# APTI Course 427

**Combustion Source Evaluation**

**Chapter 7:**

**Combustion Source Emissions**

# Chapter Overview (outline)

- Energy Use and $CO_2$ Emissions
- Emissions Monitoring
- Reciprocating Engines and Combustion Turbines
- Natural Gas, No. 2 and No. 4 Oil Fired Boilers
- Coal Fired Boilers
- Wood Firing and Stoker Furnaces

# Energy Use and $CO_2$ Emissions (outline)

- Efficiency of Various Systems
- Combustion Efficiency
- Thermal Efficiency
- Power Plant Efficiency
- $CO_2$ Efficiency

# Efficiency of Various Systems

- Efficiency
  - Combustion Efficiency
  - Thermal Efficiency

**Table 7-1. Typical Efficiency Levels**

| *System* | *Combustion Efficiency* | *Thermal Efficiency* |
|---|---|---|
| Boiler, gas-fired | 100% | 82% |
| Steam-Elect. Coal Power Plant | 99% | 34% |
| Simple Cycle Gas Turbine | 100% | 38% |
| Combined Cycle Gas Turbine | 100% | 55% |
| Cogeneration System | 100% | 50%-80% |

# Cogeneration or Combined Cycle

- Combustion turbine (or engine) generator
- Using exhaust waste heat
  - Steam cycle generator
  - Matching waste heat to electric load
- Cogeneration

# Combustion Efficiency

- Loss due to CO

$$\% \text{ Energy Loss} = 0.00027 * \text{ppm CO} * \frac{20.0}{\left(20.9 - \% O_2\right)}$$

Where:

ppm CO = CO concentration in E.G., dry basis

$\% O_2$ = Oxygen concentration in E.G., % by volume, dry basis

# Example 7-1. CO Heat Loss

How much heat is being lost out the stack of a natural gas-fired source, due to CO = 800 ppm when $O_2$ = 4.2%?

*Solution:*

Insert the values for CO and $O_2$ into Equation 7-1.

$$0.00027 * 800 * 20.9/(20.9-4.2) = 0.27\%$$

# Combustion Efficiency (2)

- Loss due to carbon in the ash

% Energy Loss = %A * %C/100 * 14100/HHV

2

Where:

%A = coal ash content, % by wt.
%C = fly ash carbon content (LOI), % by wt.
14,100 = heating value of pure carbon, BTU/lb
HHV = heating value of the coal, BTU/lb

# Example 7-2. Carbon heat loss

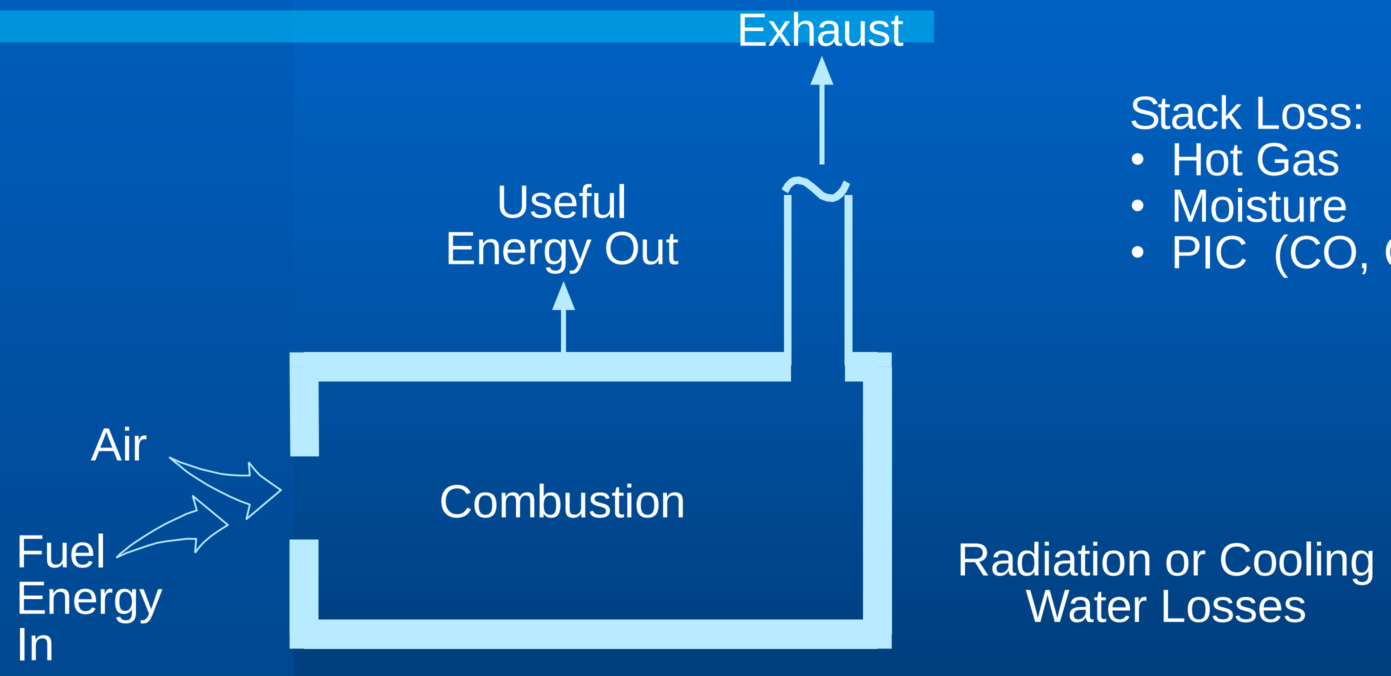
If fly ash from a coal fired source has 4% combustibles and the coal has 11% ash and 12,700 BTU/lb, what is the approximate energy loss?

*Solution:*

Insert the data in Equation 7-2.

11% * 4% /100 * 14100/12,700 = 0.49%

# Thermal Efficiency




Stack Loss:
- Hot Gas
- Moisture
- PIC (CO, Organics, Carbon)

- Efficiency can be defined several ways
- Look at combustion related efficiency, not thermodynamic cycle

# Thermal Efficiency (cont.)

% Thermal Efficiency = Useful Output Energy / Energy Input

% Thermal Efficiency = 100% - % Energy Losses

# Thermal Efficiency (cont.)

- 1. Sensible losses of hot exhaust gases venting to atmosphere.
- 2. Heat of vaporization losses from venting uncondensed water to atmosphere.
- 3. Unburned fuel in either the exhaust gases or discarded ashes.
- 4. Radiation/convection losses from the outside walls of the furnace and cooling water losses (reciprocating engines).
- 5. Miscellaneous small losses such as the energy in hot ashes that are discarded.

# Thermal Efficiency (cont.)

$$\text{Efficiency} = 100\left[1 - \left(\frac{20.9}{20.9 - \%\ O_2}\right)\left\{\left(\frac{\Delta T}{4200}\right) - \left(\frac{0.49 * \%\ H_2O}{100}\right)\right\}\right]$$

Where: $\Delta T$ = Exhaust temperature minus ambient temperature

$\%H_2O$ and $\%O_2$ are measured exhaust concentrations after the last heat exchanger

# Thermal Efficiency

- Water vapor term available from Table 4-6
- Eqn 7-4 is simplified ASME test procedure
- Note how little data is required

# Example 7-3. Thermal Efficiency

Determine the approximate efficiency of an oil-fired boiler where the stack temperature is 350°F, ambient temperature is 50°F, stack $O_2$ is 5% and stack water vapor content is estimated at 11%

*Solution:*

Entering these values in Equation 7-4 gives:

$$100 \times \left(1 - \frac{350-50}{4200} \times \frac{20.9}{20.9-5} - 0.49 \times \frac{11}{100} \times \frac{20.9}{20.9-5}\right) =$$

$$100 - 9.39 - 7.08 = 83.5\%$$

# Power Plant Efficiency

- Large high-pressure boiler
  - Boiler efficiency is similar to last example (84%)
- Overall heat rate
  - Steam power plant = 10,000 BTU/kw-hr
  - Theory (100% efficient) = 3410 BTU/kw-hr
  - e.g. 34% efficient
- Energy losses

# Example 7-4.

How much energy is required to operate a 150-megawatt (MW) power plant with a heat rate of 10,200 BTU/kw-hr? What is the overall thermal efficiency?

*Solution:*

Multiply the heat rate by the load.

150,000 kw * 10,200 BTU/kw-hr = 1530 mmBTU/hr

The efficiency is the ratio of ideal energy to actual energy:

3410/10,200 = 0.334 = 33.4%

# $CO_2$ Emissions

$$\frac{\text{lb } CO_2}{\text{mmBTU}} = \frac{\%\text{ fuel C}/100}{\text{HHV}/10^6} \times \frac{44}{12}$$

**Table 7-2. $CO_2$ Typical Emission Rates**

| *Fuel* | *$CO_2$ lb/mmBTU* |
|---|---|
| Natural Gas | 120 |
| No. 2 Oil, Diesel | 165 |
| No. 6 Oil | 180 |
| Bituminous Coal | 185 |
| Lignite | 300+ |
| Carbon | 260 |

# Example 7-5. $CO_2$ Emissions

For a power plant that burns No. 6 oil at a rate of 1530 mmBTU/hr, what is the $CO_2$ emissions rate?

- *Solution:*

Take the $CO_2$ emission rate from Table 7-2 and multiply by the heat input.

1530 mmBTU/hr * 180 lb $CO_2$/mmBTU =
275,400 lb $CO_2$/hr

# Emissions Monitoring (outline)

- Emissions Variability
- Measurement Methods
- Calculating Emissions

# Emissions Variability

- Reasons for emissions variation
  - Load changes
  - Start-up
  - Fluctuations in fuel properties
  - Operator implemented changes
  - Natural short term fluctuations
  - Changes in atmospheric conditions
- NOx and PIC fluctuations
- Boiler vs. engine emission variations

# Emission Fluctuations

**Table 7-3. Typical Variation in Emission Rates**

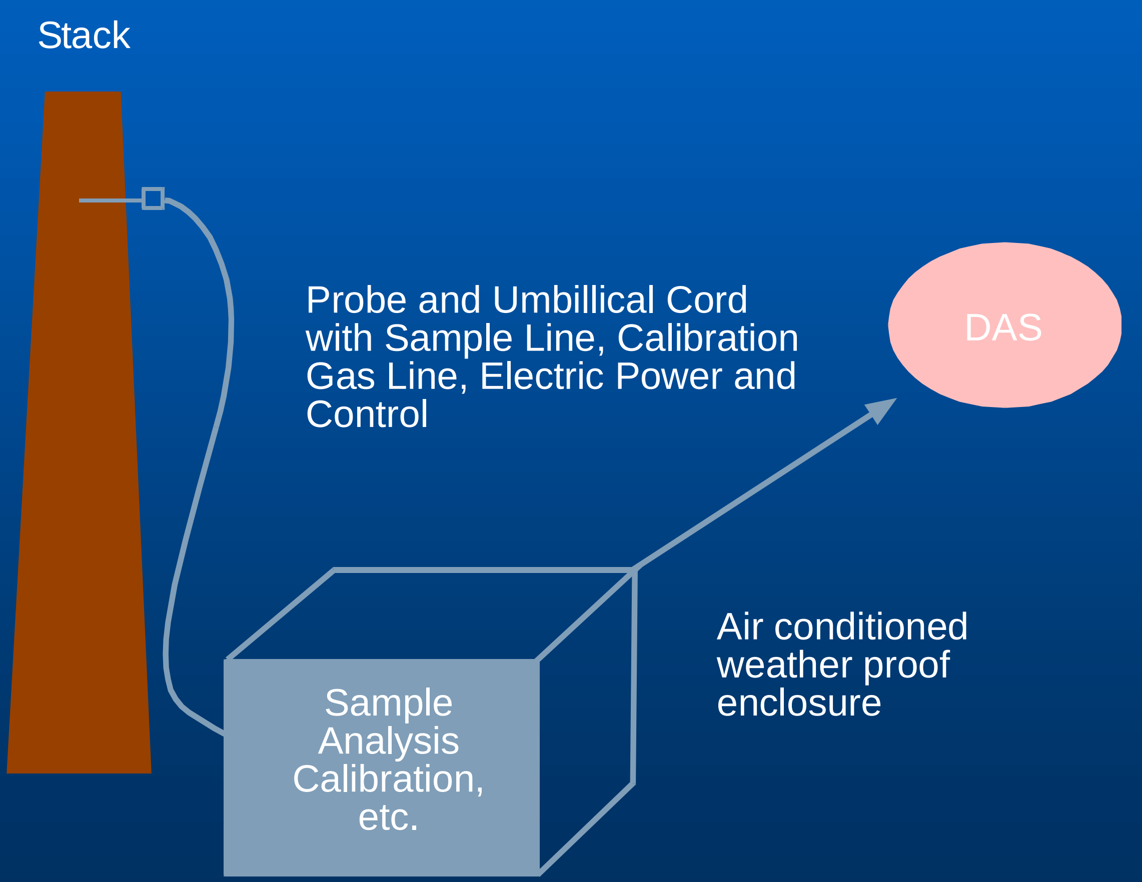
| *Source and Cause of Variation, Time Scale* | *NOx* | *PIC* |
|---|---|---|
| Boiler - operator instigated changes (1 hr) | ±15% | 0 to Excessive |
| Boiler - natural draft fluctuations (15 sec.) | ±5% | ±50% |
| Reciprocating engine - atmospheric change (12 hr) | ±5% | ±10% |
| Gas Turbine - atmospheric changes (12 hr) | ±10% | ±10% |
| Waste combustor - waste properties (15 min) | ±15% | ±75% |

# Measurement Methods

- Methods
  - Continuous Emission Monitoring Systems (CEM)
  - Federal Reference Method Sampling Trains
  - Indirect or Parametric Emission Monitoring (PEM)

- Supporting data for direct measurements
  - $O_2$ or $CO_2$ concentration
  - Exhaust flow rate
  - Exhaust moisture content
  - Fuel flow rate or power output
  - Ambient conditions

# CEM System

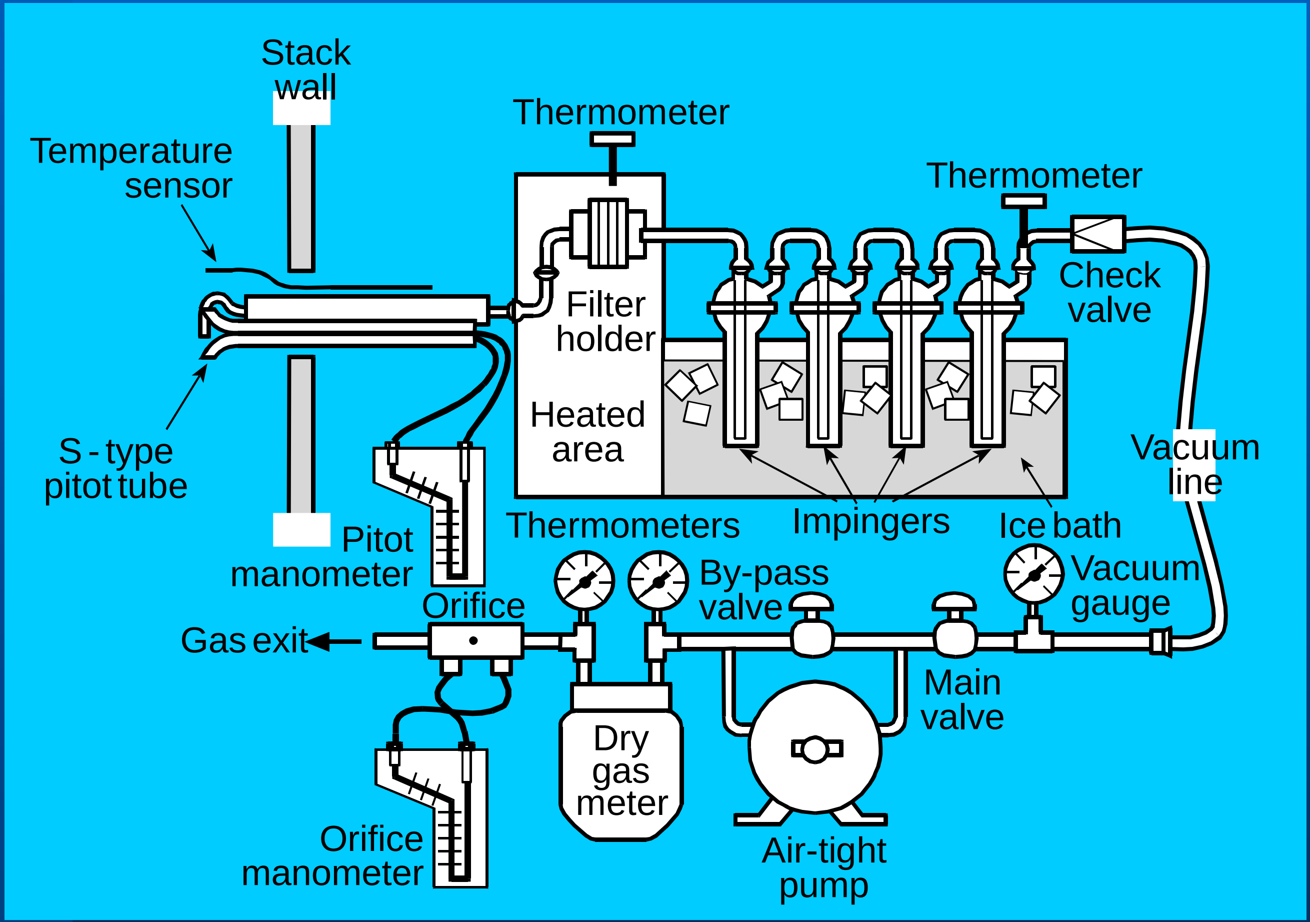

Stack
Probe and Umbillical Cord with Sample Line, Calibration Gas Line, Electric Power and Control
DAS
Sample Analysis Calibration, etc.
Air conditioned weather proof enclosure

# CEM Systems

- Dealing with water
  - Avoiding condensation
  - Integrating wet and dry data

- Common types
  - Dry extractive
  - Dilution extraction

# Federal Reference Method Sampling Trains



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# Indirect or Parametric Emission Monitoring (PEM)

- Feasibility
  - NOx on Engines
- CO, PIC uncertainty
- Basis
  - Load or fuel flow
  - Exhaust temperature

# Calculating Emissions (outline)

- Measurements are concentration, reported emissions are different units
- Correcting for Dilution
- Emissions in lb/mmBTU
- Emissions in lb/hr

# Correcting for Dilution

$$\text{ppm @ Y\%O}_2 = \text{ppm(meas.)} \times \frac{20.9 - Y}{20.9 - \%\ O_2\ \text{(meas.)}}$$

$$\text{ppm corrected to X\% CO}_2 = \text{ppm(meas.)} * \frac{x\%}{\%\ CO_2\ \text{(meas.)}}$$

Where: X and Y are percentages specified by the applicable emission standard for the source

# Example 7-6. Dilution correction

If the measured NOx = 135 ppm and $O_2$ = 4.7%, what is the NOx concentration when corrected to 3% $O_2$?

*Solution:*

Inserting the data in equation (7-6a):

$$135\text{ppm} \times \frac{20.9 - 3}{20.9 - 4.7} = 149\text{ppm}$$

# Emissions in lb/mmBTU

$$A\left(\frac{\text{lb}}{\text{mmBTU}}\right) = \frac{A\ (\text{ppmdv})}{1{,}000{,}000} \times \frac{MW_A}{385} \times F_d \times \frac{20.9}{20.9 - \%O_2}$$

Where:

| | | |
|---|---|---|
| ppmdv A | = | measured concentration of air pollutant A |
| $MW_A$ | = | molecular weight of A, 46 for $NO_2$, 64 for $SO_2$, etc. |
| $\%O_2$ | = | measured oxygen concentration, % by vol., dry basis |
| 385 | = | std $ft^3$ / lb-mole of ideal gas |
| $F_d$ | = | dry F-factor, std $ft^3$ / mmBTU |

| | |
|---|---|
| bituminous coal | 9780 |
| oil | 9190 |
| natural gas | 8710 |
| wood | 9240 |

# Emissions in lb/hr (stack data)

Measure stack flow and ppm wet

$$A \left({}^{lb}\!/_{hr}\right) = \text{exhaust flow}\left({}^{scf}\!/_{hr}\right) \times \frac{\text{ppmw of A}}{1{,}000{,}000} \times \frac{MW_A}{385}$$

Where:

A = pollutant species

$MW_A$ = molecular weight of species A

exhaust flow is the total (wet) flue gas flow in standard cubic feet per hour

A is measured in a wet (not dried) sample

385 = the number of standard cubic feet of gas in a pound mole @ 68°F. (MW/385 = gas density in $lb/^3$)

# Emissions in lb/hr (firing rate)

Measure emissions in lb/mmBTU (ppm dry & O2)

Record fuel use (firing rate)

$$\text{Emissions}\left({}^{\text{lb}}\!/\!_{\text{hr}}\right) = \text{Emissions}\left({}^{\text{lb}}\!/\!_{\text{mmBTU}}\right) \times \text{Firing Rate}\left({}^{\text{mmBTU}}\!/\!_{\text{hr}}\right)$$

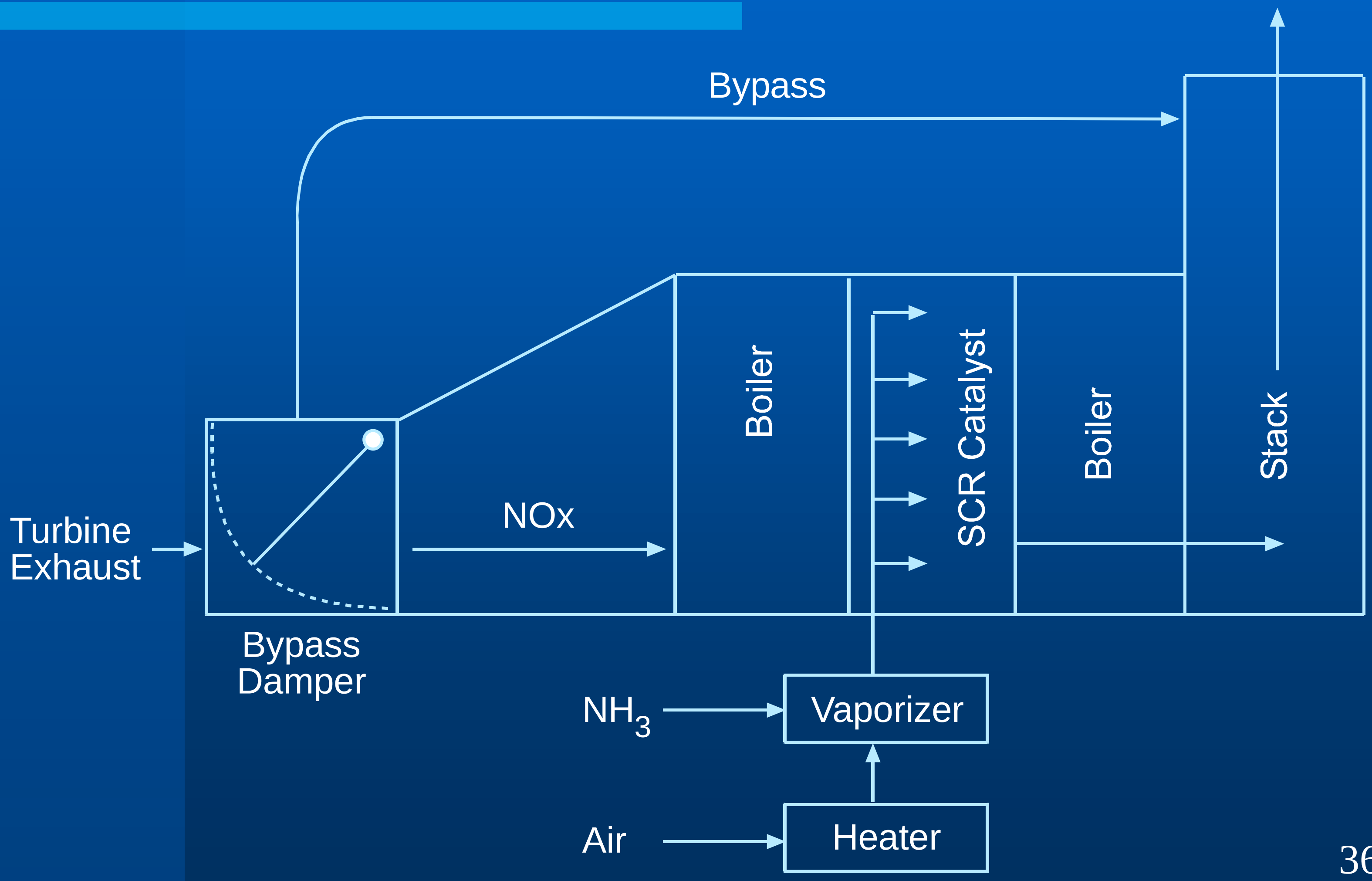
# Reciprocating Engines and Combustion Turbines

- Characteristics of Reciprocating Engines and Turbines
  - Natural gas, some with oil backup
  - Simple cycle efficiency
  - Efficiency with heat recovery
  - $CO_2$ and other emissions

# Reciprocating Engines and Combustion Turbines (cont.)

- Emissions and Control
  - PIC: low + catalyst
  - Low NOx combustors for gas
  - SCR for gas & oil firing
  - SCR temperature issues
- Combined cycle SCR
  - Startup issues

# SCR Installation



# Natural Gas & Oil Fired Boilers (outline)

- Characteristics of Boilers
- Nitrogen Oxides Control
- Sulfur Oxides Control
- Particulate Emissions

# Characteristics of Boilers

- Size range (of interest)
- Fuels/Emissions
  - Control equipment
  - PIC usually low
- Longevity
  - Some new, many older boilers

# Gas & Oil NOx Control

- Combustion NOx controls
  - Low excess air and various burner adjustments
  - Staged combustion on large furnaces using specific combinations of burners
  - Low NOx burners
  - Over fired air
  - Flue gas recirculation
  - Natural gas reburning
  - Switching fuel
- SCR and SNCR

# Gas & Oil SOx Control

- $SO_2$ Control
  - Fuel specification
  - Scrubbers
- $SO_3$ Control via plume visibility
  - Reducing oil sulfur content
  - Back end temperatures control
  - Very low excess air operation
  - Fuel additives

# Gas & Oil Particulate Emissions

- Natural gas & distillate oil
- Residual oil
- Pulverized coal
- Solid fuels

# Gas & Oil Particulate (2)

- ESP
- Ash levels
- Disposal
  - Reinjection
  - Sale
  - Land fill

# Coal Fired Boilers (outline)

- Characteristics of Pulverized Coal Boilers
- Nitrogen Oxides Control
- Sulfur Oxides and Particulate Matter

# Characteristics of PC Boilers

- Fuel flexibility - PC design vs gas/oil design
- Design and operation
  - Heat transfer area
  - Soot blowers
  - Gas flow passage size
  - Fire box size
  - Temperature control with excess air
- Emissions – NOx, particulate, $SO_3$

# PC NOx Control

- Combustion control
  - Similar to oil
  - Fuel – air distribution issues

- Fine tune the system
  - Baseline NOx reduced
  - Other problems also resolved

# Sulfur Oxides and Particulate Matter

- Alternative coal supply - impacts
- ESP problems with low S coal
- Side effects - interaction of changes

# Wood Firing and Stoker Furnaces (outline)

- Most stokers fire wood or MSW
- Characteristics of Stoker Furnaces
- Particulate Matter Emissions
- Nitrogen Oxides Control
- PIC and Dioxin-furans

# Characteristics of Stoker Furnaces

- Bed combustion control
- Over bed combustion control
- Air use
  - Amount required
  - Trade offs

# Stoker Particulate Emissions

- Grate retention of particulate
  - Inherent carryover
  - Fuel size
  - Feeder mechanism
- Built in multi-clones
- Typical emissions 0.3 – 0.7 lb/mmbtu

# Nitrogen Oxides Control

- Grate area formation → no control
- Reburning
- SNCR

# PIC and Dioxin-furans

- Amount of carbon emissions
- Over fire control of  smoke, CO & VOC
  - CO levels
- Older stoker problems
  - Designs inappropriate for MSW
  - Furnace temperature control
  - Over fired air design
- Newer stokers

# Chapter Summary

- Energy Use and $CO_2$ Emissions
- Emissions Monitoring & Measurement
- Reciprocating Engines and Combustion Turbines
- Natural Gas, No. 2 and No. 4 Oil Fired Boilers
- Coal Fired Boilers
- Wood Firing and Stoker Furnaces

# Any Questions?