

Improving Energy Efficiency of Boiler Systems

An Online Continuing Education Course for Engineers

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Improving Energy Efficiency of Boiler Systems

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When considering boiler energy savings, invariably the discussion involves the topic of boiler efficiency.

Boiler suppliers and sales personnel will often cite various numbers, such as a thermal efficiency of 85%, a combustion efficiency of 87%, a boiler efficiency of 80%, and a fuel-to-steam efficiency of 83%. What do these terms mean?

Typically:

- 1) Thermal efficiency reflects how well the boiler vessel transfers heat, and usually excludes radiation and convection losses.
- 2) Combustion efficiency typically indicates the ability of the burner to use fuel completely without generating carbon monoxide or leaving hydrocarbons unburned.
- 3) Boiler efficiency could mean almost anything. Any fuel-use figure must compare the energy put into the boiler with the energy coming out of the boiler.
- 4) Fuel-to-steam efficiency is accepted as a true input/output value.

Each term represents something different, and there is no way to tell which boiler will use less fuel in the same application. The trouble is that there are several norms to determine the efficiencies figures, and it is practically very difficult to verify these without costly test procedures. The easiest and most cost effective method is to review the basic boiler design data and estimate the efficiency value on five broad elements.

- 1) **Boiler Stack Temperature:** Boiler stack temperature is the temperature of the combustion gases leaving the boiler. This temperature represents the major portion of the energy not converted to usable output. The higher the temperature, the less energy transferred to output and the lower the boiler efficiency. When stack temperature is evaluated, it is important to determine if the value is proven. For example, if a boiler runs on natural gas with a stack temperature of 350°F, the maximum theoretical efficiency of the unit is 83.5%. For the boiler to operate at 84% efficiency, the stack temperature must be less than 350°F.
- 2) **Heat Content of Fuel:** The efficiency calculation requires knowledge of the calorific value of the fuel (heat content), its carbon to hydrogen ratio, and whether the water produced is lost as steam or is condensed and the latent heat (heat required to turn water into steam) is recovered. Disagreements exist on what is considered an "energy input." Unfortunately, any fuel has two widely published energy contents:
 - Higher Heating Value (HHV), also called Gross Calorific Value (GCV)
 - Lower Heating Value (LHV), also called the Net Calorific Value (NCV)

The gross calorific value (GCV) is the higher figure and assumes that all heat available from the fuel is to be recovered, including latent heat. This is not the case for most equipment. The calculations of efficiency based on gross calorific value will give the maximum obtainable efficiencies as much lower than 100% due to this irrecoverable loss.

Both the gross calorific value and net calorific value are equally valid, but for comparison purposes, a particular convention should be used throughout the analysis.

- 3) **Fuel Specification:** The fuel specified has a dramatic effect on efficiency. Because gaseous fuels have higher hydrogen content, more water vapor is formed during combustion. The result is energy loss, as the vapor absorbs energy in the boiler and lowers the efficiency of the equipment.

The specification used to calculate efficiency must be based on the fuel to be used at the installation. As a rule, typical natural gas has a hydrogen/-carbon (H/C) ratio of 0.31. If an H/C ratio of 0.25 is used for calculating efficiency, the value increases from 82.5% to 83.8%.

- 4) **Excess Air Levels:** Excess air is supplied to the boiler beyond what is required for complete combustion, primarily to ensure complete combustion and to allow for normal variations in combustion. A certain amount of excess air is provided to the burner as a safety factor for sufficient combustion air.
- 5) **Ambient Air temperature and Relative Humidity:** Ambient conditions have a dramatic effect on boiler efficiency. Most efficiency calculations use an ambient temperature of 80°F and a relative humidity of 30%. Efficiency changes more than 0.5% for every 20°F change in ambient temperature. Changes in air humidity would have similar effects: the higher the humidity, the lower the efficiency.

Comparing these five factors along with the stated efficiency allows you to understand efficiency values more thoroughly. It is important to make the comparisons on equal footings. Consider the examples below:

- If two boilers are stated as operating at the same stack temperature and one has less heating surface, stack temperature on the boiler with less heating surface should be challenged.
- If two boilers are stated as operating at 15% excess air and one has a very complex burner linkage design or does not include a high-quality air damper arrangement, it is questionable that it will operate at the stated excess air level.
- If two boilers of similar length and width are compared and one has more flue gas passes (the number of times the flue gas travels through the boiler heat exchanger), the boiler with the greater number of passes should have a lower stack temperature.

Evaluating Boiler Efficiencies

The most basic efficiency norm is the “input/output” ratio:

$$\text{Efficiency } (\eta) = \frac{E_{\text{out}}}{E_{\text{in}}}$$

Where

- E_{out} is the energy needed to convert feed water entering the boiler at a specific pressure and temperature to steam leaving the boiler at a specific pressure and temperature. (This includes the energy picked up by the blow down and not converted into steam.)
- E_{in} is the input energy into the boiler. The heat input is based on the high heat (gross calorific) value of fuel for efficiency calculations in the US, UK and many other countries. Germany uses low heat (net calorific) value basis, implying that for an identical boiler, the stated efficiency shall be higher.

There are two methods of assessing boiler efficiency:

1. Input – output or direct method
2. Heat loss or indirect method

Direct Method for Calculating Boiler Efficiency

The direct method compares the energy gain of the working fluid (water and steam) to the energy content of the fuel. This is also known as the ‘input-output method’ due to the fact that it needs only the useful output (steam) and the heat input (i.e., fuel) for evaluating the efficiency. The efficiency is then estimated using equation below:

$$\% E = \frac{\text{Output}}{\text{Input}} = \frac{\text{Enthalpy of Steam} - \text{Enthalpy of feedwater}}{\text{Heat released in Boiler}} * 100$$

Procedure:

- 1) Measure the quantity of steam flow kg (or lb.) over a set period; e.g., one hour period. Use steam integrator readings if available, and correct for orifice calibration pressure. Alternatively, use the feedwater integrator if available, which will in most cases not require a correction for pressure.
- 2) Measure the quantity of fuel used over the same period. Use the gas or oil integrator, or determine the mass of solid fuel used.

- 3) Determine the working pressure in Kg/cm^2 (psi) and superheat temperature, $^{\circ}\text{C}$ ($^{\circ}\text{F}$), if any.
- 4) Determine the temperature of feedwater $^{\circ}\text{C}$ ($^{\circ}\text{F}$.)
- 5) Convert steam flow, feedwater flow and fuel flow to identical energy units; e.g., kJ/kg or Btu/lb.
- 6) Determine the type of fuel and gross calorific value of the fuel (GCV or HHV) in kJ/kg or Btu/lb.
- 7) Calculate the efficiency using equation:

$$\% E = \frac{\text{Output}}{\text{Input}} = \frac{\text{Enthalpy of Steam} - \text{Enthalpy of feedwater}}{\text{Heat released in Boiler}} * 100$$

The direct method is simple in that it requires few parameters for computations and needs few instruments for monitoring. However, this method may not be as accurate due to errors in metering fuel flow and steam flow. In practice, only very large industrial set ups and electric utility companies are instrumented well enough to obtain the required data.

Indirect Method or Heat Loss Method for Calculating Boiler Efficiency

With the indirect method, the efficiency is estimated by summing the losses and compared to the heat input. The major heat losses from boiler are due to:

1. High temperature flue gas leaving the stack
2. Moisture in fuel and combustion air
3. Combustion of hydrogen (leaves boiler stack as water vapor)
4. Heat in un-burnt combustibles in refuse
5. Radiation from the boiler surfaces
6. Unaccounted for un-measured losses

Sum up the losses and calculate the efficiency using equation:

$$\text{Efficiency (\% E)} = 100 - \Sigma \text{ Losses}$$

Or

$$\% E = \frac{\text{Heat Input} - \text{Heat Losses}}{\text{Heat Input}}$$

$$\% E = 100 - \left(\frac{\text{Heat losses}}{\text{Heat in fuel}} \right) * 100$$

Evaluating Heat Losses from Boiler

The procedure for calculating boiler efficiency by indirect method is illustrated below.

1) **Dry Flue Gas Loss (LDG)**

Heat is lost in the "dry" products of combustion, which carry only sensible heat since no change of state was involved. These products are carbon-dioxide (CO₂), carbon monoxide (CO), oxygen (O₂), nitrogen (N₂) and sulphur dioxide (SO₂.) Concentrations of SO₂ and CO are normally in the parts-per-million (ppm) range. Therefore, from the viewpoint of heat loss, they can be ignored.

Calculate the dry flue gas loss (LDG) using the following formula:

$$\text{LDG, \%} = [\text{DG} \times \text{Cp} \times (\text{FGT} - \text{CAT})] \times 100 / \text{HHV}$$

Where

- DG is the weight of dry flue gas, lb/lb of fuel
- Cp is the specific heat of flue gas, usually assumed to be 0.24
- FGT is the flue gas temperature, °F
- CAT is the combustion air temperature, °F
- HHV is the higher heating value of the fuel, Btu/lb

The formula can be simplified to $\text{LDG, \%} = [24 \times \text{DG} \times (\text{FGT} - \text{CAT})] / \text{HHV}$

If temperatures are measured in °C, other units remaining unchanged, the formula becomes

$$\text{LDG} = [43.2 \times \text{DG} \times (\text{FGT} - \text{CAT})] \div \text{HHV}$$

The weight of dry gas (DG) varies with fuel composition, and the amount of excess air used for combustion. For the normal case of zero CO or unburned hydrocarbons, it can be calculated as:

$$\text{DG} = (11\text{CO}_2 + 8\text{O}_2 + 7\text{N}_2) \times (\text{C} + 0.375\text{S}) / 3\text{CO}_2$$

Where

- CO₂ and O₂ are % by volume in the flue gas
- N₂ is % by volume in the flue gas = 100 - CO₂ - O₂
- C and S are weight fractions from the fuel analysis (lb/lb fuel)

What do you need to determine LDG?

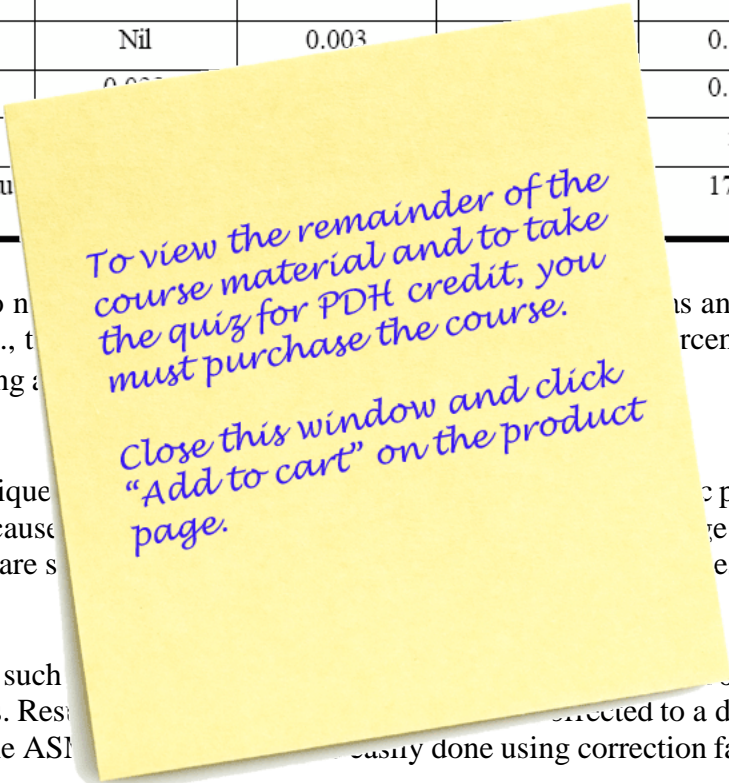
The calculation of dry flue gas loss requires the following:

- 1) Measurements of flue gas temperature and combustion air temperature. These can be measured using a thermocouple type digital indicator. Sometimes these readings are directly available from the installed instrumentation.
- 2) Flue gas analysis for CO₂ and O₂. These readings can be determined from the ORSAT/FYRITE combustion analysis kit or digital type portable flue gas analyzer. Some plants have continuous gas analyzers in place. By looking at O₂ levels in the flue gas, conclusions can be drawn about the excess air levels.
- 3) Heating content in fuel. This can be determined through lab testing of the fuel sample.

Typical indicative values are shown below for guidance.

HIGH HEAT VALUE OF VARIOUS FEULS

Fuel	Natural Gas	No. 2 Oil (light oil)	No. 4 Oil (bunker A)	No. 6 Oil (bunker C)
HHV, Btu/lb	22,450	19,450	18,750	18,350
<u>Ultimate analysis, weight fraction</u>				
Carbon	0.721	0.865	0.867	0.867
Hydrogen	0.239	0.132	0.115	0.108
Sulphur	Nil	0.003		0.020
Nitrogen	0.005			0.005
Oxygen				nil
lb CO ₂ /10 ⁶ Btu input				173.2



It is important to n...
the dry basis; i.e., t...
volume, excluding a...

... analysis to be reported on
percentage of the dry flue gas

Analytical technique...
dry gas basis because...
These analyzers are s...
sample.

... principles, measure on a...
... to the detection cells.
... moisture from the gas

Some analyzers, such...
the wet gas basis. Res...
can be used in the ASI...

... oxide cell, measure on...
... directed to a dry gas basis before they...
... easily done using correction factors: