

# APTI Course 427

## Combustion Source Evaluation

### Chapter 4: Fundamentals of Combustion

# Chapter Overview (outline)

- Introduction
- Combustion Mass Flows, Stoichiometry
- Enthalpy of Combustion & Heating Values
- Combustor Size and Residence Time

# Introduction (outline)

- Chemical Balance
- Heat Input Rate- Conservation of Energy
- Fuels & Air Flow- Conservation of Mass
- Excess Air
- Water Vapor in Exhaust Gas

# Chemical Balance



# Chemical Balance (methane)



- Chemical balance  $\rightarrow$  air flow matches fuel flow
- Combustion products are non polluting even if the fuel is legally hazardous/toxic
- Considerable water is generated
- Nitrogen (most of the air) isn't shown

# Missing Elements

- Nitrogen
  - Air is 78%  $N_2$ , about 79% “inert” species
  - Fuel is <10% of the combustion mass flow
- Extra air – excess air – required for complete combustion
- Contaminants in the fuel
  - Inorganic elements cause air pollution

# Heat Input Rate

- Conservation of energy
  - Fuel flow: enough to satisfy load demand
- Design capacity, heat input, or firing rate
  - May be expressed as the maximum BTU/hr, horsepower, MW, steam flow rate, etc.
  - Fundamental limit is heat transfer – mmBTU/hr
  - Design capacity appears on name plate or original construction documents

# Heat Input Rate (cont.)

- Rated capacity can change by a small amount
  - Up rated if original hardware was oversize
  - Down rated from deterioration or deliberate change
- Operating a system above rated capacity can greatly increase maintenance & repair costs.
- Boiler system components have some margin
  - Fuel feeders to handle substandard fuel
  - Fans to accommodate air leaks



# Heat Input Rate (cont.)

- Boiler is limited by max heat flux (mmBTU/hr)
- Fuel feed matches boiler design firing rate:
  - cubic feet per hour (gas fuels)
  - gallons/hour (oil)
  - tons/hr (coal, wood or waste)

- Relationship

$$\text{Fuel energy (BTU/lb)} * \text{Fuel mass flow (lb/hr)} = \text{Firing rate (BTU/hr)}$$

# Example 4-1. Boiler oil flow

- Determine the oil flow rate to a boiler operating at 85 mmBTU/hr. Residual oil HHV is 150,000 BTU/gallon.
- *Solution:*

$$\frac{85 * 10^6 \text{ BTU/hr}}{150,000 \text{ BTU/gal}} = 567 \text{ gal/hr (9.4 gal/min)}$$

# Fuel and Air Flow – Conservation of Mass

- Combustion requires fuel and air – the total exhaust flow is the sum (eqn 4-3)

Fuel mass flow + Air mass flow = Exhaust gas mass flow

- Fuel flow is 1/10 or less of the total flow
- Fuel flow varies with load.
- Fuel/air ratio should be fairly constant.

# Excess Air

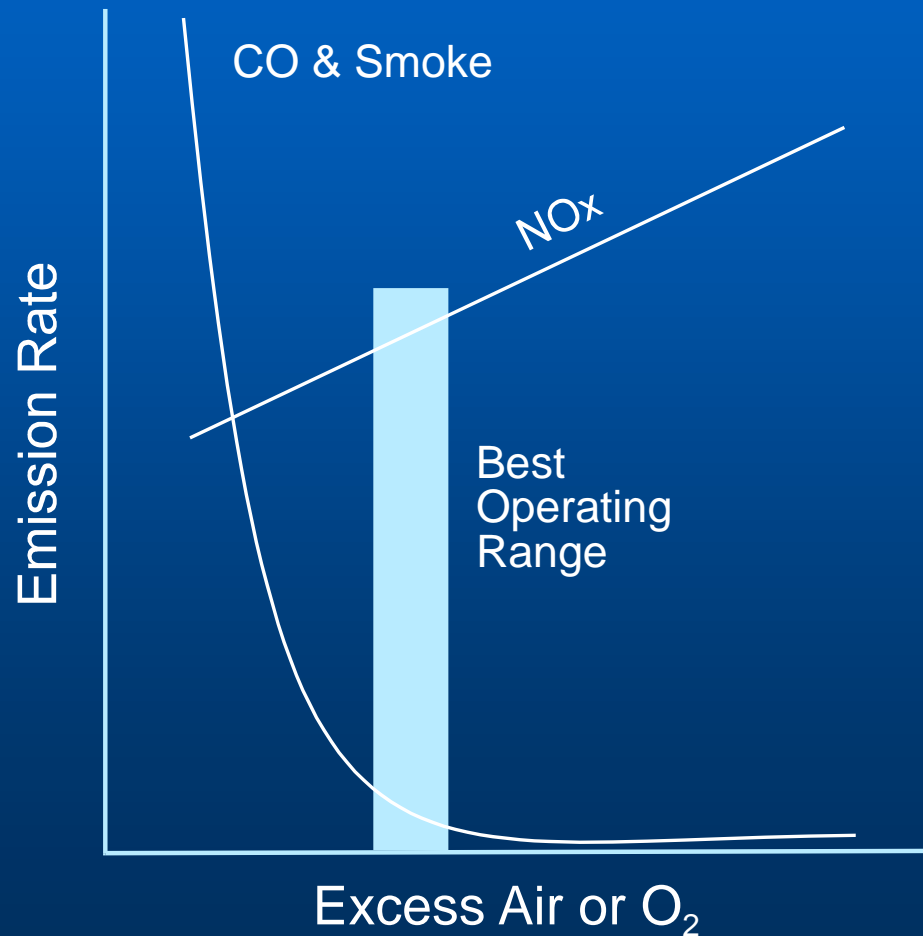
- Stoichiometric air flow – amount of air required per chemical balance
- Equivalence ratio = actual A/F over stoich A/F
  - Equiv ratio = 1 when air flow is stoich
  - Equiv ratio <1 with insufficient air (smoking)
  - Equiv ratio >1 with excess air

- Excess air defined

Total air flow = Stoichiometric air + Excess air

- Products of incomplete combustion (PIC)

# NOx and CO Emissions vs. Excess Air



# Excess Air (cont.)

- The amount of excess air required depends on the combustion system
- The better the combustion system, the less excess air required.
  - The best oil & gas systems can operate at about 3% excess air without significant PIC.

# Excess Air Ranges

**Table 4-1. Typical Minimum Excess Air Levels**

<i>Type of Combustion</i>	<i>Excess Air</i>	<i>% Oxygen</i>
Suspension firing: oil, gas, pulverized coal	5-15%	1-3%
Cyclone (crushed coal)	10-15%	2-3%
Stoker grate: coal, wood, solid waste	30-75%	5-9%
Fluidized bed	5-150%	1-13%
Combustion Turbine	250%	15%
Lean burn reciprocating engine	>5%	>1%

# Excess Air (cont'd)

- Reasons to operate at LEA
  - Better thermal efficiency
  - Lower NO<sub>x</sub>
  - More load capacity on some boilers
- Objectives of good combustion performance
  - System capable of LEA
  - Continuous operation at LEA



# Water Vapor in Exhaust Gas

- Water from fuel hydrogen
- Typical flue gas amounts
  - Natural gas 20% by vol.
  - Oil 10% by vol.
  - Coal 6% by vol.
  - Green wood 18% by vol.
  - Ambient air 2% by vol.
- Water condenses when flue gas cools

# Effects of Water Vapor

- HHV
- Condensation
- Flame temperature

# Combustion Mass Flows, Stoichiometry

- Objective: show that firing rate can be calculated from stack data
  - Primary data required are stack flow and  $O_2$
- This is true except when
  - Source is firing very wet fuel
  - Source process adds gas to the flow
- Using stack data to get firing rate is useful
  - When the firing rate is unknown or questioned
  - As a QC check of emissions test data

# Combustion Mass Flows, Stoichiometry (outline)

- Stoichiometric Air Flow
- Excess Air
- Water Vapor
- Calculating Gas Volume and Density

# Stoichiometric Air Flow



- Chemical balance defines air/fuel mass ratio
- Deriving an equation for air & real fuel:
  - Insert fuel analysis data for C, H, S, O
  - Insert molecular weights
  - Insert air data (20.9% O<sub>2</sub>, etc)
- Result is exhaust gas composition (lb/lb fuel)

# Stoichiometric Air Flow (2)

- Carry this exercise a bit further
  - Insert fuel heating value (HHV)
  - Insert exhaust gas density (lb/ft<sup>3</sup>)
- Result is ft<sup>3</sup> flue gas / mmBTU -- Definition of the F-factor.

*Volume of exhaust gas generated by burning one mmBTU of fuel with no excess air.*

# F-factor

**Table 4-5. “F-factors” for Various Fuels (scf/mmBTU)**

Fuel Types	F <sub>d</sub> - dry	F <sub>w</sub> - wet	F <sub>c</sub> - carbon
Anthracite coal	10100	10540	1970
Bituminous coal	9780	10640	1800
Lignite	9860	11950	1910
Wood	9240	----	1830
Oil	9190	10320	1420
Natural gas	8710	10610	1040

# F-factor (cont.)

- F-Factor is the key relationship between stack flow and firing rate.

$$F_d = \frac{10^6}{\text{HHV}} \times [3.64 (\%H) + 1.53 (\%C) + 0.57 (\%S) + 0.14 (\%N) - 0.46 (\%O)]$$

- Wet F-factor (eqn 4-6)
- Dry F-factor (eqn 4-7)
- $F_c$



# Stack Flow & Firing Rate

- F-factor means firing rate can be determined without measuring fuel flow

$$\text{E.G. Stoich. Flow} \left( \frac{\text{std ft}^3}{\text{hr}} \right) = \text{Firing Rate} \left( \frac{\text{mmBTU}}{\text{hr}} \right) \times F_w \left( \frac{\text{std ft}^3}{\text{mmBTU}} \right)$$

Note: We still need to account for excess air to relate firing rate to the actual (total) stack flow

## Example 4-2

If stoichiometric exhaust flow is 45,000 scfm, what is the approximate oil or gas firing rate?

Solution:

$$45,000 \text{ (ft}^3\text{/min)} * 60 \text{ (min/hr)} / 10,500 \text{ (ft}^3\text{/mmBTU)} = 257 \text{ (mmBTU/hr)}$$

(We could have started with firing rate and calculated stack stoich flow)

# Excess Air (outline)

- Excess air is necessary for complete combustion
  - Insufficient air assures incomplete combustion - PIC
- Management
- Measurement
- Diagnostic uses

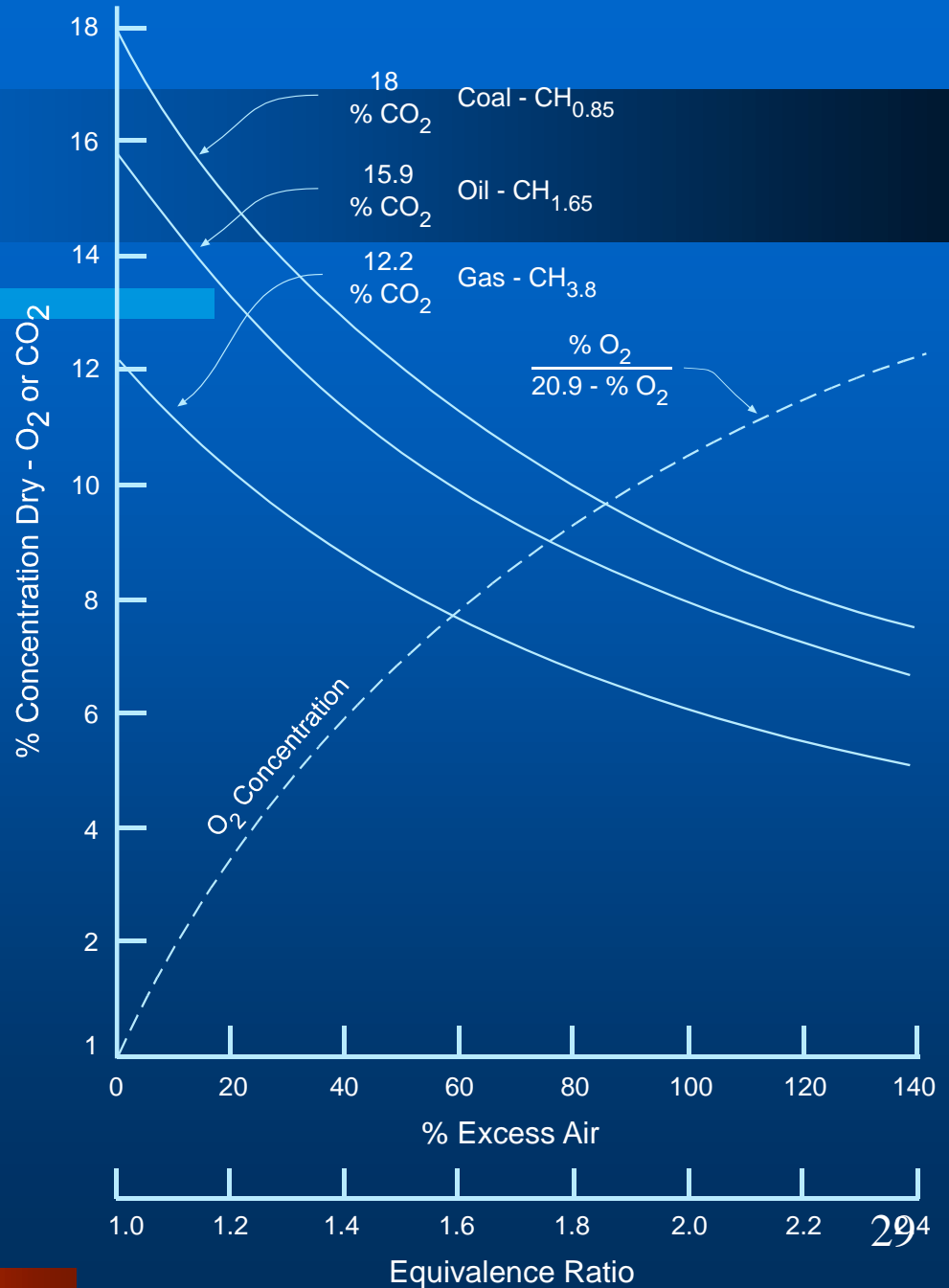
# Excess Air Management

- Combustor controls couple air flow to fuel flow
  - This gives approximately correct air flow
- Exhaust O<sub>2</sub> concentration measures excess air (air/fuel equivalence ratio)

$$\% \text{ Excess Air} = \frac{\% \text{ O}_2}{20.9 - \% \text{ O}_2} \times 100$$

- Definition, not a rigorous derivation

# Excess Air vs. O<sub>2</sub> & CO<sub>2</sub>



# Equivalence Ratio

$$\text{Equivalence Ratio} = \frac{20.9}{20.9 - \%O_2}$$

- Also called the “excess air correction factor”
  - Same information as excess air
- Note that the range of values is 1 to infinity

# Excess Air vs. $O_2$ & $CO_2$ (cont.)

- $CO_2$  can be use to determine excess air – but value depends on fuel type.
- $O_2$  is easier to use
- $CO_2$  use dates from early measurement technology - the Orsat device

# Total Exhaust Flow and Firing Rate

$$\text{Exhaust Flow} = \text{Stoich. Flow} \times \left( \frac{20.9}{20.9 - \% \text{O}_2} \right)$$

$$\text{Firing Rate} \left( \frac{\text{mmBTU}}{\text{hr}} \right) = \frac{\text{Exhaust Flow} \left( \frac{\text{ft}^3}{\text{hr}} \right) \times \frac{20.9 - \text{O}_2}{20.9}}{F_w \left( \frac{\text{ft}^3}{\text{mmBTU}} \right)}$$



## Example 4-3

Determine the firing rate of a source with 20,000 scfm stack flow at 4.0% O<sub>2</sub>.

Solution: Use eqn 4-11

$$\frac{20,000 \text{ ft}^3/\text{min} \times 60 \text{ min}/\text{hr} \times \frac{20.9 - 4.0}{20.9}}{10,500 \text{ ft}^3/\text{mmBTU}} = 92.4 \text{ mmBTU}/\text{hr}$$

Where we use a generic F-factor = 10,500

# Oxygen Measurement

- O<sub>2</sub> data are used for two purposes:
  - Excess air control
  - Emissions measurement
- Possible issues
  - Uniformity in duct flows
  - Interpreting the source of oxygen

# Water Vapor (outline)

- Water from Fuel Hydrogen
- Water from Fuel Moisture
- Water from Combustion Air

# Water from Fuel Hydrogen

Stoichiometric water vapor concentration is given below where  $y$  is the fuel H/C ratio given by  $12 * \%H/\%C$

$$V_{w^1} = \frac{y/2}{4.78 + 1.45 \times y} \times 100$$

The exhaust concentration depends on the amount of air dilution, so:

$$V_w \text{ (actual exhaust concentration)} = V_{w^1} \times \left( \frac{20.9 - \% O_2}{20.9} \right)$$

# Water Vapor from Fuel Moisture

Fuel moisture contributes according to the formula  
where  $w$  = % moisture in the fuel

$$\% \text{ Flue Gas Water Vapor} = 25 \times \left( \frac{w}{100 - 0.75 w} \right)$$

This is stoichiometric, so actual concentration is reduced by  
the amount of excess air.

In practice measured data are preferred over a mass balance

# Calculating Gas Volume and Density

## Ideal Gas Law

$$PV = nRT$$

Where:

P is pressure in lb/ft<sup>2</sup>

V is volume in ft<sup>3</sup>

n is number of moles

V/n = 385 ft<sup>3</sup>/mole for gas at 68°F (528°R)

R is the universal gas constant = 1545 ft-lb/(lb-mole °R)

T is temperature in degrees Rankin

# Calculating Gas Volume and Density (cont.)

$$V_1 = V_2 \times (T_1/T_2) \times (P_2/P_1)$$

Typically (1) is standard conditions and (2) is stack

$$T_{\text{std}} = 528\text{K (68F)}$$

$$P_{\text{std}} = 29.92 \text{ inches Hg}$$

## Example 4-4.

Stack test data show 8,000 ft<sup>3</sup>/min at 310°F, 28.67 inches Hg, and a stack draft of –0.45 inches w.g. Determine the flow rate in standard cfm (std ft<sup>3</sup>/min).

Solution: First determine stack pressure

$$P_s = 28.67 - 0.45/13.6 = 28.64 \text{ inches Hg}$$

Second, use Eqn 4-14

$$\begin{aligned} V_{\text{std}} &= 8000 \text{ acfm} * [528^\circ\text{R}/(460 + 310)^\circ\text{R}] * [28.64/29.92] \\ &= 5251 \text{ scfm} \end{aligned}$$



# Example 4-5. Molecular weight

Stack data show water vapor = 8% by vol. and  $O_2$  = 5% by vol.  
What is the approximate density of the exhaust at STP?

Solution:

First find the average MW. Use Fig 4-2 to estimate  $CO_2$  at 14%. Determine  $N_2$  by difference:

$$\%N_2 = 100 - 8 - 5 - 14 = 73\%$$

Flue gas MW is the weighted average of constituents

$$MW_{avg} = [73*28 + 14*44 + 5*32 + 8*18]/100 = 29.6$$

# Example 4-5. (cont'd)

Use Eqn 4-15 for density

$$\begin{aligned}\rho &= 29.6 \text{ (lb/lb-mole)} / 385 \text{ (std ft}^3 \text{ / lb-mole)} \\ &= 0.077 \text{ (lb/ std ft}^3\text{)}\end{aligned}$$

# Wet & Dry Molecular Wt

EPA Method 2 relates wet & dry MW

$$MW_s = (1 - B_{ws}) * MW_d + 18 * B_{ws}$$

Where:  $MW_s$  is for (stack) exhaust gas  
 $MW_d$  is for dry exhaust gas  
 $B_{ws}$  is the gas volume fraction of water

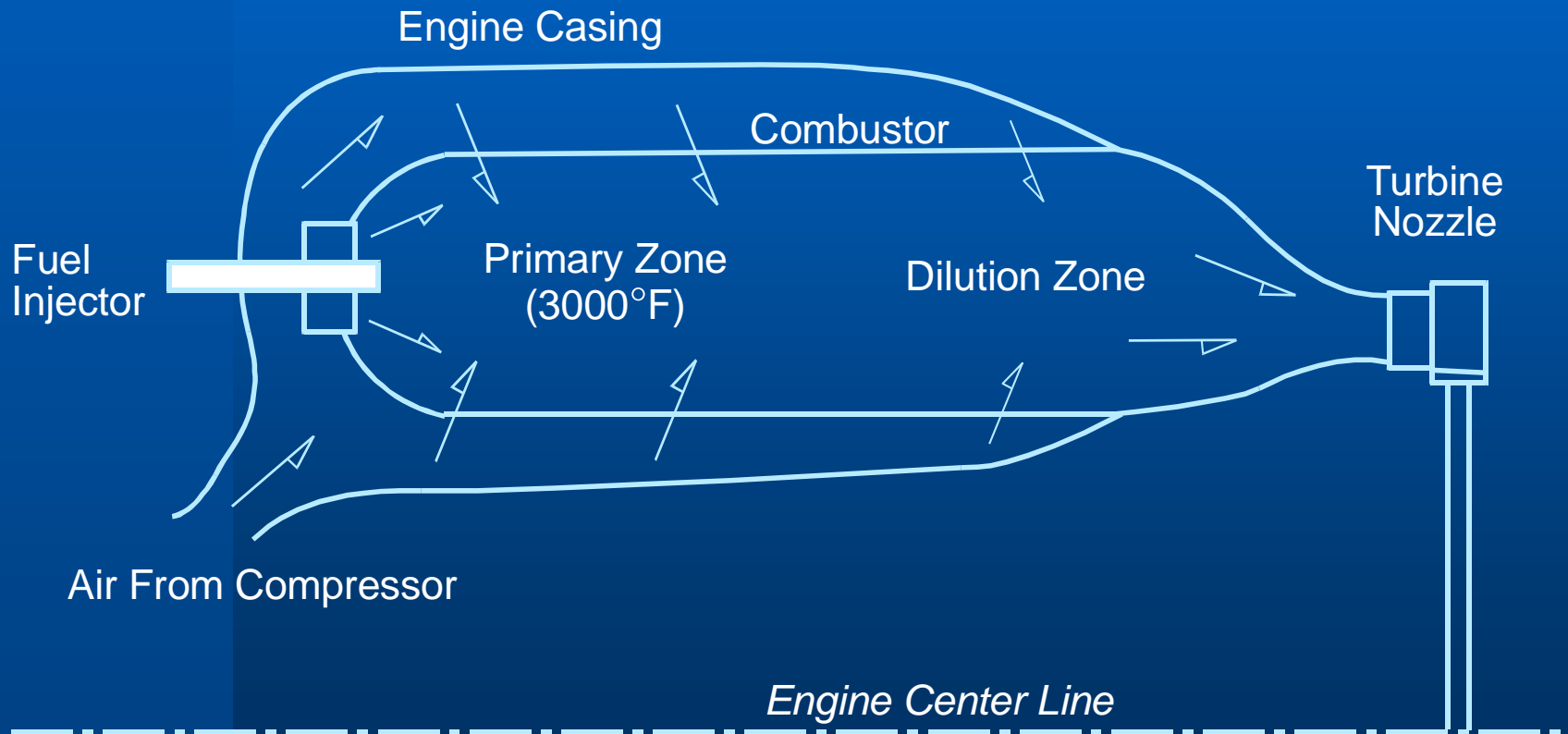
# Enthalpy of Combustion and Heating Values (outline)

- Flame Structure - Primary and Dilution Zones
- Combustion Temperature Levels
- Energy Content of the Flue Gas

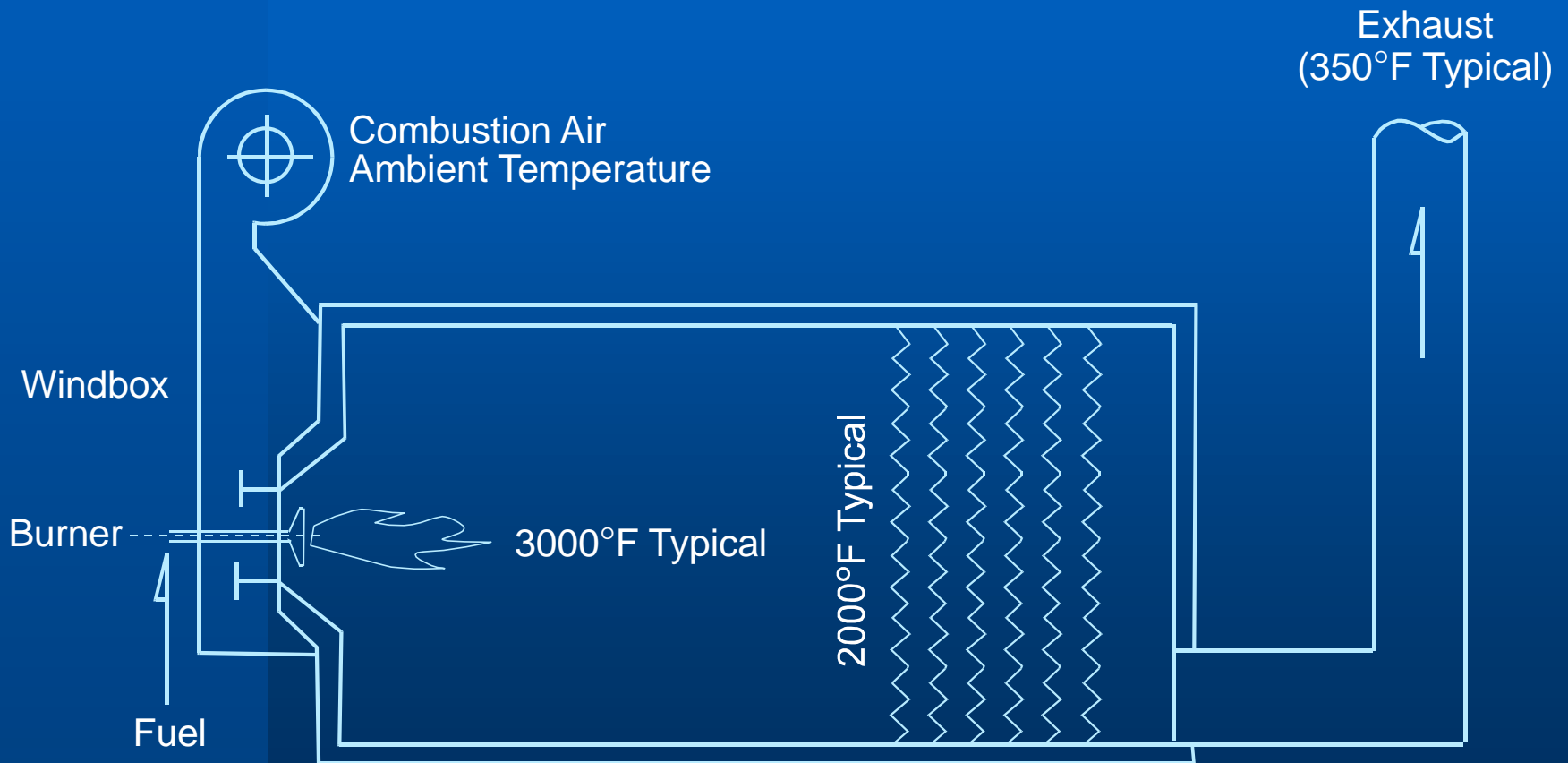
# Flame Structure

- Combustion temperatures
  - Chemical reactions at any temp., but
  - Flames require at least 2500°F
  - Fire is either hot or it goes out
- Gas Turbine Combustor
  - Hot primary zone followed by dilution
- Boiler Combustor
  - Hot flames followed by heat transfer

# Gas Turbine Combustor



# Boiler Combustor



# Physical and Chemical Processes

- Fuel & air mixing & burning occur simultaneously in most commercial combustors
  - Chemistry is fast, so mixing usually limits the burning rate.
- A hot primary zone is a key element of flame stability.
  - Local peak temps probably about 4000°F
  - Radiative cooling is very fast at these temps.



# Combustion Temperature Levels

(outline)

- Stoichiometric Flame Temperature
- Adiabatic Temperature with Excess Gas
- Local versus Average Temperature

# Stoichiometric Flame Temperature

- Adiabatic temperature
  - Theoretical temperature with no heat loss
  - Think of fire in an insulated box
- Basic energy balance
  - Fuel energy released = Enthalpy of the exhaust gas
  - Can be used to derive “flame temperature” – a theoretical maximum combustion temperature
  - Maximum delta-T is about 4000°F

# Energy Balance (1)

Fuel energy = Exhaust enthalpy (eqn 4-16)

$$Q \text{ (BTU)} = V \text{ (std ft}^3\text{)} \times \left(\frac{29}{385}\right) \left(\frac{\text{lb}}{\text{std ft}^3}\right) \times C_p \left(\frac{\text{BTU}}{\text{lb}^\circ\text{F}}\right) \times \Delta T \text{ (}^\circ\text{F)}$$

Where:

Q = Fuel energy released

V = E.G. volume at standard conditions

C<sub>p</sub> = E.G. specific heat

delta T = E.G. temperature rise

# Energy Balance (2)

- Solve equation 4-16 for delta-T – the adiabatic temperature rise.

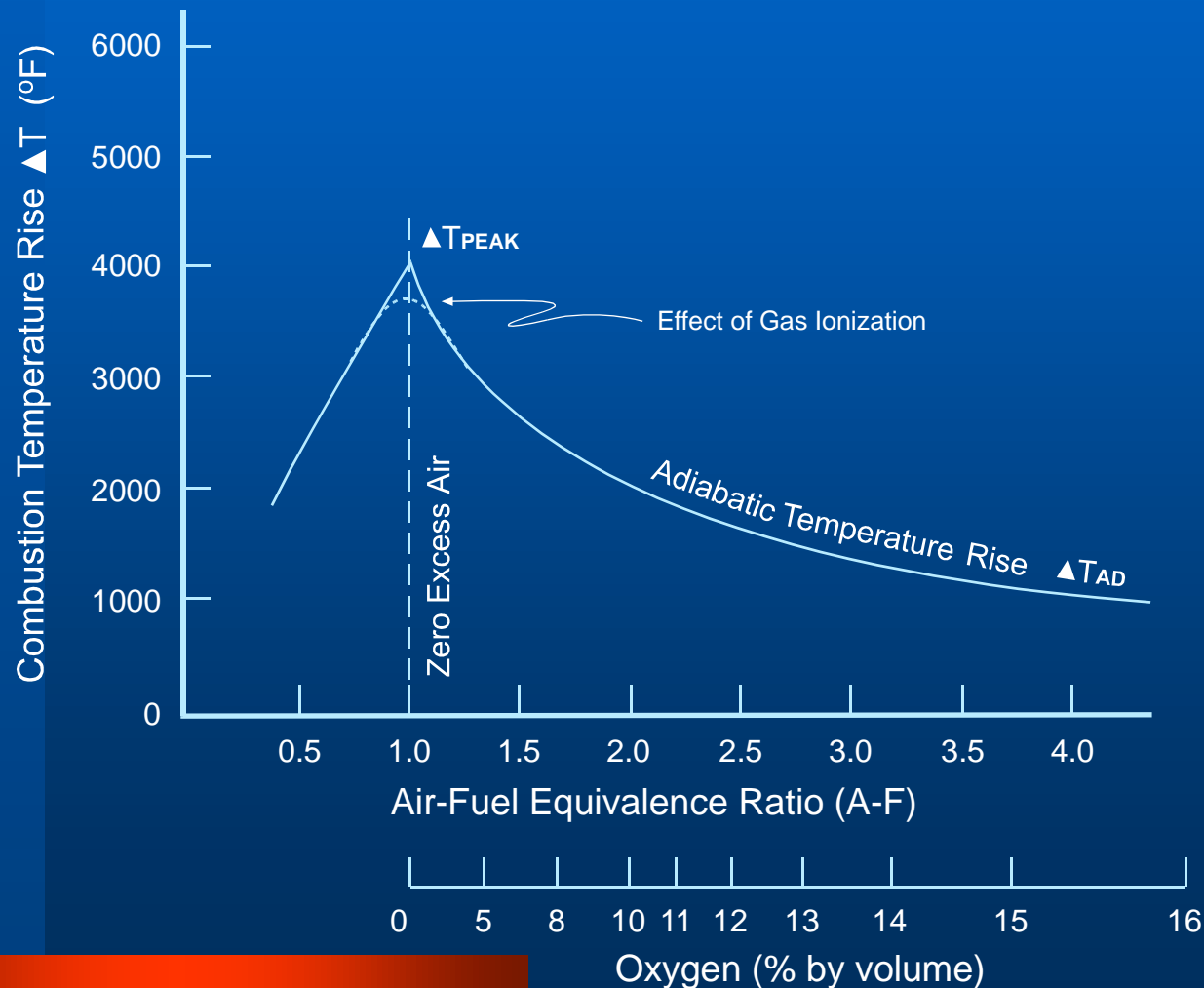
$$\Delta T(^{\circ}\text{F}) = \frac{Q}{V \times C_p} \times \frac{385}{29}$$

- When Q is one mmBTU, the F-factor gives the volume V (approx) = 10,500 ft<sup>3</sup> -- so delta-T can be calculated.

# Energy Balance (3)

- Except
  - Energy balance is based on LHV
  - F-factor is based on HHV
- So adjust the volume (F-factor) by the ratio HHV/LHV
- With typical data,  $\Delta T = 4000^{\circ}\text{F}$

# Adiabatic Temperature with Excess Gas



## Example 4-6

- A thermal oxidizer treats air from an oven at 250°F. The stack oxygen measured during an emission tests is 14.0%. What was the oxidizer temperature?

Solution 1: Read delta-T from Figure 4-5 and add 250°F to give about 1600°F

# Example 4-6 cont'd

Solution 2: Use equation 4-18.

First determine the LHV F-factor:

$$F_w = 10610 * 22,200/20,000 = 11,777 \text{ (std ft}^3\text{/mmBTU)}$$

Use  $C_p = 0.30$  and insert the data in eqn 4-18

$$\Delta T = \frac{10^6}{11,777 \times 0.30} \times \frac{20.9 - 14.0}{20.9} \times \frac{385}{29} = 1240^\circ\text{F}$$

Add  $250^\circ$  inlet temperature to get  $1510^\circ\text{F}$



## Example 4-6 cont'd

Solutions 1 & 2 differ because Figure 4-5 is based on oil data and solution 2 was for gas.

The objective was an approximate, not exact, value to use for a data QC check.

The point is that *the exhaust O<sub>2</sub> implies the maximum average incinerator temperature.*

# Local vs. Average Temperature

- The average combustor exit temperature is lower than the peak combustion temperature for two reasons:
  - (1) radiative heat loss from the flame, and
  - (2) the fact that fuel mixes with air in the flame.
- Fuel-air mixing during combustion means
  - Non uniform temperatures
  - Local temperatures that approach adiabatic

# Diffusion & Premix Flames

- Most combustors mix fuel & air simultaneous with burning – diffusion combustion
- A few (gasoline engines) premix fuel & air prior to combustion.
- Peak temperatures of diffusion combustion are invariably high; premix temperatures depend on equivalence ratio (Fig. 4-5)

# Energy Content of the Flue Gas

- Flue gas has energy in three forms
  - Latent Heat
  - Sensible Energy
  - Specific Heat
- It gives up some of this energy to useful work or heat.
- At the exhaust point (stack) the remaining energy is lost

# Latent Heat of Water Vapor

$$Q_{LH} \left( \frac{\text{BTU}}{\text{hr}} \right) = W_{EG} \left( \frac{\text{lb}}{\text{hr}} \right) \times \left( \frac{\% \text{H}_2\text{O}}{100} \right) \times \left( \frac{18}{29} \right) \times 1000 \left( \frac{\text{BTU}}{\text{lb}} \right)$$

Where:

$Q_{LH}$  = flue gas latent heat, BTU/hr

$W_{EG}$  = flue gas mass flow rate, lb/hr

$\% \text{H}_2\text{O}$  = concentration of water vapor in the E.G., % by volume

18 = molecular weight of water, lb  $\text{H}_2\text{O}$ /lb-mole  $\text{H}_2\text{O}$

29 = molecular weight of E.G., lb E.G./lb-mole E.G.

18/29 = factor to convert water fraction from a volume to a mass basis

# Latent Heat (cont.)

This is more useful expressed as a fraction of the total heat input.

Use the F-factor and a value of 10,500 to simplify it.

$$\frac{Q_{LH}}{Q_{Tot}} = \frac{\% H_2O}{100} \times \frac{20.9}{20.9 - \% O_2} \times \frac{F_w}{1000} \times \frac{18}{385}$$

$$\frac{Q_{LH}}{Q_{Tot}} = \frac{\% H_2O}{100} \times \frac{20.9}{20.9 - \% O_2} \times 0.49$$

# Example 4-7. Exhaust latent heat

What % of the fuel energy is carried by uncondensed water in the stack of a gas-fired source where data show 4.5% O<sub>2</sub> and 17% water vapor by volume?

$$\frac{Q_{\text{LH}}}{Q_{\text{Tot}}} = \frac{17}{100} \times \frac{20.9}{20.9 - 4.5} \times 0.49 = 0.106$$

So 10.6% of the fuel energy (HHV) is lost

# Latent Heat (cont.)

For dry fuel, the latent heat loss can be determined from fuel analysis alone – no stack data is required.

**Table 4-6. Approximate Exhaust Latent Heat Energy**

Fuel	C/H Ratio	HHV (BTU/lb)	$Q_{LH}/Q_T$
Natural Gas	CH <sub>3.8</sub>	23,000	0.094
Heavy Oil	CH <sub>1.7</sub>	18,500	0.060
Bitumin. Coal	CH <sub>0.8</sub>	13,500	0.042



# Sensible Energy

$$Q_S \text{ (BTU/hr)} = W_{EG} \text{ (lb/hr)} + C_p \text{ (BTU/lb/°F)} * \Delta T \text{ (°F)}$$

Where:

$Q_S$  = flue gas sensible heat, BTU/hr

$W_{EG}$  = E.G. mass flow rate, lb/hr

$C_p$  = E.G. specific heat, BTU/lb/°F

$\Delta T$  = temperature difference between flue gas and ambient air, °F

# Sensible Energy (cont.)

This is more useful expressed as a fraction of the total heat input.

Divide by eqn 4-11 and use the F-factor with a value of 10,500 to simplify it.

$$\frac{Q_s}{Q_{\text{Tot}}} = \Delta T \times \frac{20.9}{20.9 - \% \text{ O}_2} \times \frac{C_p \times F_w}{10^6} \times \frac{\text{MW}_{\text{FG}}}{385}$$

$$\frac{Q_s}{Q_T} = \frac{\Delta T}{4200} \times \frac{20.9}{20.9 - \% \text{ O}_2}$$

# Example 4-8. Sensible energy

Stack measurements show  $T = 375^\circ\text{F}$  and  $\text{O}_2 = 3.3\%$  when the ambient temperature is  $50^\circ\text{F}$ . What fraction of the fuel energy is lost in the form of hot gas?

$$\frac{Q_s}{Q_{\text{Tot}}} = \frac{375 - 50}{4200} \times \frac{20.9}{20.9 - 3.3} = 0.092$$

# Specific Heat

**Table 4-7. Specific Heat [BTU/(lb-°F) or kcal/(kg-°C)]**

<i>Temperature</i>	<i>Air</i>	<i>CO<sub>2</sub></i>	<i>Water Vapor</i>
68°F	0.242	0.200	0.445
212	0.244	0.218	0.452
500	0.249	0.245	0.470
1100	0.260	0.285	0.526
2200	0.278	0.315	0.622
3000	0.297	0.325	0.673
3800	0.303	0.330	0.709

# Specific Heat (2)

- At moderate temperatures specific heat of dry exhaust gas is about 0.25
- Specific heat of water vapor is about 2x that of air or dry flue gas
- At high temperatures  $C_p$  increases

# Example 4-9. Specific heat

What is the specific heat of a combustion source exhaust gas with 18% H<sub>2</sub>O and a stack temperature of 475°F?

Solution:

Assume dry gas  $C_p = 0.25$

$$0.18 * 0.47 + (1 - 0.18) * 0.25 = 0.290 \text{ BTU/(lb-}^\circ\text{F)}$$

# Combustor Size and Residence Time

- Combustor Size

- Volume will be designed proportional to firing rate
- Volume will be inversely proportional to pressure
- Fuel mixing/combustion rate affects design size

- Combustion Loading

- Expressed/defined as  $\text{BTU}/(\text{hr}\cdot\text{ft}^3)$

# Example 4-10. Furnace loading

What is the thermal loading of a furnace with firebox dimensions of 7 ft x 8 ft x 25 ft, fired at design maximum rate of 120 mmBTU/hr?

*Solution:*



The furnace volume is:  $7 * 8 * 25 = 1400 \text{ ft}^3$

Thermal loading is  $120(10^6)/1400 = 85,700 \text{ BTU}/(\text{hr-ft}^3)$



# Combustor Size and Residence Time (cont.)

- Concept of residence time has regulatory significance for waste combustors
- Formula for average residence time is

$$t_{\text{res}} = \text{Furnace volume (ft}^3\text{) / Actual gas flow (ft}^3\text{/second)}$$

- Residence time is related to thermal loading

# Example 4-11. Residence time

Determine the residence time of a thermal oxidizer with an exhaust flow of 2600 std ft<sup>3</sup>/min and an operating temperature of 1450°F in a 350ft<sup>3</sup> chamber.

- *Solution:*

First, determine the gas flow at actual ft<sup>3</sup> per second.

$$\text{Actual flow} = 2600 * \{(1450+460)/528\}/60 = 157 \text{ acf/sec}$$

Now use Equation 4-25

$$\text{Residence time} = 350/157 = 2.2 \text{ seconds}$$

# Conclusions

- Combustion is a complex process
- Laws of Conservation of Mass and Energy
- Using exhaust gas data
- Firing rate & thermal efficiency

# Chapter Summary

- Basic combustion chemistry
- Laws of Conservation of Mass and Energy
- Definitions
- Calculations
- Energy balance