ASME PTC-4 – Indirect Method: Stack Loss Method

This method approximates the stack losses of a boiler to estimate boiler efficiency.

Parameters

The parameters needed to calculate this method are given below. These data are calculated during source testing.

1. Stack temperature (T_{Stack})
2. Dry oxygen in flue gas ($O_{2,Dry,\%}$) in percent

Summary of Calculations

Calculation of mass of dry gas per standard cubic feet of fuel:

$$DG = 14.7365\left(\frac{O_{2\%}}{21\% - O_{2\%}}\right) + 15.371 \quad \text{Eq-5}$$

Calculation of Dry Losses in stack:

$$L_{DG}[\%] = 0.001044 \times DG \times (T_{Stack} - 70) \quad \text{Eq-7}$$

Calculation of Wet Losses in stack:

$$L_{WG}[\%] = 9.482 + 0.004351 \times T_{Stack} \quad \text{Eq-11}$$

Boiler Efficiency:

$$BE = 100\% - L_{DG} - L_{WG} - 1\%_{Other\ Losses} \quad \text{Eq-12}$$

Assumptions

The assumptions used in this calculation are the following:

1. One percent energy loss from radiation and surface convection.
2. Loss associated with carbon monoxide in flue gas is negligible.
3. Loss associated with moisture in fuel is negligible.
4. Loss associated with moisture in air is negligible.

ARB assumed the following natural gas composition in these calculations:

Table 1: Assumed composition of natural gas.

Constituent	Molecular Formula	Volumetric Percentage
Methane	CH_4	95%
Ethane	C_2H_6	2%
Propane	C_3H_8	1%
Nitrogen	N_2	2%

Staff used the following additional fuel data.

Table 2: Additional fuel data.

Data	Value	Units
Density of Fuel	0.0445	lbs/cubic ft
HHV	1022.71	BTU/cubic ft
HHV	22983.189	BTU/lb

Supporting Calculations

Combustion of natural gas.

The stoichiometric combustion of natural gas is shown in the equation below.

$$0.95CH_4 + 0.02C_2H_6 + 0.01C_3H_8 + 0.02N_2 + 2.02(O_2 + 3.76N_2) \rightarrow 1.02CO_2 + 2H_2O + 7.62N_2$$

Eq-1

The number of moles of dry flue gas constituents is equal to the sum of the moles of N_2 and CO_2, 8.64 lbmols.

Staff converted the flue gas constituents from a volumetric proportion to a mass proportion. The conversion of carbon dioxide and nitrogen is given in the following equations.

$$M_{CO_2} = \frac{1.02\ mole\ CO_2}{mole\ fuel} \times \frac{44\ lb\ CO_2}{1\ mole\ CO_2} \times \frac{mole\ fuel}{16.8\ lb\ fuel} = \frac{2.671\ lb\ CO_2}{lb\ fuel}$$

$$M_{N_2} = \frac{7.62\ mole\ N_2}{mole\ fuel} \times \frac{28\ lb\ N_2}{1\ mole\ N_2} \times \frac{mole\ fuel}{16.8\ lb\ fuel} = \frac{12.700\ lb\ N_2}{lb\ fuel}$$

Eqns-2

To calculate the additional weight of excess air, Staff uses measurements from boiler source tests that are taken in conjunction with air permits. Staff uses the volumetric proportion of oxygen to dry flue gas. The equation also utilizes the percent of oxygen in air: 21 percent. The calculation is the following.

$$Excess\ Air\left[\frac{ft^3_{air}}{ft^3 fuel}\right] = 8.64 \times \left(\frac{O_{2\%}}{21\% - O_{2\%}}\right) \qquad \text{Eq-3}$$

To convert the above equation from a volumetric proportion to a mass proportion, Staff multiplied Excess Air by the density of air at 60F and sea level: 0.0759 lbs per cubic foot.

$$Excess\ Air\left[\frac{lb\ air}{lb\ fuel}\right] = Excess\ Air\left[\frac{ft^3_{air}}{ft^3 fuel}\right] \times \frac{0.0759\ lbs\ air}{ft^3 air} \times \frac{ft^3 fuel}{0.0445\ lbs\ fuel}$$

$$Excess\ Air\left[\frac{lb\ air}{lb\ fuel}\right] = 14.7365\left(\frac{O_{2\%}}{21\% - O_{2\%}}\right) \qquad \text{Eq-4}$$

The result was then added to the other flue gas constituents in Equations 2 to calculate the total weight of dry gas per cubic foot of fuel.

$$DG = 14.7365\left(\frac{O_{2\%}}{21\% - O_{2\%}}\right) + 2.671 + 12.700$$

$$DG = 14.7365\left(\frac{O_{2\%}}{21\% - O_{2\%}}\right) + 15.371 \qquad \text{Eq-5}$$

The energy loss from sensible heating of the flue gas is equal to the product of the weight of the flue gasses, the specific heat, and the change in temperature. Staff assumes an initial temperature of 70F. Staff estimated the specific heat of air to be 0.24 BTU per lb.

$$E_{sensible} = DG \times 0.24 \times (T_{Stack} - 70) \qquad \text{Eq-6}$$

The percent energy loss is equal to the ratio of sensible energy per pound of fuel divided by the higher heating value.

$$L_{DG}[\%] = \frac{E_{sensible}}{HHV} = \frac{0.24}{22983.189} \times DG \times (T_{Stack} - 70) \times 100\%$$

$$L_{DG}[\%] = 0.001044 \times DG \times (T_{Stack} - 70) \qquad \text{Eq-7}$$

Staff calculated the wet gas losses from vaporizing and water from combustion. To do this, Staff first needed to calculate the mass of water in the flue gas. This equation is similar to Equations 2.

$$M_{water} = \frac{2\ mole\ H_2O}{mole\ fuel} \times \frac{18\ lb\ H_2O}{1\ mole\ H_2O} \times \frac{mole\ fuel}{16.8\ lb\ fuel} = \frac{2.143\ lb\ H_2O}{lb\ fuel}$$

Eqns-8

Staff then needed to calculate the change in enthalpy of the water from state one, a liquid at 70 F, to superheat steam at state two, vapor at T_{Stack}. Albeit, enthalpy requires two states to be calculated, Staff found small changes in the partial pressure of water made little change in the enthalpy of liquid water and superheated steam. In the range of 1 to 5 PSIA, the enthalpy change was less than 0.1 percent. Staff calculated the enthalpy of water at 70F to be 38.06 BTU per lb. The enthalpy of superheat steam was calculated using the following equation.

$$h_{steam} = 1055 + (0.467 \times T_{Stack}) \qquad \text{Eq-9}$$

Equation 9 is valid for the operating range of stack temperatures, 200-500F, with less than a 0.1% error.

To calculate the energy used to vaporize and heat the water, Staff multiplied the change in enthalpy of the water by the mass of water per pound of fuel.

$$E_{Water} = M_{water} \times \Delta h = 2.143 \times (1055 + (0.467 \times T_{Stack}) - 38.06)$$

$$E_{Water} = 2179.3 + T_{Stack} \qquad \text{Eq-10}$$

The percent energy loss is equal to the ratio of energy per pound of fuel divided by the higher heating value.

$$L_{WG}[\%] = \frac{E_{Water}}{HHV} = \frac{2179.3 + T_{stack}}{22983} \times 100\%$$

$$L_{WG}[\%] = 9.482 + 0.004351 \times T_{Stack} \qquad \text{Eq-11}$$

The final boiler efficiency is the sum of the losses plus any unaccounted for losses. Staff estimated 1 percent for unaccounted for losses to include any radiative and convective losses. Thus, the final boiler efficiency equation is given below.

$$BE = 100\% - L_{DG} - L_{WG} - 1\%_{Other\ Losses} \qquad \text{Eq-12}$$