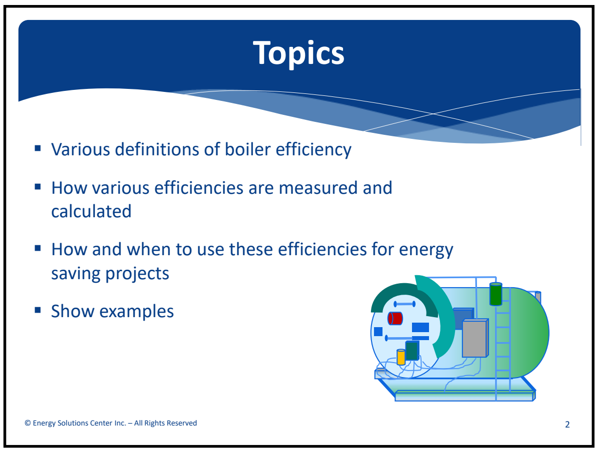
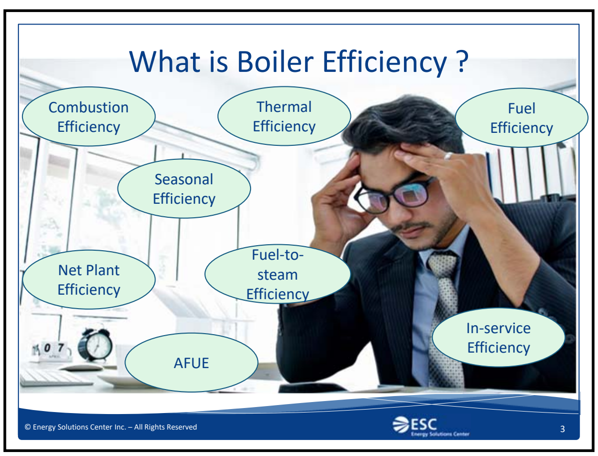

Track: Industrial
Unit 12
Understanding Boiler Efficiencies and their Applications
Prepared by: Aqeel Zaidi, M.Sc., P.Eng., CEM, CMVP
on behalf of Energy Solutions Center
© Energy Solutions Center Inc. – All Rights Reserved

1


Topics
Various definitions of boiler efficiency
How various efficiencies are measured and calculated
How and when to use these efficiencies for energy saving projects
Show examples
© Energy Solutions Center Inc. – All Rights Reserved
2

2


What is Boiler Efficiency ?
Combustion Efficiency
Thermal Efficiency
Fuel Efficiency
Seasonal Efficiency
Net Plant Efficiency
Fuel-to-steam Efficiency
In-service Efficiency
AFUE
© Energy Solutions Center Inc. – All Rights Reserved
3

3

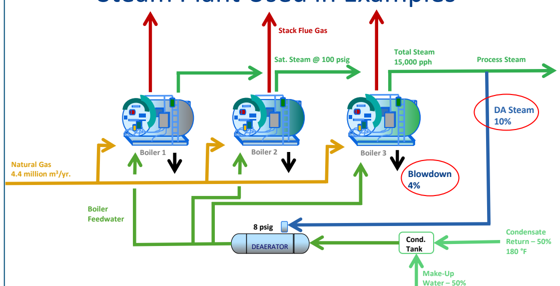
Why is it Important to understand Various Efficiencies

- Boiler efficiency has different meaning for different people
- Different interpretations are used by different vendors, consultants and boiler operators
- Understanding of boiler efficiency is important when:
  - evaluating performance of existing boilers and steam plant
  - Considering to install a control or heat recovery device on the boiler (linkageless control, economizer) or in steam plant (blowdown heat recovery system)
  - Considering to replace/upgrade a steam utilization equipment outside the steam plant in production facility
  - Considering to replacing existing boiler with a new one
  - Safety aspect

 ESC 4

4

Steam Plant Used in Examples



Boilers: 3 X 500 BHP
Rated input per boiler: 20.9 MMBtu/hr
Average firing rate: 50%
Hourly gas consumption: 10.5 MMBtu/hr

Plant operating hours: 8,000 hrs.
Each boiler runs For 5,000 hrs.
Natural gas cost: 0.25 $/m3 ($0.7/therm)
Annual gas cost: $1.1 million/yr.

 5

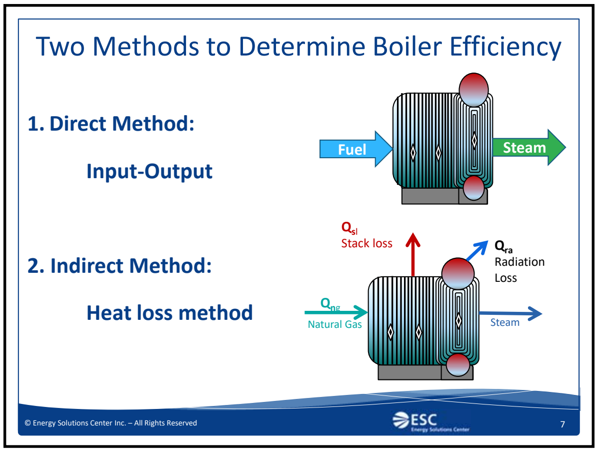
5

Training Objectives

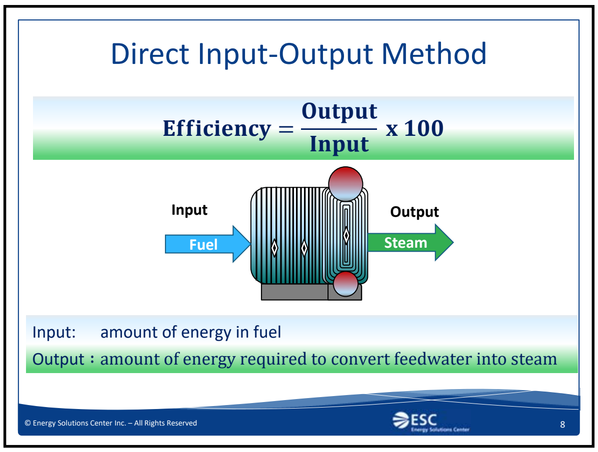
1. Calculate various efficiencies
2. Use examples to show how appropriate efficiencies are used to determine energy savings for various boiler and steam projects

 ESC 6

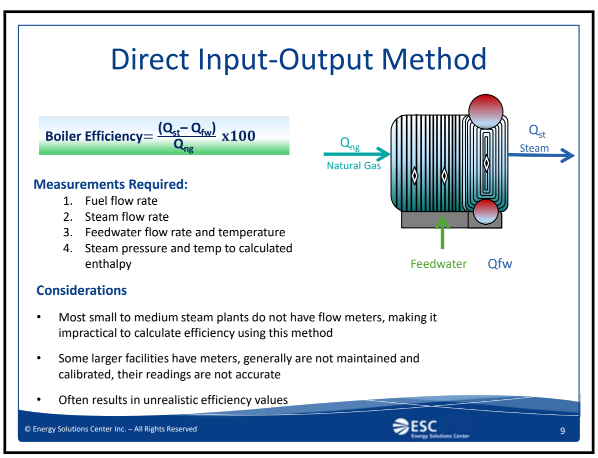
6


Two Methods to Determine Boiler Efficiency
1. Direct Method:
Input-Output
Fuel
Steam
2. Indirect Method:
Heat loss method
Qsl
Stack loss
Qra
Radiation
Loss
Qng
Natural Gas
Steam
© Energy Solutions Center Inc. – All Rights Reserved
7

7


Direct Input-Output Method
Efficiency = Output / Input x 100
Input
Output
Fuel
Steam
Input: amount of energy in fuel
Output : amount of energy required to convert feedwater into steam
© Energy Solutions Center Inc. – All Rights Reserved
8

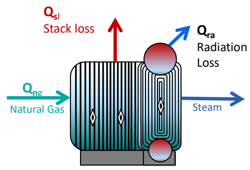
8


Direct Input-Output Method
Boiler Efficiency= (Qst – Qfw) / Qng x100
Qng
Natural Gas
Qst
Steam
Feedwater
Qfw
Measurements Required:
1. Fuel flow rate
2. Steam flow rate
3. Feedwater flow rate and temperature
4. Steam pressure and temp to calculated enthalpy
Considerations
• Most small to medium steam plants do not have flow meters, making it impractical to calculate efficiency using this method
• Some larger facilities have meters, generally are not maintained and calibrated, their readings are not accurate
• Often results in unrealistic efficiency values
© Energy Solutions Center Inc. – All Rights Reserved
9

9

Indirect Heat Loss Method

- Indirect method is based on calculating heat losses such as stack loss and radiation loss
- Does not require gas and steam flow measurements
- **Gives an opportunity to see how well the combustion is**
- **Identifies opportunities for combustion improvements**



 ESC 10

10

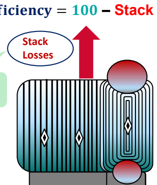
Combustion Efficiency

$$\text{Combustion Efficiency} = \frac{\text{Input Energy} - \text{Stack Losses}}{\text{Input Energy}}$$

$$\text{Combustion Efficiency} = 1 - \frac{\text{Stack Losses}}{\text{Input Energy}}$$

$$\frac{\left[\frac{\text{Btu}}{\text{lb of fuel}}\right]}{\text{HHV}\left[\frac{\text{Btu}}{\text{lb of fuel}}\right]}$$

$$\text{Combustion Efficiency} = 100 - \text{Stack Losses as a \% of fuel}$$



How do we measure these losses

There is no need to measure gas consumption or steam production to establish combustion efficiency.

 ESC 11

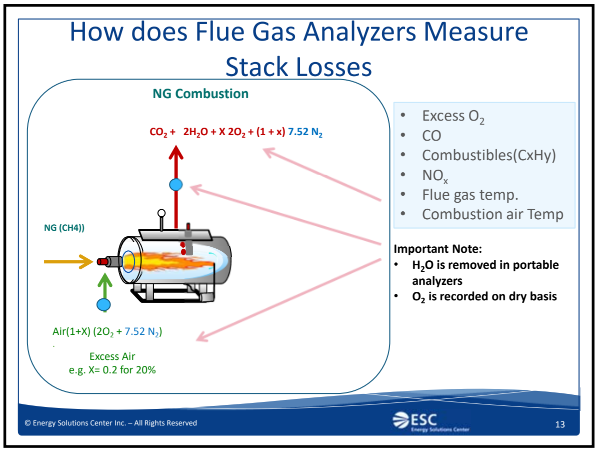
11

Flue Gas Analyzers Measure Stack Losses for Combustion Efficiency Calculations

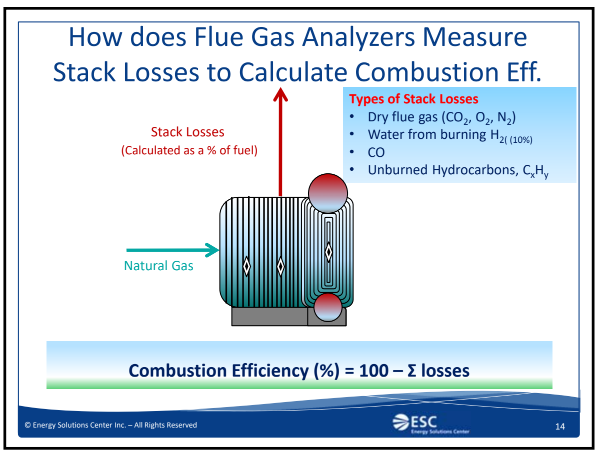


 ESC 12

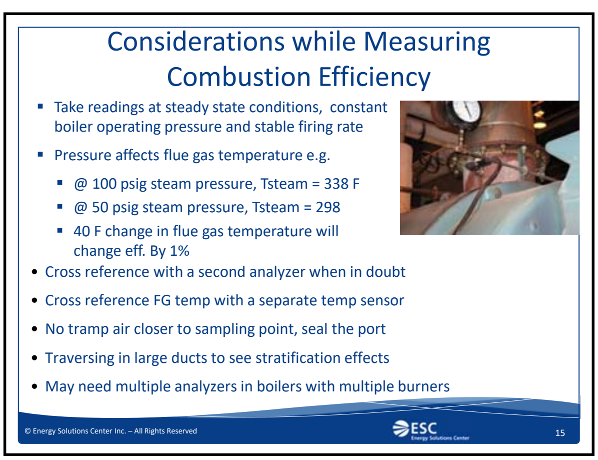
12


How does Flue Gas Analyzers Measure Stack Losses
NG Combustion
CO2 + 2H2O + X 2O2 + (1 + x) 7.52 N2
NG (CH4))
Air(1+X) (2O2 + 7.52 N2)
Excess Air
e.g. X= 0.2 for 20%
• Excess O2
• CO
• Combustibles(CxHy)
• NOx
• Flue gas temp.
• Combustion air Temp
Important Note:
• H2O is removed in portable analyzers
• O2 is recorded on dry basis
© Energy Solutions Center Inc. – All Rights Reserved
ESC
13

13


How does Flue Gas Analyzers Measure Stack Losses to Calculate Combustion Eff.
Stack Losses
(Calculated as a % of fuel)
Types of Stack Losses
• Dry flue gas (CO2, O2, N2)
• Water from burning H2((10%)
• CO
• Unburned Hydrocarbons, CxHy
Natural Gas
Combustion Efficiency (%) = 100 – Σ losses
© Energy Solutions Center Inc. – All Rights Reserved
ESC
14

14


Considerations while Measuring Combustion Efficiency
▪ Take readings at steady state conditions, constant boiler operating pressure and stable firing rate
▪ Pressure affects flue gas temperature e.g.
▪ @ 100 psig steam pressure, Tsteam = 338 F
▪ @ 50 psig steam pressure, Tsteam = 298
▪ 40 F change in flue gas temperature will change eff. By 1%
• Cross reference with a second analyzer when in doubt
• Cross reference FG temp with a separate temp sensor
• No tramp air closer to sampling point, seal the port
• Traversing in large ducts to see stratification effects
• May need multiple analyzers in boilers with multiple burners
© Energy Solutions Center Inc. – All Rights Reserved
ESC
15

15

How to Calculate Combustion Efficiency

Use the Combustion Efficiency Chart or Combustion Calculator to determine the combustion efficiency based on the following parameters:

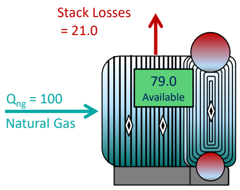
Excess O_2 = 8%
Flue Gas Temp. T_{fg} = 460 °F
Combustion Air Temp. T_{air} = 80 °F
Calculate Delta T = (460 – 80) °F
= 380 °F

Excess, %	FG Temperature - Combustion Air				
O2	340	360	380	400	420
7.00	80.6	80.1	79.5	79.0	78.4
7.50	80.4	79.8	79.2	78.6	78.0
8.00	80.0	79.4	78.9	78.3	77.7
8.50	79.7	79.1	78.5	77.9	77.2

16

Combustion Efficiency What does it mean?

- 79% combustion efficiency means that 79% of fuel energy is delivered to Boiler
- For process heating application, this is also called Available Heat



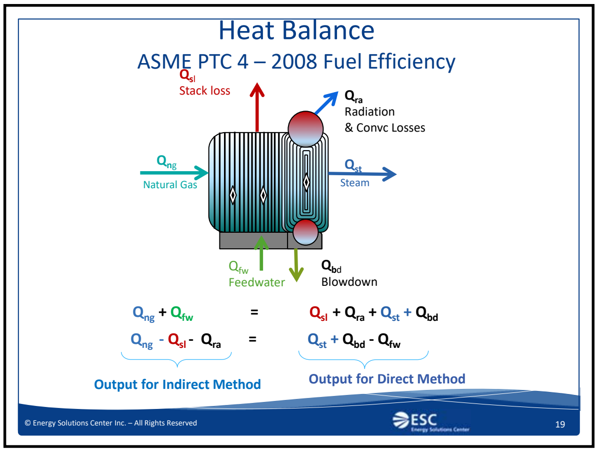
17

Fuel Efficiency as per ASME PTC 4 - 2008

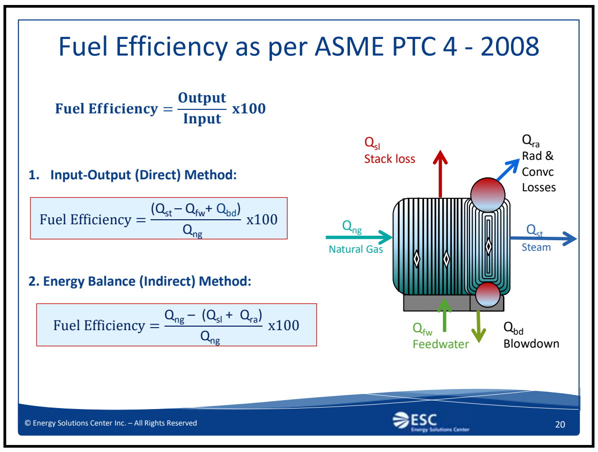
$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100$$

- Includes all energy absorbed by the working fluid as output and chemical energy of fuel as input
- Describes methodology for calculating efficiency using **Direct and Indirect** method
- Takes into account radiation and blowdown losses
- Based on Steam Generator **Energy Balance**

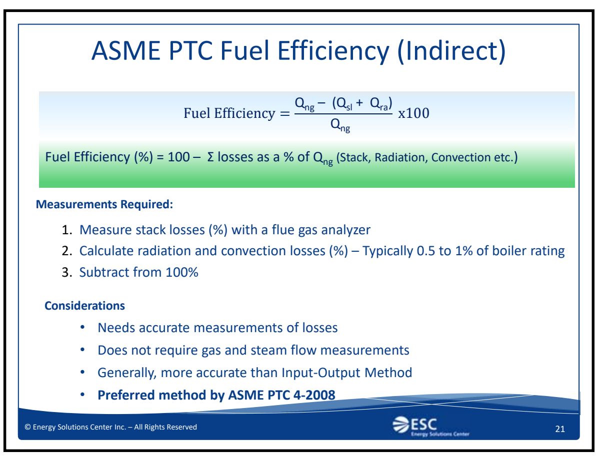
18


Heat Balance
ASME PTC 4 – 2008 Fuel Efficiency
Q_{sl} Stack loss
Q_{ra} Radiation & Convc Losses
Q_{ng} Natural Gas
Q_{st} Steam
Q_{fw} Feedwater
Q_{bd} Blowdown
$Q_{ng} + Q_{fw} = Q_{sl} + Q_{ra} + Q_{st} + Q_{bd}$
$Q_{ng} - Q_{sl} - Q_{ra} = Q_{st} + Q_{bd} - Q_{fw}$
Output for Indirect Method
Output for Direct Method
© Energy Solutions Center Inc. – All Rights Reserved
ESC
19

19


Fuel Efficiency as per ASME PTC 4 - 2008
$\text{Fuel Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100$
1. Input-Output (Direct) Method:
$\text{Fuel Efficiency} = \frac{(Q_{st} - Q_{fw} + Q_{bd})}{Q_{ng}} \times 100$
2. Energy Balance (Indirect) Method:
$\text{Fuel Efficiency} = \frac{Q_{ng} - (Q_{sl} + Q_{ra})}{Q_{ng}} \times 100$
Q_{sl} Stack loss
Q_{ra} Rad & Convc Losses
Q_{ng} Natural Gas
Q_{st} Steam
Q_{fw} Feedwater
Q_{bd} Blowdown
© Energy Solutions Center Inc. – All Rights Reserved
ESC
20

20


ASME PTC Fuel Efficiency (Indirect)
$\text{Fuel Efficiency} = \frac{Q_{ng} - (Q_{sl} + Q_{ra})}{Q_{ng}} \times 100$
Fuel Efficiency (%) = 100 – Σ losses as a % of Q_{ng} (Stack, Radiation, Convection etc.)
Measurements Required:
1. Measure stack losses (%) with a flue gas analyzer
2. Calculate radiation and convection losses (%) – Typically 0.5 to 1% of boiler rating
3. Subtract from 100%
Considerations
• Needs accurate measurements of losses
• Does not require gas and steam flow measurements
• Generally, more accurate than Input-Output Method
• Preferred method by ASME PTC 4-2008
© Energy Solutions Center Inc. – All Rights Reserved
ESC
21

21

Fuel-to-Steam (F-t-S) Efficiency

Practical efficiency

- Reflects the amount of fuel energy converted to steam
- *No standard definition like Fuel Efficiency in ASME PTC 4-2008*
- Assumes blowdown as a loss, not a useful output as suggested in PTC 4-2008
- Expect 3% drop in combustion efficiency when calculating F-t-S efficiency

$$\text{F-t-S Efficiency(indirect)} = \frac{Q_{ng} - \overbrace{Q_{sl} - Q_{ra} - Q_{bd}}^{\text{Losses}}}{Q_{ng}} \times 100$$

$$= 100 - \Sigma \text{ losses (\% of } Q_{ng})$$

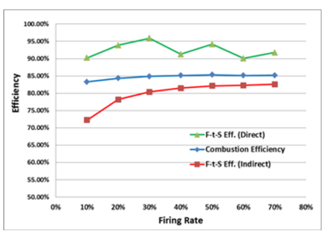
$$\text{F-to-S Efficiency (direct)} = \frac{(Q_{st} - Q_{fw})}{Q_{ng}} \times 100$$

ESC Energy Solutions Center 22

22

How Firing Rates Impact Fuel-to-Steam Efficiency

- Radiation loss (%of fuel input) is constant at all firing rates
  - A higher percentage of fuel input is lost at low firing rates
- Efficiency is reduced at low firing rates due to high excess O_2 and high radiation loss
- Optimum efficiency to operate boiler at is generally higher than 50% firing rate



Note: High F-t-S efficiency by direct method (green line) reflects issues with measuring equipment's

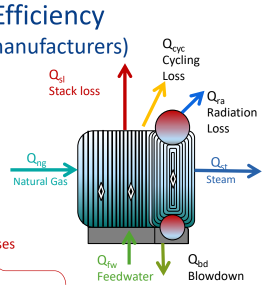
ESC Energy Solutions Center 23

23

In-service Efficiency

(used by some manufacturers)

- Add other losses such as cycling and startup/shutdown losses
- Cycling caused by low turn down ratio, improper load matching
- All these losses could be captured in F-t-S efficiency and no need to call it "in-service efficiency"



$$\text{F-t-S Efficiency} = \frac{Q_{ng} - \overbrace{Q_{sl} - Q_{ra} - Q_{bd} - Q_{cyl}}^{\text{Losses}}}{Q_{ng}} \times 100$$

$$= 100 - \Sigma \text{ losses (\% of } Q_{ng})$$

ESC Energy Solutions Center 24

24

Thermal Efficiency

- Generally used for commercial hot water boilers
- ASHRAE's definition is similar to combustion efficiency
- Ignores convection and radiation losses from appliances located indoors, these are considered as useful heat

25

Seasonal Efficiency

Annual Fuel Utilization Efficiency (AFUE)

- Also called AFUE
- Actual season-long average efficiency
  - total output/total input
- Generally, applies to residential and commercial boilers and heating appliance

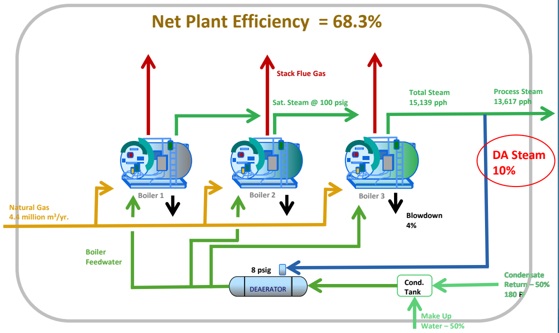
26

Net Plant Efficiency

- Shows how efficiently steam was produced as it leaves the steam plant
- **Takes into account steam supplied to Deaerator (DA)**
- Requires heat and mass balance around the steam plant, taking into account the condensate being returned to the plant

27

Net Plant Efficiency



 28

28

Wrap-up of Efficiency Definitions

Efficiency	What does it mean
Combustion Efficiency	% of fuel energy delivered to boiler
Fuel Efficiency	% of fuel energy picked up by the boiler feedwater
Fuel-to-Steam Efficiency	% of fuel energy used to produce steam
In-service Efficiency	Similar to F-t-S, but accounts for cycling and start-up losses
Net plant Efficiency	% of fuel energy used to deliver steam out of steam plant

 ESC Energy Solutions Center 29

29

How and Where to Apply Various Efficiencies

 30

30

Where to Apply Combustion Efficiency

- Any improvements to combustion systems
  - Burner tune-up
  - Optimizing excess O2
  - Linkageless controls
  - Reducing/eliminating CO and combustibles etc.
- Reducing flue gas temperature

 ESC Energy Solutions Center 31

31

Example 1 – Calculate Energy Saving by Reducing excess O2 from 8% - 5%

Use Combustion Efficiency Chart or Combustion Calculator to calculate combustion efficiencies

η_{old} = 78.9 %

Calculate new η
η_{new} = 80.6 %

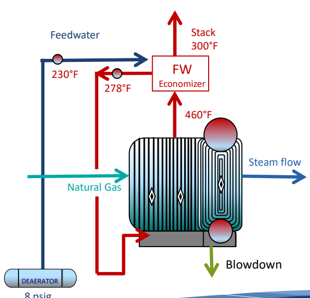
Excess, %	FG Temperature - Combustion Air				
O2	340	360	380	400	420
4.00	82.0	81.5	81.1	80.6	80.1
4.50	81.8	81.3	80.8	80.4	79.9
5.00	81.6	81.1	80.6	80.1	79.6
5.50	81.4	80.9	80.4	79.9	79.3
6.00	81.2	80.6	80.1	79.6	79.0
6.50	80.9	80.4	79.8	79.3	78.7
7.00	80.6	80.1	79.5	79.0	78.4
7.50	80.4	79.8	79.2	78.6	78.0
8.00	80.0	79.4	78.9	78.3	77.7
8.50	79.7	79.1	78.5	77.9	77.2

Energy Saving = Q_{in} x $\{1 - (\eta_{old}/\eta_{new})\}$

 ESC Energy Solutions Center 32

32

Example 2 – Calculate Energy Savings for Installing a FW Economizer to Preheat FW



 ESC Energy Solutions Center 33

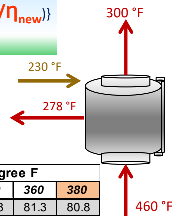
33

Example 2 – FW Economizer

Use Combustion Efficiency Chart or Combustion Calculator to identify the new efficiency level after installing a feedwater economizer and then calculate the associated savings.

Parameters
$\eta_{w/o\ econo.}$ = 80.6 %
O_2 = 5%
T_{out} = 300 °F
T_{air} = 80 °F
Delta T = 220 °F

Energy Savings = $Q_{in} \times \{1 - (\eta_{old}/\eta_{new})\}$



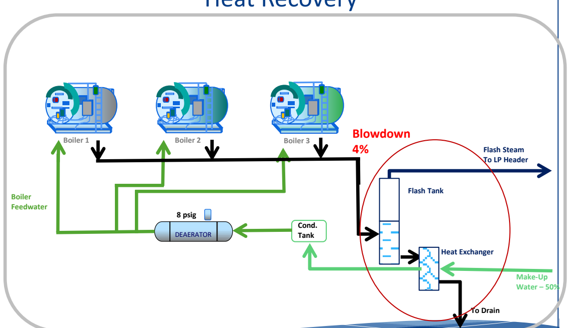
η_{new} = 84.6 %

xcess,	FG Temperature - Combustion Air Temp,Degree F									
O2	200	220	240	260	280	300	320	340	360	380
4.50	85.3	84.8	84.3	83.8	83.3	82.8	82.3	81.8	81.3	80.8
5.00	85.1	84.6	84.1	83.6	83.1	82.6	82.1	81.6	81.1	80.6
5.50	85.0	84.5	84.0	83.5	82.9	82.4	81.9	81.4	80.9	80.4

 ESC 34

34

Example 3 – Use of F-t-S Efficiency for Blowdown Heat Recovery



 ESC 35

35

Example 3 – Use of F-t-S Efficiency for Blowdown Flash Tank Heat Recovery

Flash Steam Flow = %Flash x BD Flow Rate

Flash Steam Savings = Flash Steam Flow Rate x Enthalpy

Annual Flash Steam Savings = Flash Steam Savings / $\eta_{fuel\text{-}to\text{-}steam}$

 ESC 36

36

Where to Apply Net Plant efficiency

- Any improvements outside the steam plant
- Examples:
  - Repairing leaks
  - Reducing process vent steam
  - Replacing steam coil makeup air unit with gas-fired unit
  - Decentralizing large steam plant with smaller boilers

 ESC Energy Solutions Center 37

37

Example 4 - Use Net Plant Efficiency to Calculate Saving from De-centralizing a Large Central Steam Plant

Install a new small decentralized Boiler		
Building energy consumption =	11,667	MMBtu/yr
Centralized steam system efficiency=	62.2	%
New decentralized boiler efficiency =	80	%
Energy Saving=	11,667 x (1 - 62.2/80)	
	2,596	MMBtu/yr
Annual Gas Saving=	72,638	m3/yr

 ESC Energy Solutions Center 38

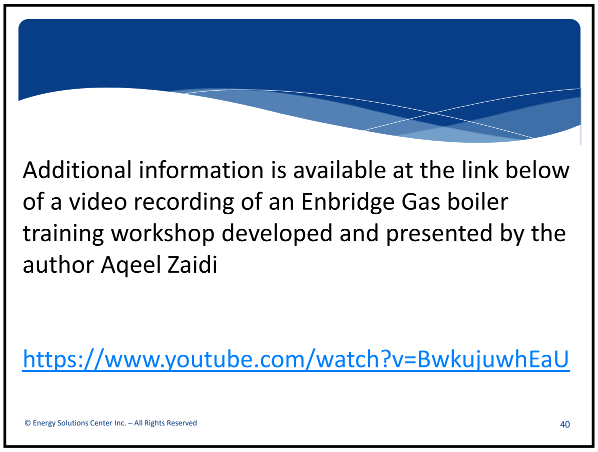
38

Key Messages

1. Different efficiencies have different meanings. Ask Qs about what is meant by reported efficiency
2. Indirect Stack Loss method gives reasonable indication of boiler performance and identifies opportunities for combustion improvements
3. Apply proper efficiency to evaluate boiler performance and to establish gas savings for efficiency improvement projects

 ESC Energy Solutions Center 39

39


Additional information is available at the link below of a video recording of an Enbridge Gas boiler training workshop developed and presented by the author Aqeel Zaidi
https://www.youtube.com/watch?v=BwkujuwhEaU
© Energy Solutions Center Inc. – All Rights Reserved
40

40


Thank you …
© Energy Solutions Center Inc. – All Rights Reserved

41