APTI Course 427

Combustion Source Evaluation

Chapter 4:
Fundamentals of Combustion

Chapter Overview (outline)

- Introduction
- Combustion Mass Flows, Stoichemistry
- 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

$CH_4 + 2O_2 \rightarrow \text{HEAT} + CO_2 + 2H_2O$

(fuel) (air) (exhaust gas)

Chemical Balance (methane)

$$\underset{\text{(fuel)}}{CH_4} + \underset{\text{(air)}}{2O_2} \rightarrow HEAT + \underbrace{CO_2 + 2H_2O}_{\text{(exhaust gas)}}$$

- Chemical balance → 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

Fuel energy (BTU/lb) * Fuel mass flow (lb/hr) = 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:*

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

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

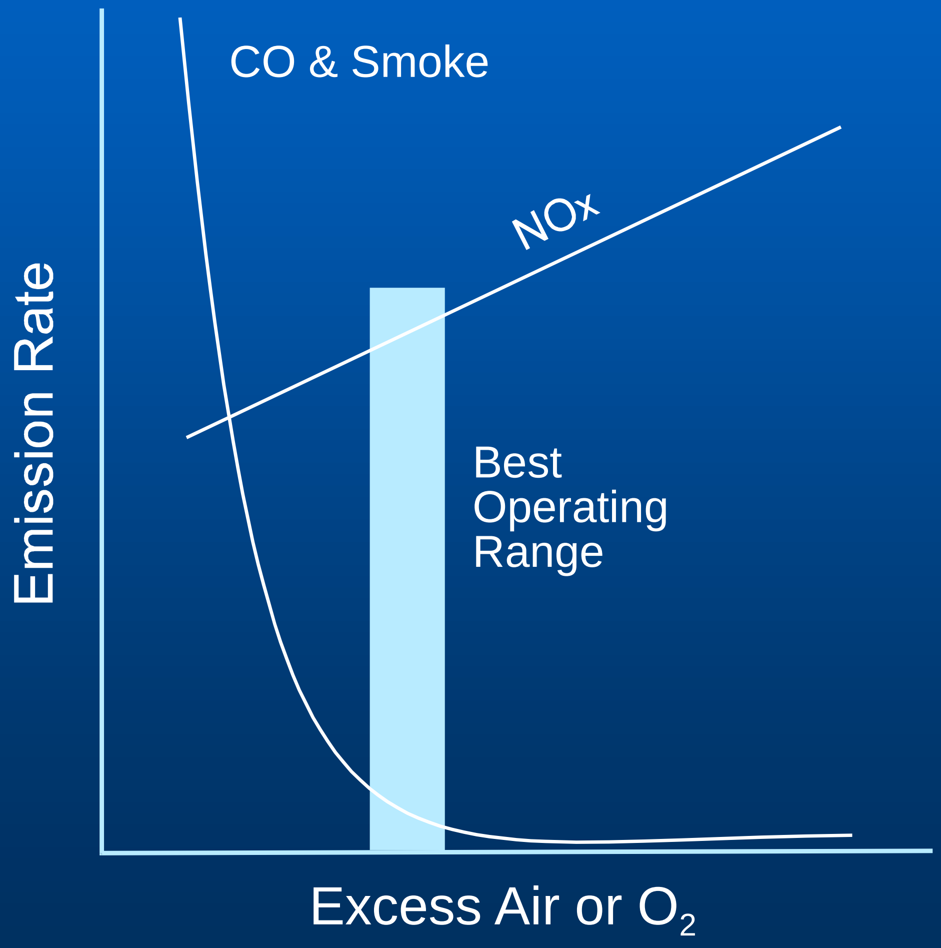
- Equivalence ratio = actual A/F over stoich A/F
  - Equiv ratio = 1 when air flow is stoich
  - Equiv ratio <1 with insufficient air (smoking)
  - Equiv ratio >1 with excess air

- 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

Type of Combustion	*Excess Air*	*% Oxygen*
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 NOx
  - 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

$$CH_4 + 2O_2 \rightarrow HEAT + CO_2 + 2H_2O$$

- 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_2, 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^3)

- Result is ft^3 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_d - dry	F_w - wet	F_c - 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.

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

- 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 (ft^3/min) * 60 (min/hr) / 10,500 (ft^3/mmBTU) = 257 (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

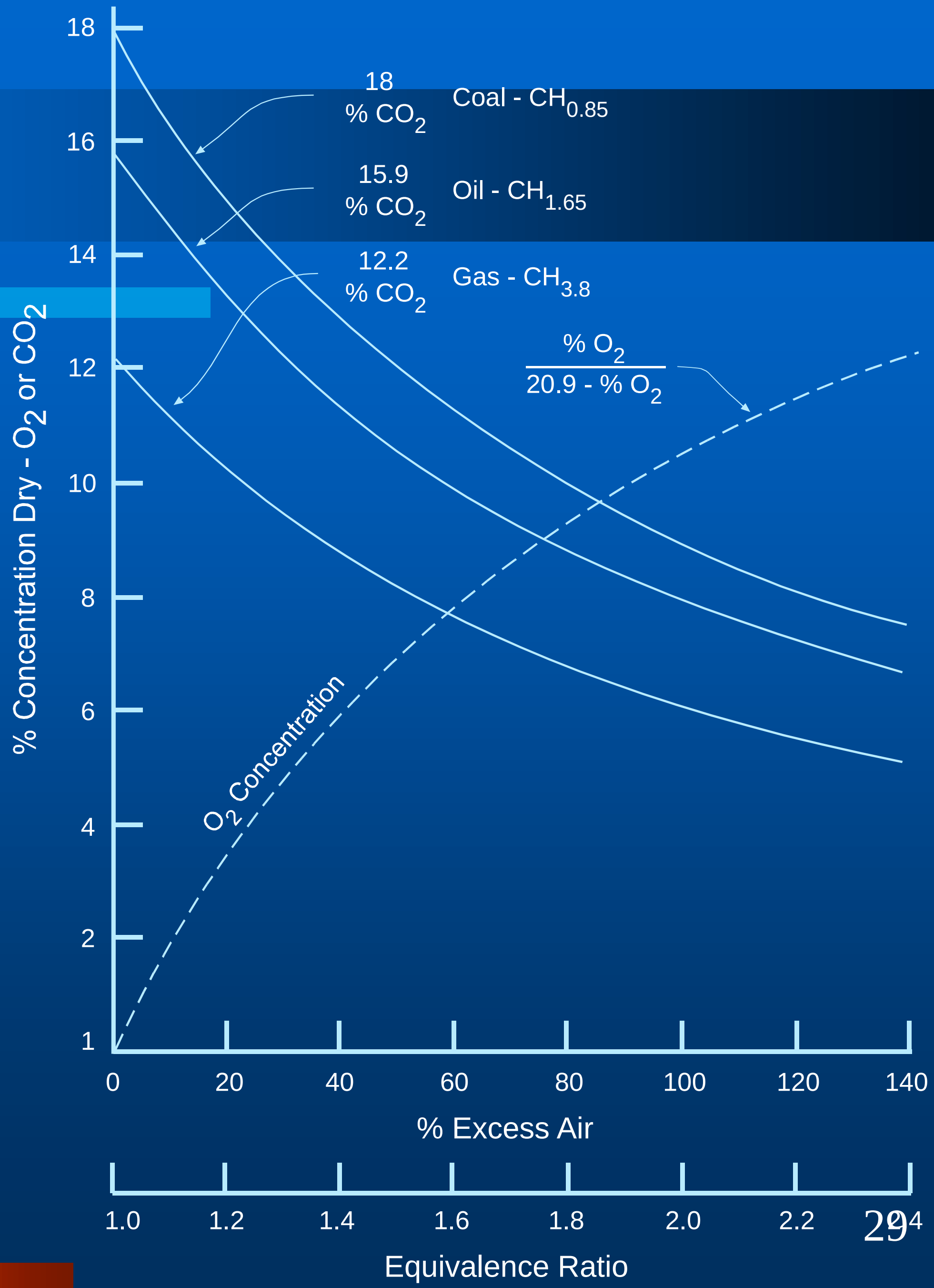
- Combustor controls couple air flow to fuel flow
  - This gives approximately correct air flow

- Exhaust O2 concentration measures excess air (air/fuel equivalence ratio)

$$\%\ \text{Excess Air} = \frac{\%\ O_2}{20.9 - \%\ O_2} \times 100$$

- Definition, not a rigorous derivation

Excess Air vs. O_2 & CO_2



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

$$\text{Exhaust Flow} = \text{Stoich. Flow} \times \left(\frac{20.9}{20.9 - \%\ O_2} \right)$$

$$\text{Firing Rate}\left(\frac{\text{mmBTU}}{\text{hr}}\right) = \frac{\text{Exhaust Flow}\left(\frac{\text{ft}^3}{\text{hr}}\right) \times \frac{20.9 - O_2}{20.9}}{F_w\left(\frac{\text{ft}^3}{\text{mmBTU}}\right)}$$

Example 4-3

Determine the firing rate of a source with 20,000 scfm stack flow at 4.0% O_2.

Solution: Use eqn 4-11

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

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

Oxygen Measurement

- O2 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:

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

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^2

V is volume in ft^3

n is number of moles

V/n = 385 ft^3/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.)

$$V_1 = V_2 \text{ x } (T_1/T_2) \text{ x } (P_2/P_1)$$

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

T_{std} = 528K (68F)

P_{std} = 29.92 inches Hg

Example 4-4.

Stack test data show 8,000 ft^3/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^3/min).

Solution: First determine stack pressure

P_s = 28.67 – 0.45/13.6 = 28.64 inches Hg

Second, use Eqn 4-14

V_{std} = 8000acfm * [528°R/(460 + 310)°R] * [28.64/29.92] = 5251 scfm

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

$$\rho = 29.6 \text{ (lb/lb-mole) / 385 (std ft}^3\text{ / lb-mole)}$$

$$= 0.077 \text{ (lb/ std ft}^3\text{)}$$

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

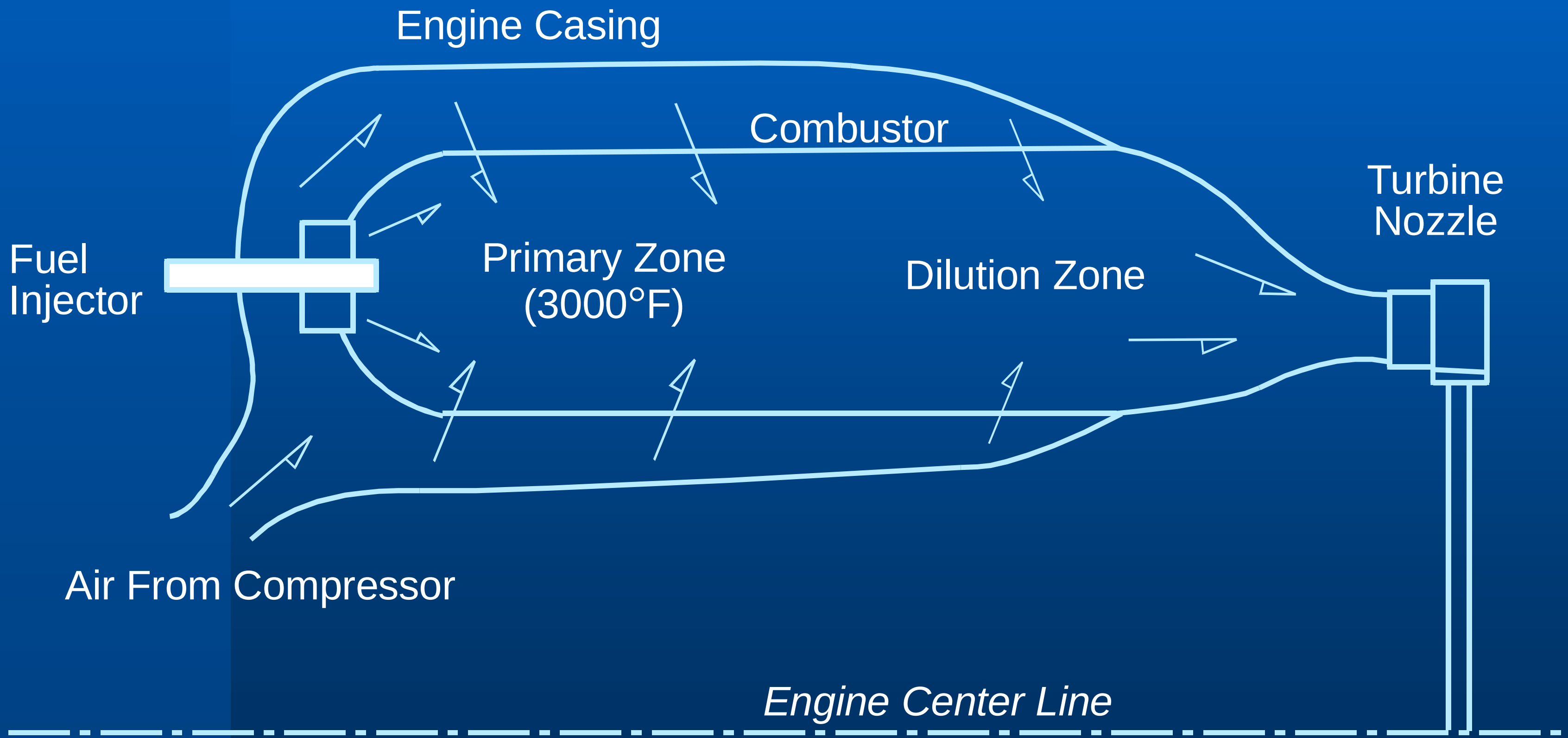
Enthalpy of Combustion and Heating Values (outline)

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

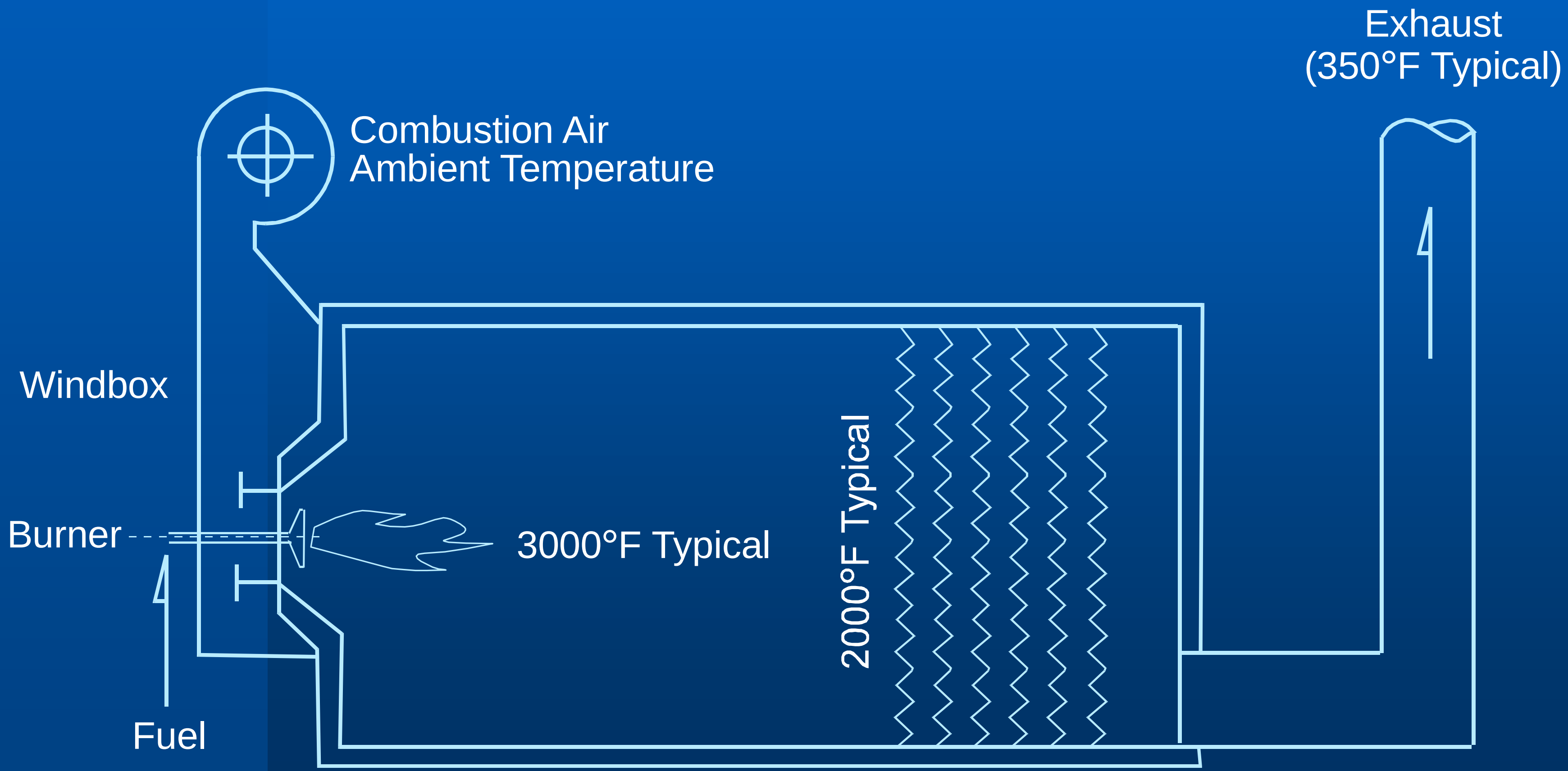
Flame Structure

- 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)

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

Where:

Q = Fuel energy released

V = E.G. volume at standard conditions

Cp = E.G. specific heat

delta T = E.G. temperature rise

Energy Balance (2)

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

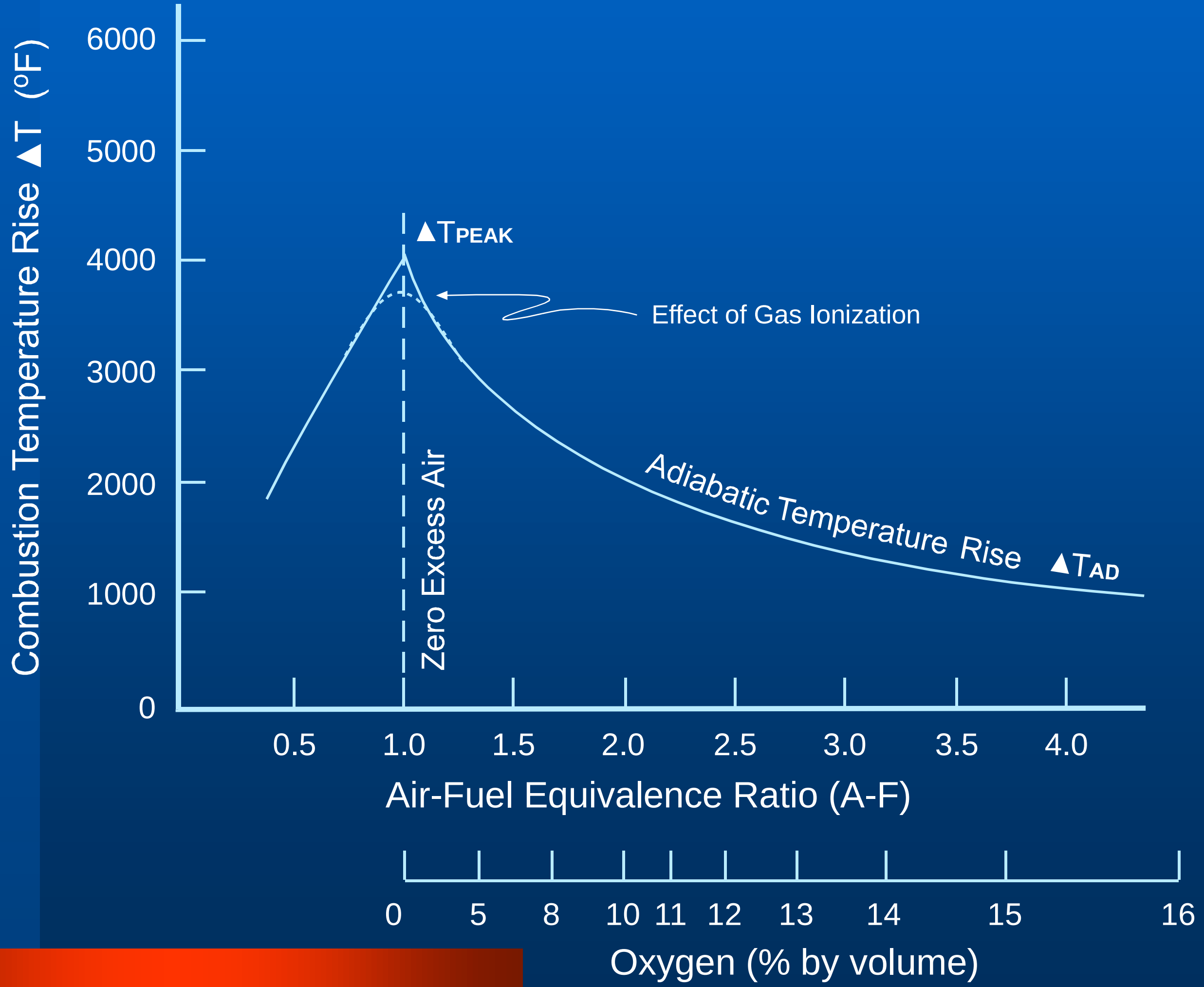
$$\Delta T(^\circ F) = \frac{Q}{V \times C_p} \times \frac{385}{29}$$

- When Q is one mmBTU, the F-factor gives the volume V (approx) = 10,500 ft^3 -- 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°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 (std ft^3/mmBTU)

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

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

Add 250° inlet temperature to get 1510°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 O2 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

$$Q_{LH}\left(\frac{BTU}{hr}\right) = W_{EG}\left(\frac{lb}{hr}\right) \times \left(\frac{\%\,H_2O}{100}\right) \times \left(\frac{18}{29}\right) \times 1000\left(\frac{BTU}{lb}\right)$$

Where:

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

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

$\%H_2O$ = concentration of water vapor in the E.G., % by volume

18 = molecular weight of water, lb H_2O/lb-mole H_2O

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_2 and 17% water vapor by volume?

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

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	$CH_{3.8}$	23,000	0.094
Heavy Oil	$CH_{1.7}$	18,500	0.060
Bitumin. Coal	$CH_{0.8}$	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

ΔT = 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.

$$\frac{Q_S}{Q_{Tot}} = \Delta T \times \frac{20.9}{20.9 - \%\ O_2} \times \frac{C_p \times F_w}{10^6} \times \frac{MW_{FG}}{385}$$

$$\frac{Q_S}{Q_T} = \frac{\Delta T}{4200} \times \frac{20.9}{20.9 - \%\ O_2}$$

Example 4-8. Sensible energy

Stack measurements show T = 375°F and O_2 = 3.3% when the ambient temperature is 50°F. What fraction of the fuel energy is lost in the form of hot gas?

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

Specific Heat

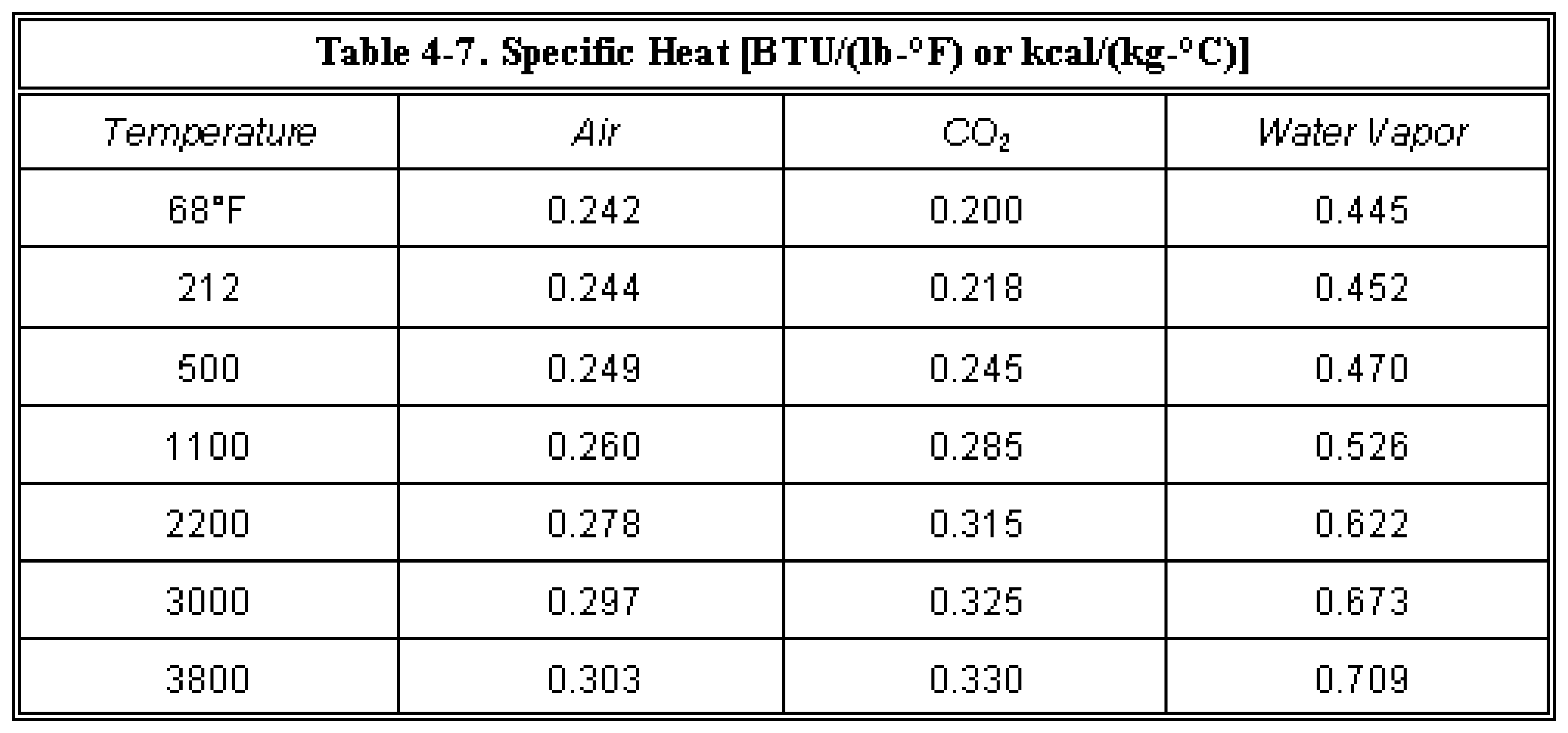


Table 4-7. Specific Heat [BTU/(lb-°F) or kcal/(kg-°C)]

Temperature	*Air*	*CO_2*	*Water Vapor*
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_2O and a stack temperature of 475°F?

Solution:

Assume dry gas Cp = 0.25

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

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 BTU/(hr-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: $7 * 8 * 25 = 1400\ ft^3$

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

Combustor Size and Residence Time (cont.)

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

t_{res} = Furnace volume (ft^3)/Actual gas flow (ft^3/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^3/min and an operating temperature of 1450°F in a 350ft^3 chamber.

- *Solution:*

First, determine the gas flow at actual ft^3 per second.

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

Now use Equation 4-25

Residence time = 350/157 = 2.2 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