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

$$\% \text{ Energy Loss} = \%A * \%C/100 * 14100/HHV$$

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

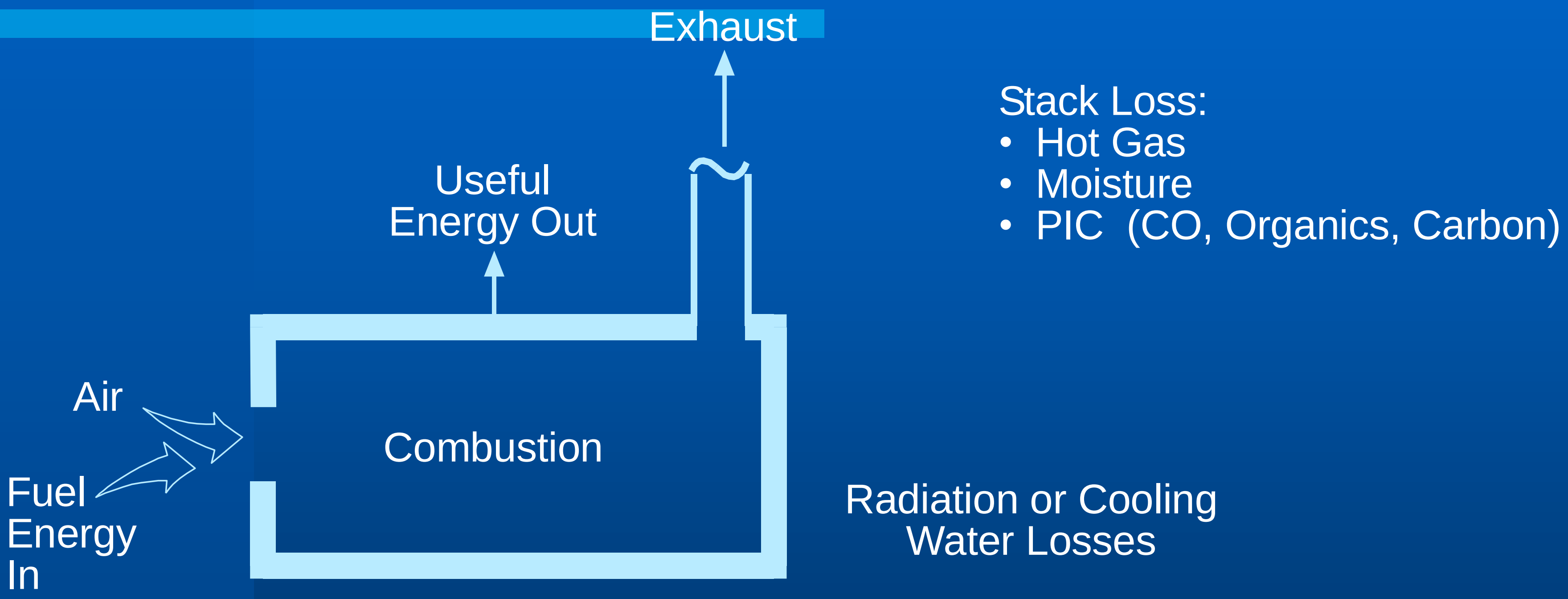
If fly ash from a coal fired source has 4% combustibles and the coal has 11% ash and 12,700 BTU/lb, what is the approximate energy loss?

Solution:

Insert the data in Equation 7-2.

$$11\% * 4\% /100 * 14100/12{,}700 = 0.49\%$$

Thermal Efficiency



- 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: ΔT = 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

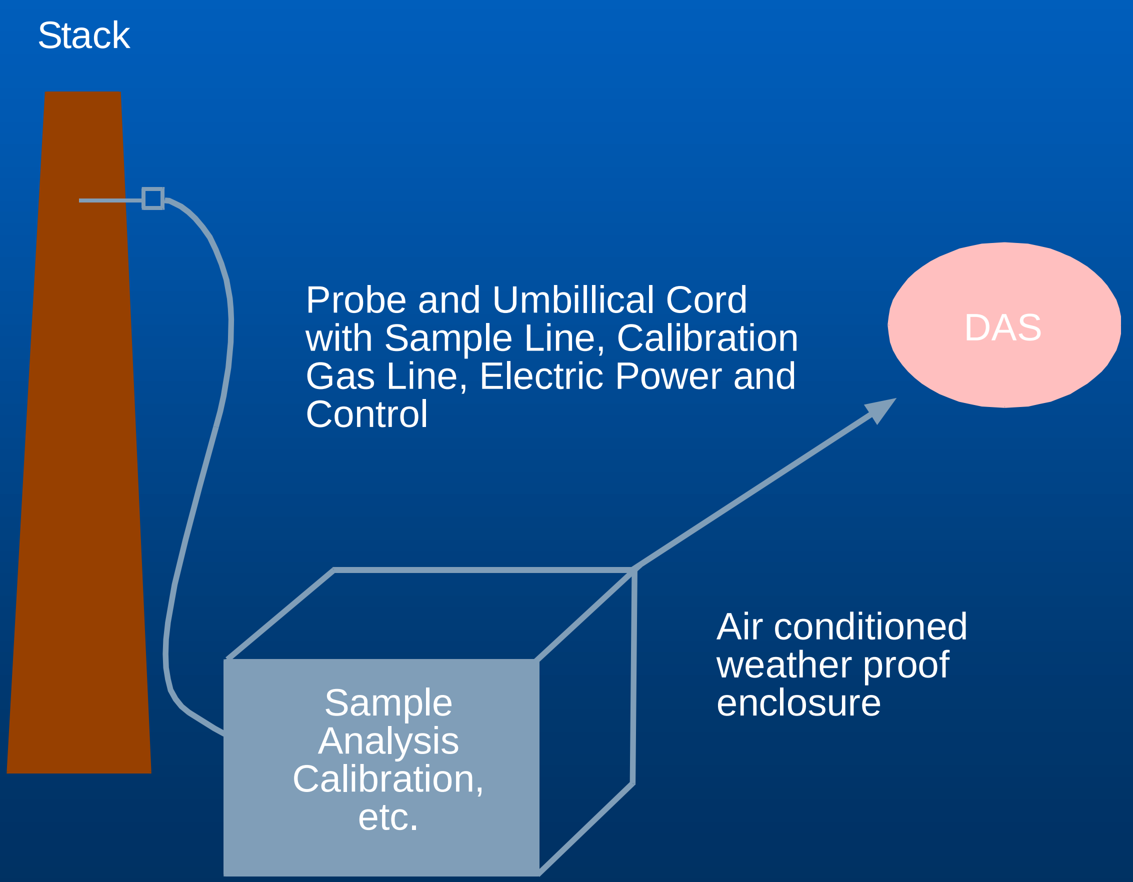
Source and Cause of Variation, Time Scale	*NOx*	*PIC*
Boiler - operator instigated changes (1 hr)	±15%	0 to Excessive
Boiler - natural draft fluctuations (15 sec.)	±5%	±50%
Reciprocating engine - atmospheric change (12 hr)	±5%	±10%
Gas Turbine - atmospheric changes (12 hr)	±10%	±10%
Waste combustor -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

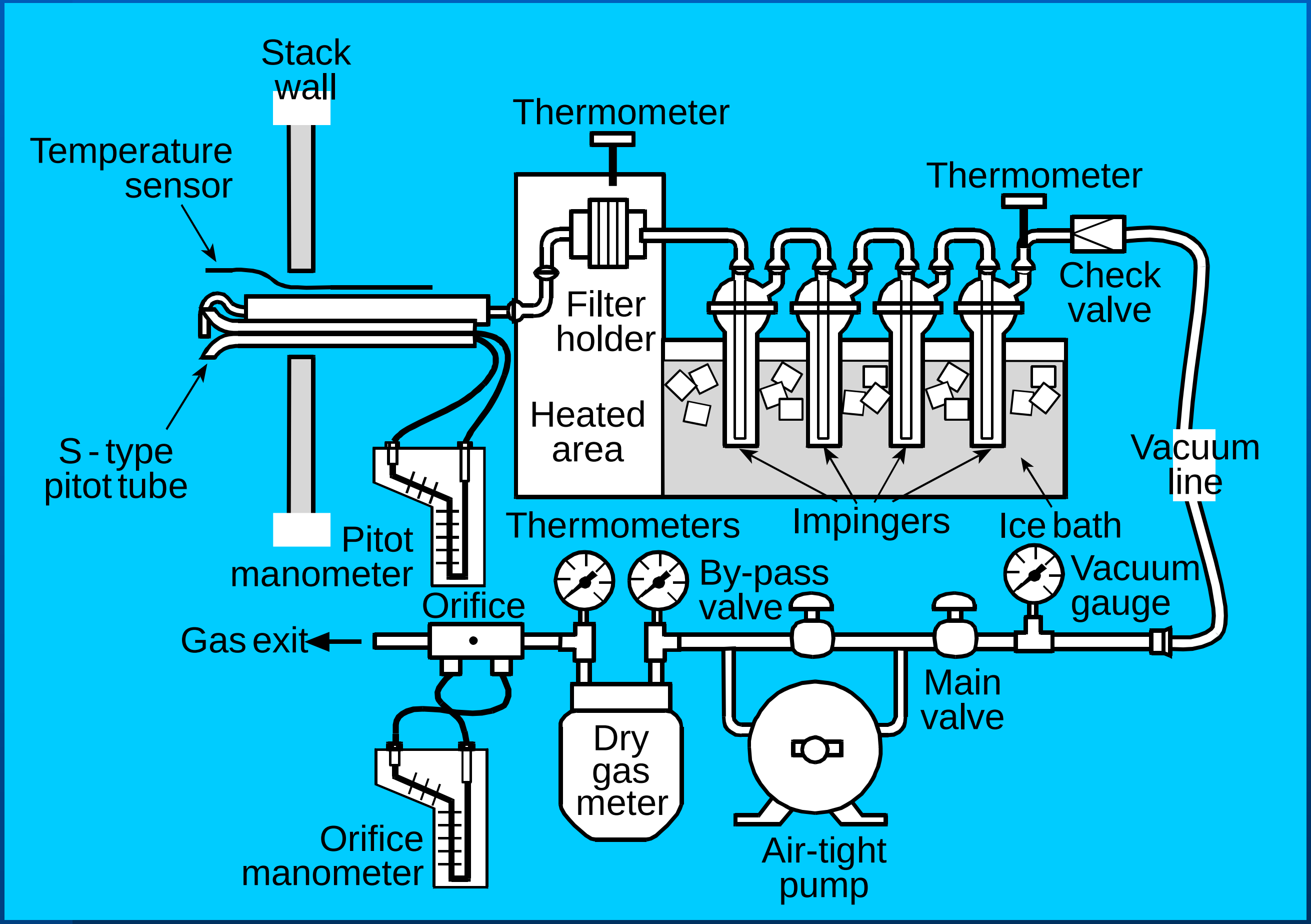


Stack
Probe and Umbillical Cord
with Sample Line, Calibration
Gas Line, Electric Power and
Control
DAS
Sample
Analysis
Calibration,
etc.
Air conditioned
weather proof
enclosure

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

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

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)

$$\text{Emissions}\left(\frac{\text{lb}}{\text{hr}}\right) = \text{Emissions}\left(\frac{\text{lb}}{\text{mmBTU}}\right) \times \text{Firing Rate}\left(\frac{\text{mmBTU}}{\text{hr}}\right)$$

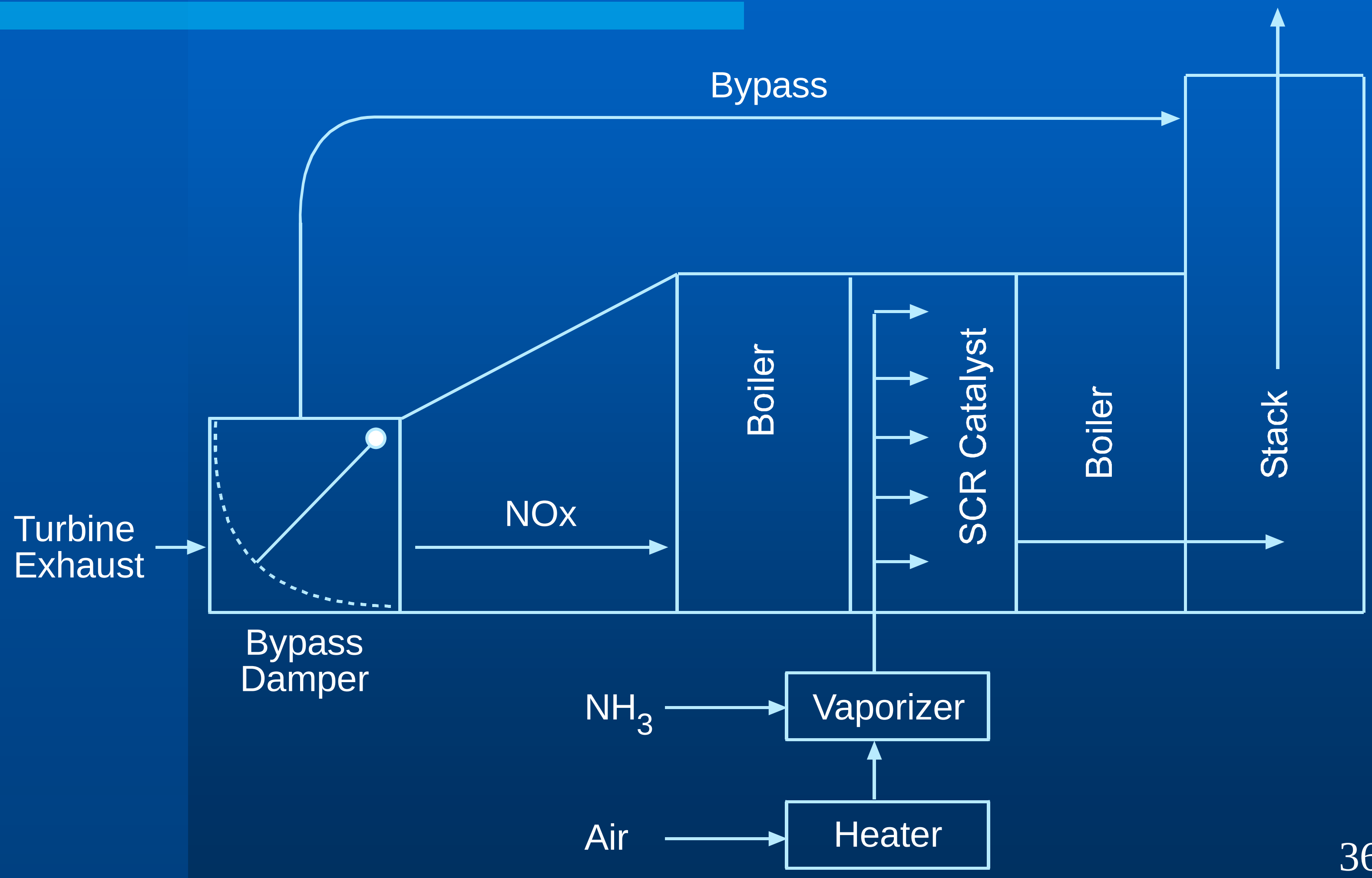
Reciprocating Engines and Combustion Turbines

- 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



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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?