **x** (the H/C molar ratio).
- The following Equation gives a generic equation for hydrocarbons with air:



- Volumes of flue gas species to excess air for a given fuel H/C:
 - oxygen-to-fuel ratio (O/F): $O/F = (1 + x/4)(1 + \varepsilon)$
 - air-to-fuel ratio (A/F): $A/F = (100/21)(O/F)$
 - Total wet product (TWP): $TWP = A/F + x/4$
 - Total dry product (TDP): $TDP = A/F - x/4$
- In situ analyzers measure the flue gas species in the actual hot wet environment → wet
- extractive analyzers remove the flue gas, condense the water, and measure the concentration of the flue gas species in the dry gas → dry

- Volume fraction (f):

$$f_{O_2,wet} = \varepsilon(1 + x/4)/TWP \quad f_{O_2,dry} = \varepsilon(1 + x/4)/TDP$$

$$f_{CO_2,wet} = 1/TWP \quad f_{CO_2,dry} = 1/TDP$$

$$f_{N_2,wet} = 79/21(1 + \varepsilon)(1 + x/4)/TWP$$

$$f_{N_2,dry} = 79/21(1 + \varepsilon)(1 + x/4)/TDP$$

$$f_{H_2O,wet} = x/(2 TWP)$$

- Because of the strong relationship between oxygen and excess air, the **excess oxygen can be used as a measure of excess air** :

$$f_{O_2,wet} = \frac{0.21\varepsilon}{K_{wet} + \varepsilon} \quad f_{O_2,dry} = \frac{0.21\varepsilon}{K_{dry} + \varepsilon}$$

$$K_{wet} = \frac{4 + 1.21x}{4 + x} \quad K_{dry} = \frac{4 + 0.79x}{4 + x}$$

$$\varepsilon = K_{wet} \left(\frac{f_{O_2,wet}}{0.21 - f_{O_2,wet}} \right) \quad \varepsilon = K_{dry} \left(\frac{f_{O_2,dry}}{0.21 - f_{O_2,dry}} \right)$$

Heat of Combustion

- One measure of the chemical energy of a fuel is the **heat of combustion**
- Heat of combustion is reported as either **net heating value** (lower heating value, LHV) or **gross heating value** (higher heating value, HHV).
- When methane burns, it produces two products: CO₂ and H₂O. The CO₂ → a gas, however, H₂O → either a liquid or a vapor, depending on how much heat is extracted from the process.
- If so much heat is extracted that the **H₂O condenses**, then the combustion yields its **HHV**.
- If **water is released from the stack as a vapor**, then combustion yields the **LHV**. The LHV excludes the heat of vaporization
- The process industry usually uses the LHV. Boiler and turbine calculations usually use the HHV → must be consistent

Heating Value

- **Determination of the heating value** of a fuel involves two arbitrary but conventional standard states for the water formed in the reaction:
 - All the water formed is a liquid (gross heating value, frequently called higher heating value [HHV])
 - All the water formed is a gas (net heating value, frequently called lower heating value [LHV])
- The heating value is normally calculated at 60°F and 1 atm (15.6°C and 1.01 atm), standard conditions for the gas industry, and, thus at equilibrium, the water would be partially liquid and partially vapor.
- Heating values for custody transfer are determined either by direct measurement, in which bomb calorimetry is used, or by computation of the value on the basis of gas analysis

$$H_v^{id}(dry) = \sum_{i=1}^n x_i H_{vi}^{id}$$

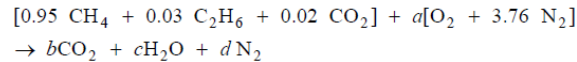
$$H_v^{id}(sat) = (1 - x_w) \sum_{i=1}^n x_i H_{vi}^{id}$$

Example of Heating Value Calculation

- **Problem:** A natural gas has a volumetric analysis of 95% CH₄, 3% C₂H₆, and 2% CO₂. For conditions of 14.7 psia and 77°F, calculate (a) the higher heating value of the fuel, Btu/ft³ of gas; and (b) the lower heating value of the fuel, Btu/ft³ of gas.

- **Solution:**

- Stoichiometric equation:



Carbon atom balance:

$$0.02 + 0.95 + 0.06 = b = 1.03$$

Hydrogen atom balance:

$$(4)(0.95) + (6)(0.03) = 2c \quad c = 1.99$$

Oxygen atom balance:

$$(2)(0.02) + 2a = (2)(1.03) + 1.99 \quad a = 2.005$$

Nitrogen atom balance:

$$d = 3.76a = (3.76)(2.005) = 7.539$$

- **Energy balance:**

$$Q = \sum_{i=\text{prod}} N_i [\bar{h}_f^0 + \Delta\bar{h}]_i = \sum_{j=\text{react}} N_j [\bar{h}_f^0 + \Delta\bar{h}]_j$$

or

$$Q = 1.03[\bar{h}_f^0 + \Delta\bar{h}]_{\text{CO}_2} + 1.99[\bar{h}_f^0 + \Delta\bar{h}]_{\text{H}_2\text{O}} \\ + (3.76)(2.005)[\bar{h}_f^0 + \Delta\bar{h}]_{\text{N}_2} - 0.95[\bar{h}_f^0 + \Delta\bar{h}]_{\text{CH}_4} \\ - 0.03[\bar{h}_f^0 + \Delta\bar{h}]_{\text{C}_2\text{H}_6} - 0.02[\bar{h}_f^0 + \Delta\bar{h}]_{\text{CO}_2} \\ - 2.005[\bar{h}_f^0 + \Delta\bar{h}]_{\text{O}_2} - (2.005)(3.76)[\bar{h}_f^0 + \Delta\bar{h}]_{\text{N}_2}$$

- higher heating value assumes water in the products is a liquid

$$Q = (1.03)(-94,054) + 1.99(-68,317) - 0.95(-17,889) \\ - 0.03(-20,236) - 0.02(-94,054) = -213,344$$

$$\overline{HHV} = 213,340 \text{ cal/gmole}$$

$$= (213,340 \text{ cal/gmole})(1.8001 \frac{\text{Btu/lbmole}}{\text{cal/gmole}})$$

$$= 384,033 \text{ Btu/lbmole}$$

- Density of Fuel:

$$\bar{\rho} = \frac{P}{RT} = \frac{(14.7 \text{ lbf/in}^2)(144 \text{ in}^2 / \text{ft}^2)}{(1,545 \text{ ft} \cdot \text{lbf/lbmole} \cdot ^\circ\text{R})(537^\circ\text{R})}$$

$$= 0.00255 \text{ lbmole/ft}^3$$

- Higher heating value, water as liquid in product"

$$HHV = (384,033 \text{ Btu/lbmole})(0.00255 \text{ lbmole/ft}^3)$$

a. $HHV = 980 \text{ Btu/ft}^3$

- Lower heating value, water as vapor in product:

$$LHV = HHV - 1.99 h_{fg}(68^\circ\text{F})$$

$$LHV = +384,033 \text{ Btu/lbmole fuel}$$

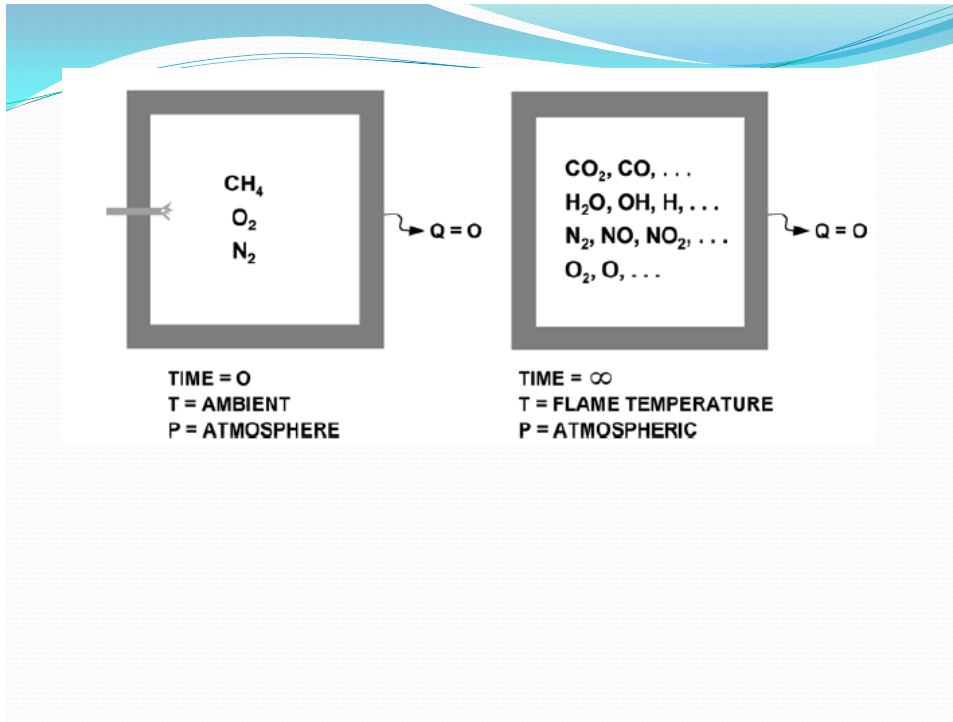
$$- \left(1.99 \frac{\text{lbmole H}_2\text{O}}{\text{lbmole fuel}} \right) \left(1,054 \frac{\text{Btu}}{\text{lbm H}_2\text{O}} \right) \left(18 \frac{\text{lbm}}{\text{lbmole H}_2\text{O}} \right)$$

b. $LHV = 346,279 \text{ Btu/lbmole}$

Adiabatic Flame Temperature

- Heat (Q) <=====> Temperature (T)\
- **Heat is energy** in transit. When a body absorbs heat, it stores it as another form of energy, increasing the body's **temperature** and expanding it.
- The same amount of heat absorbed in different materials will yield different temperature increases and expansions
→ depends on **heat capacity (Cp)**
- For a given mass of fuel, m. the total energy is:

$$Q = m\Delta H = mC_p\Delta T$$



Example 1:

- **Problem:** If 1 lb CH_4 combusts in 15% excess air, what is the maximum possible flame temperature.
- **Solution:**
- From stoichiometric equation:



- Use the basis of 1 lb CH_4 and ratio all other components by the molecular weight of CH_4 to obtain the following:

IN		OUT	
CH_4 :	1.00 lb	CO_2 : $1 * (44.01/16.05) =$	2.74 lb
		H_2O : $2 * (18.02/16.05) =$	2.24
O_2 : $1.15 * 2 * (32.00/16.05) =$	4.59	O_2 : $0.30 * (32.00/16.05) =$	0.60
N_2 : $1.15 * 2 * 79/21 * (28.02/16.05) =$	15.11	N_2 : $8.65 * (28.02/16.05) =$	15.11
	20.7 lb		20.7

- The highest possible flame temperature presumes no loss from the flame whatsoever. This is known as the **adiabatic flame temperature**.
- total energy from combustion of 1 lb of fuel:
1 lb * 22,000 Btu/lb = 22,000 Btu

$$\Delta T = \Delta H / mC_p$$

- Because there are several species in the flue gas, the contribution of each species must be used for mC_p .

$$mC_p = m_{\text{CO}_2} C_{p\text{CO}_2} + m_{\text{H}_2\text{O}} C_{p\text{H}_2\text{O}} + m_{\text{O}_2} C_{p\text{O}_2} + m_{\text{N}_2} C_{p\text{N}_2}$$

- If $C_p = 0.30 \text{ BTU/lb}\cdot^\circ\text{F}$, then the **adiabatic flame temperature** becomes:

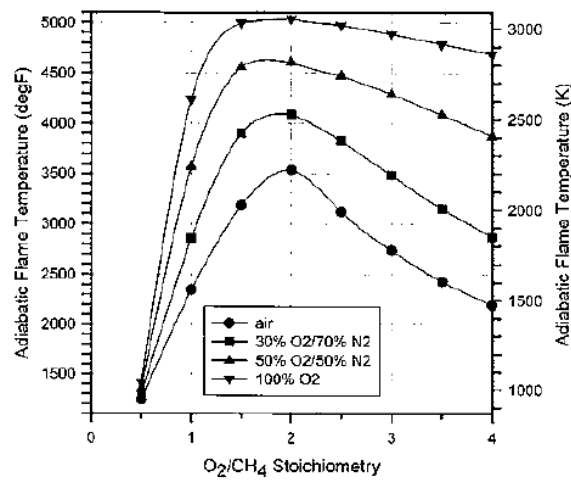
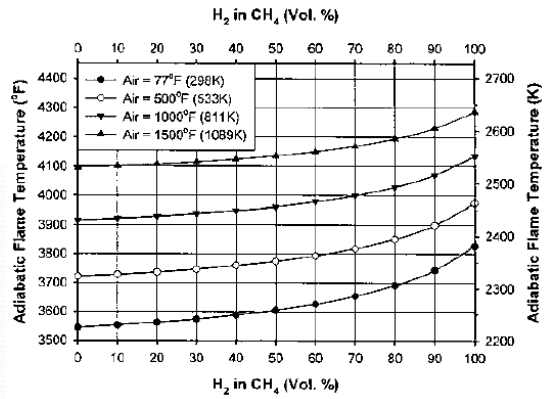
$$\Delta T = 22,000 \frac{\text{Btu}}{\text{lb}} \left(\frac{\text{lb}\cdot^\circ\text{F}}{0.30 \text{ Btu}} \right) \left(\frac{1}{20.7 \text{ lb}} \right) = 3543^\circ\text{F}$$


- For air and fuel at 60°F , the adiabatic fuel temperature becomes:
AFT = 3543 + 60 = 3603 °F

- Note that the actual flame temperature will be much cooler than this, because heat will transfer from the flame to the surroundings via convection and radiation.
- at high temperatures, $\text{CO}_2 \rightarrow \text{CO} + 0.5 \text{ O}_2$ and $\text{H}_2\text{O} \rightarrow \text{H}_2 + 0.5 \text{ O}_2$, reducing the adiabatic flame temperature.

TABLE 2.1
Adiabatic Flame Temperatures

Fuel	Air		O ₂	
	°F	K	°F	K
H ₂	3807	2370	5082	3079
CH ₄	3542	2223	5036	3053
C ₂ H ₂	4104	2535	5556	3342
C ₂ H ₄	3790	2361	5256	3175
C ₂ H ₆	3607	2259	5095	3086
C ₃ H ₆	4725	2334	5203	3138
C ₃ H ₈	3610	2261	5112	3095
C ₄ H ₁₀	3583	2246	5121	3100
CO	3826	2381	4901	2978





NEXT ON “Sub-stoichiometric
Combustion; equilibrium
thermodynamics; Combustion
Kinetics; Flame Properties”