ENERGY SURVEYS FOR Boiler and PLANT OPERATIONS

The efficient use of energy is fast becoming a top concern for industry. As business managers become more conscientious about their energy use, they are realizing that effective energy conservation can result in significant returns to their companies. Energy surveys are key to helping them achieve their goals.

In today's world—as the cost of fuel steadily increases while the supply decreases—energy conservation is a must. For industry to conserve energy without lowering production, it must find ways to use resources more efficiently.

Energy management is the judicious control of energy to accomplish a purpose: the production of a product, the completion of a process, or heating and cooling a building. Energy management is required to get the most out of every Btu of fuel and every KWH of electricity. Energy conservation is becoming an important issue along with reliability, fuel flexibility, and pollution control.

Stewart Cohen/Stone

Organizing an energy conservation program is not an easy task. To be effective, the program needs a reasonable target and timetable, adequate technical information and resources for implementation, a firm commitment on the part of management and all members of the organization, and a sound, consistent plan of action.

To begin an energy conservation effort, managers need to pinpoint areas of high fuel and electric power consumption. This requires an energy audit detailing all the energy inputs and distribution throughout the plant. Preparing a plan requires a detailed survey. In addition, it is necessary to visually inspect the equipment and components, and to conduct various tests at critical points to determine energy consumption. This article aims to illustrate the different boiler energy losses and present an accurate picture of energy use that is easy to follow and understand.

To understand the flow of energy (Btu) through a system, you need to understand the first law of thermodynamics; simply stated it says that energy (Btu) can neither be created nor destroyed. Energy can only be transformed from one form to another. For the end-user then, we can diagram a complete energy analysis (heat balance) of all energy inputs into the system, and all energy discharges out of the system.

Since energy can't be created or destroyed, the summation of total energy inputs must equal the summation of the total energy discharges. To put it another way, the sum of the energy (potential, kinetic, thermal, chemical, and electrical) entering a process must equal the sum of the energy leaving.

A properly prepared energy balance sheet analysis of a system or an entire plant is an excellent way to present your energy survey results to management. Terms such as combustion efficiency, boiler efficiency, and plant efficiency should be included in the energy survey and the losses, but these terms can be confusing. The confusion results from the many different ways to calculate these terms. Therefore, it is important to show the calculation procedures and to provide all information on losses.

Combustion Efficiency

Combustion efficiency is a measure of the percent of available energy in the fuel and air, which is released in the combustion process. Stated another way, it is the ratio of available heat (after losses) divided by the fuel input. Table 1 shows the combustion efficiency equation and the associated losses.

Heat loss (due to dry gas) is heat carried away (out of the stack) by the hot flue gases. This loss is usually called "dry flue gas" loss. Hotter stack temperatures and large quantities of excess air increase the loss. Excess air beyond stoichiometric conditions is required to ensure complete combustion and to allow for proper control. The sensible heat loss in the dry chimney gases is one of the losses. For complete combustion, solid fuels require the greatest excess air and dry flue gas losses, and gaseous fuels the least. A flue gas temperature well above the acid dew point temperature is a good indicator of excessive dry gas losses.

The ratio of hydrogen atoms to carbon atoms in a given fuel greatly affects the efficiency of a boiler. In complete combustion, hydrogen atoms in the fuel combine with oxygen in the combustion air to form water, which consumes the heat of vaporization to become water vapor in the flue gas. The latent heat of vaporization is lost when water vapor leaves the boiler stack because the vapor cannot be condensed due to an inherent corrosion problem due to the presence of SO_3 in the flue gas. Some commercial furnaces do offer secondary stainless-steel heat exchangers so that this latent heat can be recovered. See Table 3 for typical values for water vapor formation from hydrogen in the fuel. The table shows that natural gas produces much more water vapor than coal due to its higher hydrogen content. Natural gas also has much higher losses in this category than coal.

1. Combustion efficiency losses (Btuh)
   a. Dry flue gas loss
   b. Loss due to evaporation of hydrogen-formed water
   c. Loss from evaporation of fuel moisture
   d. Loss from superheating the moisture in the combustion air
   e. Loss from unburned CO in the flue gas
   f. Total flue gas loss (a+b+c+d+e)
   g. Loss due to unburned carbon in the refuse
   h. Total combustion losses (f+g)
2. Total flue gas loss = flue gas discharge (Btuh) – Comb. air input (Btuh)
3. Combustion efficiency = 100 – (Flue gas loss + unburned carbon loss)
   a. Combustion efficiency =
   $$\frac{\text{[Fuel input – (Flue gas discharge – Comb. air input + Unburned carbon loss)] (Btuh)}}{\text{Fuel input (Btuh)}} \times 100$$
   b. Combustion efficiency =
   $$\frac{\text{(Fuel input – Combustion losses)}}{\text{Fuel input}} \times 100$$

TABLE 1. ***Combustion efficiency.***

Moisture in fuel reduces the efficiency of the boiler by discharging heat up the stack in the form of highly superheated vapor. The water present in the fuel consumes latent heat of vaporization (from the available energy) to become water vapor in the flue gas. There is also a sensible heat loss due to superheating the vapor. The total loss for this category can be a significant loss for solid fuels, but tends to be small for gaseous fuels.

If insufficient oxygen (air) is supplied, the mixture is "rich" and the fire is "reducing," which results in a flame that tends to be longer and sometimes smoky. This is usually called incomplete combustion, which occurs when the fuel particles combine with some oxygen but cannot get enough to burn completely. Incomplete combustion results in the formation of carbon monoxide gas, which is another loss in the combustion process, because the fuel introduced into the boiler is not completely burned.

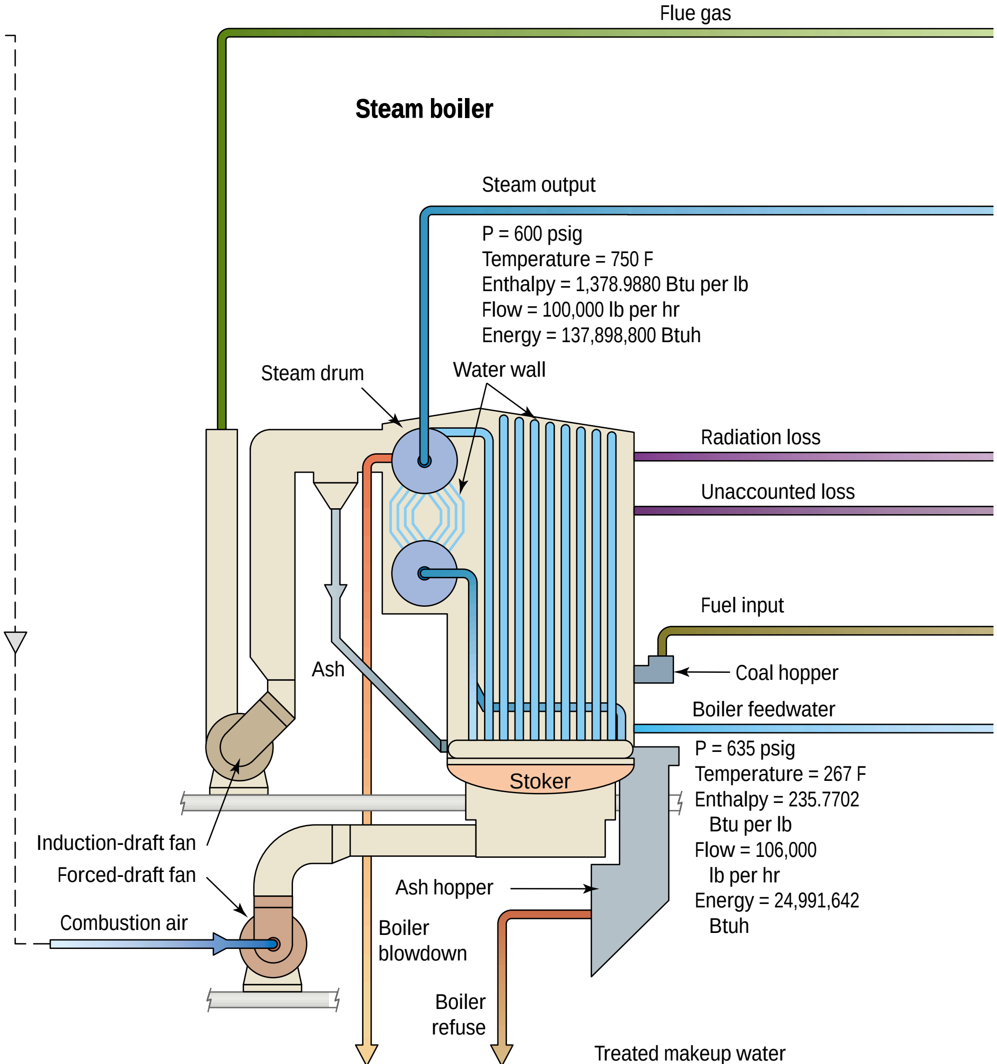
With perfect combustion of hydrocarbon fuels, the carbon is heated in the presence of air; oxygen in the air combines with the carbon to form carbon dioxide. The hydrogen in the fuel combines with the oxygen in the air to form water vapor. For greatest efficiency, the fuel-and-air mixture should be adjusted so there is little to no carbon monoxide in the flue gas. To maintain high boiler efficiency, the carbon monoxide concentration in the flue gas must be kept below 15 to 20 ppm (wet basis).

The last combustion efficiency loss is unburned carbon. This can be unburned carbon or partially burned carbon found in the ash pit or the flue gas (fly ash). This is a loss that occurs in the burning of solid fuels such as coal. A low value for coal is 2 lb of carbon per 100 lb

Combustion air:
t_{DB} = 80 F
t_{WB} = 69.59 F
t_{DP} = 64.79 F
RH = 60 percent
$W\left(\frac{\text{lb wv}}{\text{lb dry air}}\right) = 0.01311294$
$\upsilon\left(\frac{\text{ft wet air}}{\text{lb dry air}}\right) = 13.892432$
ACFM = 31,345.1050
$\mathring{m}\left(\frac{\text{lb dry air}}{\text{hr}}\right) = 135{,}376.31$
$\mathring{m}\left(\frac{\text{lb wv}}{\text{hr}}\right) = 1{,}775.19$
$\mathring{m}\left(\frac{\text{lb total}}{\text{hr}}\right) = 137{,}151.50$
Q sensible = 1,561,433 Btuh
Q latent = 1,946,743 Btuh
Q total = 3,508,176 Btuh

Efficiency data:
Combustion efficiency = 88.23 percent
Boiler efficiency = 85.02 percent
Plant efficiency = 81.41 percent
Percent excess air = 35 percent

Potential energy savings:
- Reduce flue-gas temperature from 350 to 300 F: $36,000 per year
- Reduce excess air from 35 to 30 percent: $6,700 per year
- Blowdown heat-recovery energy savings: $21,200 per year



Boiler blowdown:
Pressure = 635 psig
Temperature = 495 F
Enthalpy = 481.7644 Btu per lb
Flow = 6,000 lb per hr
Energy = 2,890,586 Btuh

Treated makeup water
Temperature = 143 F
Enthalpy = 110.89 Btuh
Flow = 42,463.38 lb per hr
Energy = 4,708,764 Btuh

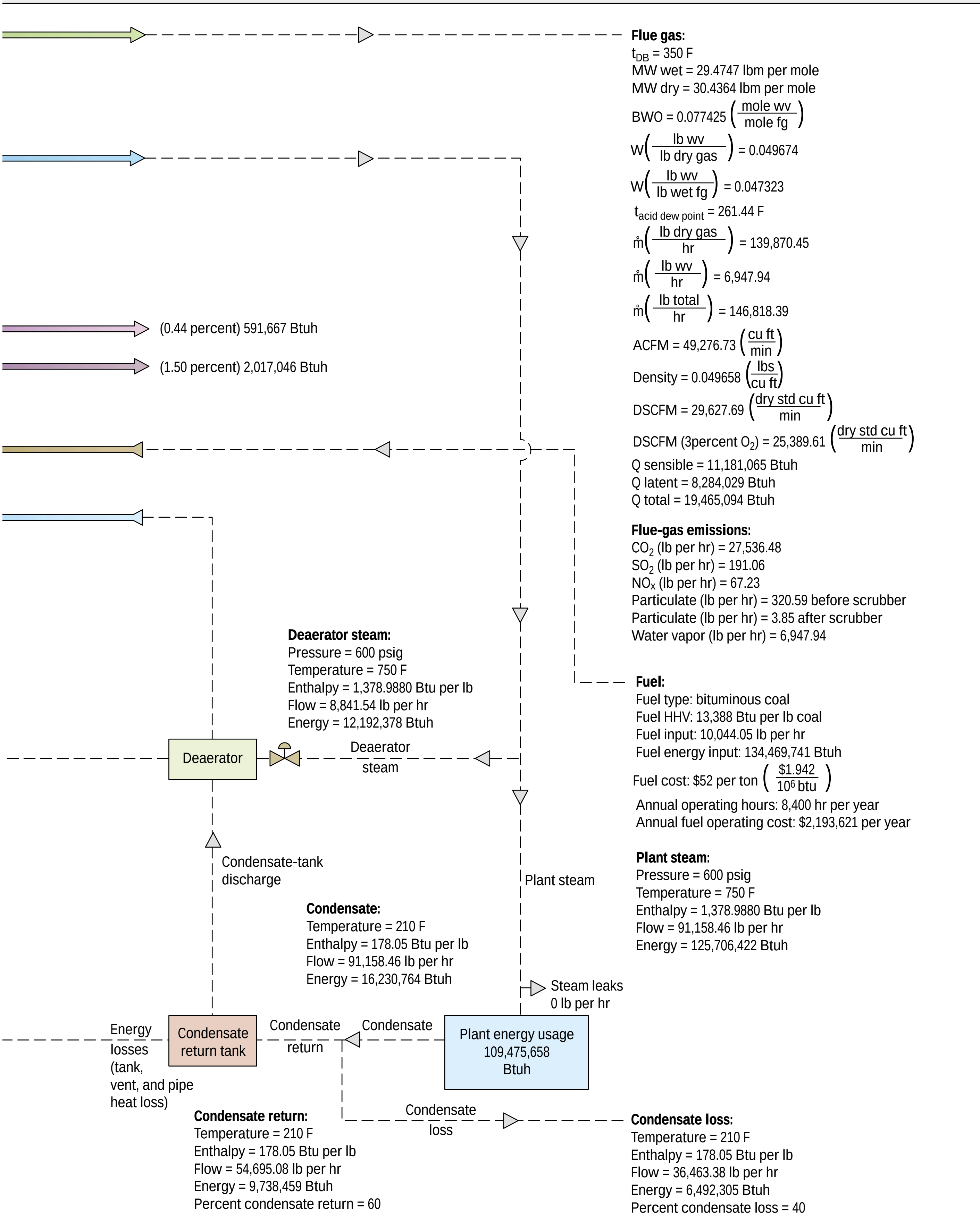
Boiler refuse:
Total ash produced = 369.6210 lb per hr
Unburned carbon = 7.5433 lb per hr
Total refuse produced = 377.1643 lb per hr
Fly ash discharge to atmosphere = 3.85 lb per hr
Total refuse collected = 373.3143 lb per hr

Condensate-tank discharge:
Temperature = 180 F
Enthalpy = 147.92 Btu per lb
Flow = 54,695.08 lb per hr
Energy = 8,090,496 Btuh

1,647,963 Btuh

Boiler losses:	**Btuh**	**Percent**
Dry-gas heat loss	9,085,245	6.76
Evaporation of hydrogen-formed water	5,388,834	4.01
Evaporation of fuel moisture	1,028,209	0.76
Water vapor in combustion air	217,152	0.16
Carbon monoxide	0	0
Unburned carbon in flue gas	106,366	0.08
Radiant loss	591,667	0.44
Unaccounted loss	2,017,046	1.50
Blowdown loss	1,707,766	1.27
Total	20,141,985	14.98

FIGURE 1. ***A plant system energy survey.***


Flue gas:
t_{DB} = 350 F
MW wet = 29.4747 lbm per mole
MW dry = 30.4364 lbm per mole
BWO = 0.077425 $\left(\frac{\text{mole wv}}{\text{mole fg}}\right)$
$W\left(\frac{\text{lb wv}}{\text{lb dry gas}}\right)$ = 0.049674
$W\left(\frac{\text{lb wv}}{\text{lb wet fg}}\right)$ = 0.047323
$t_{\text{acid dew point}}$ = 261.44 F
$\dot{m}\left(\frac{\text{lb dry gas}}{\text{hr}}\right)$ = 139,870.45
$\dot{m}\left(\frac{\text{lb wv}}{\text{hr}}\right)$ = 6,947.94
$\dot{m}\left(\frac{\text{lb total}}{\text{hr}}\right)$ = 146,818.39
ACFM = 49,276.73 $\left(\frac{\text{cu ft}}{\text{min}}\right)$
Density = 0.049658 $\left(\frac{\text{lbs}}{\text{cu ft}}\right)$
DSCFM = 29,627.69 $\left(\frac{\text{dry std cu ft}}{\text{min}}\right)$
DSCFM (3percent O_2) = 25,389.61 $\left(\frac{\text{dry std cu ft}}{\text{min}}\right)$
Q sensible = 11,181,065 Btuh
Q latent = 8,284,029 Btuh
Q total = 19,465,094 Btuh
Flue-gas emissions:
CO_2 (lb per hr) = 27,536.48
SO_2 (lb per hr) = 191.06
NO_x (lb per hr) = 67.23
Particulate (lb per hr) = 320.59 before scrubber
Particulate (lb per hr) = 3.85 after scrubber
Water vapor (lb per hr) = 6,947.94
(0.44 percent) 591,667 Btuh
(1.50 percent) 2,017,046 Btuh
Deaerator steam:
Pressure = 600 psig
Temperature = 750 F
Enthalpy = 1,378.9880 Btu per lb
Flow = 8,841.54 lb per hr
Energy = 12,192,378 Btuh
Fuel:
Fuel type: bituminous coal
Fuel HHV: 13,388 Btu per lb coal
Fuel input: 10,044.05 lb per hr
Fuel energy input: 134,469,741 Btuh
Fuel cost: \$52 per ton $\left(\frac{\$1.942}{10^6 \text{ btu}}\right)$
Annual operating hours: 8,400 hr per year
Annual fuel operating cost: \$2,193,621 per year
Deaerator
Deaerator steam
Condensate-tank discharge
Plant steam
Plant steam:
Pressure = 600 psig
Temperature = 750 F
Enthalpy = 1,378.9880 Btu per lb
Flow = 91,158.46 lb per hr
Energy = 125,706,422 Btuh
Condensate:
Temperature = 210 F
Enthalpy = 178.05 Btu per lb
Flow = 91,158.46 lb per hr
Energy = 16,230,764 Btuh
Steam leaks
0 lb per hr
Energy losses (tank, vent, and pipe heat loss)
Condensate return tank
Condensate return
Condensate
Plant energy usage 109,475,658 Btuh
Condensate loss
Condensate return:
Temperature = 210 F
Enthalpy = 178.05 Btu per lb
Flow = 54,695.08 lb per hr
Energy = 9,738,459 Btuh
Percent condensate return = 60
Condensate loss:
Temperature = 210 F
Enthalpy = 178.05 Btu per lb
Flow = 36,463.38 lb per hr
Energy = 6,492,305 Btuh
Percent condensate loss = 40

of refuse (carbon and ash), or less. High-end values can be 6 to 10 lb per lb. The retrofitting of low NOx burners can increase the amount of unburned carbon in the refuse.

Boiler Efficiency

The equations used for this article may be found in Table 1. Boiler efficiency loss is a combination of combustion efficiency losses plus some additional losses found in Table 2. Boiler efficiency as presented here is the amount of energy transferred from the combustion side to the water side (of a steam boiler) after losses and divided by the fuel input.

The boiler efficiency losses (for non-cycling boilers) include the combustion efficiency losses plus:

- Radiant heat loss
- Blowdown losses, and
- Unaccounted losses.

Radiant heat loss from a boiler is the radiant and convection heat loss from the hot surfaces of the boiler. The American Boiler Manufacturers Association (ABMA) provides a chart for estimating this heat loss. It is important to remember that the radiant loss (Btuh) does not change with boiler load, therefore a 50,000 lb of steam per hr boiler with a radiation loss of 1 percent (or 500 lb per hr) will still have the same radiation loss when the boiler runs at 10,000 lb of steam per hr. Therefore, at the lower boiler load of 10,000 lb of steam per hr, our radiation loss is now 5 percent of the boiler load. If the boiler cycles on and off, the radiant loss as a percentage of boiler output gets worse.

Boiler blowdown losses can be reduced with the installation of a heat recovery system. Boiler feedwater introduces soluble salts, silt, and other solids into the boiler system. Build-up of the solids will lead to scaling and / or corrosion on the boiler's internal surfaces. Build-up can be controlled with chemical treatment and blowdown of the boiler water. Blowdown of the boiler drum bleeds-off a portion of water containing a high concentration of solids and replaces it with treated low concentration make-up water. The percent blowdown equation is listed below:

$$\text{percent blowdown} = \frac{\text{blowdown (lb per hr)}}{\text{steam output (lb per hr)}} \times 100$$

The last boiler efficiency loss is unaccounted losses. These are customarily included in a heat balance to provide a margin of safety or tolerance in the calculated efficiency. The typical value for these losses is around 1.5 percent.

The losses discussed so far have been for non-cycling boilers. Cyclic losses occur when the plant demand (Btuh) is lower than the low-fire limit (Btuh) of the boiler. The oversized boiler must then cycle off and on to maintain the plant demand. Cyclic losses are subtracted from the boiler efficiency. It is not unusual to have a boiler efficiency of 80 percent or greater and to end up with an overall efficiency below 50 percent due to high cyclic losses.

There are four types of cyclic

1. Boiler efficiency losses (Btuh)
   - a. Dry flue gas loss
   - b. Loss due to evaporation of hydrogen-formed water
   - c. Loss from evaporation of fuel moisture
   - d. Loss from superheating the moisture in the combustion air
   - e. Loss from unburned CO in the flue gas
   - f. Loss from unburned carbon
   - g. Radiant heat loss
   - h. Boiler blowdown loss
   - i. Unaccounted losses
   - j. Total boiler efficiency losses (a+b+c+d+e+f+g+h+i)
   - k. Or total boiler efficient losses =
     Flue gas discharge – Combustion air input + Unburned carbon + Radiation loss + Unaccounted losses + Boiler blowdown
     = Combustion efficiency losses + Radiation loss + Unaccounted losses + Boiler blowdown loss
2. Boiler efficiency

Boiler efficiency (percent) =

$$\frac{\text{[Fuel input (Btuh) – Boiler efficiency losses (Btuh)]}}{\text{Fuel input (Btuh)}} \times 100$$

Boiler efficiency (percent) =

$$\frac{\left[\dot{m}\left(\frac{\text{Lb steam}}{\text{hour}}\right) \times \text{(h stream - h feed water)} \frac{\text{BTU}}{\text{lb steam}}\right]}{\text{Fuel input (Btuh)}} \times 100$$

TABLE 2. ***Boiler efficiency.***

1.	Anthracite coal	0.22	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
2.	Bituminous coal	0.49	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
3.	No. 6 Fuel oil	0.84	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
4.	No. 5 Fuel oil	0.97	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
5.	No. 4 Fuel oil	1.04	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
6.	No. 2 Distillate oil	1.12	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
7.	No. 1 Distillate oil	1.20	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
8.	Gasoline	1.30	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
9.	Propane	1.62	$\frac{\text{lb w.v.}}{\text{lb fuel}}$
10.	Natural gas	2.03	$\frac{\text{lb w.v.}}{\text{lb fuel}}$

TABLE 3. ***Water vapor formation from combustion of hydrogen in the fuel.***

	Enthalpy for 80 F dry air	Temp. of dry air at zero enthalpy	Temp. of water vapor at zero enthalpy
1. Psychrometrics by Zimmerman and Lavine	$11.534 \frac{BTU}{lb\ dry\ air}$	32 F	32 F
2. ASHRAE	$19.220 \frac{BTU}{lb\ dry\ air}$	0 F	32 F
3. Gas tables by Keenan, Chao and Kaye	$109.90 \frac{BTU}{lb\ dry\ air}$	-459.67 F	-459.67 F
4. Thermodynamic properties of steam by Keenan and Keyes	–	–	32 F

TABLE 4. ***Enthalpy calculation procedures.***

losses: those resulting from pre-purge and post-purge drafts, shell radiant losses, and natural draft losses. Pre- and post-purge procedures can result in draft losses because they involve forcing air through the boiler to remove unburned combustibles before start-up and after shutdown. While this eliminates the possibility of a boiler explosion due to too much fuel in the combustion chamber, unfortunately, the air traveling through the boiler removes heat at the same time. Pre- and post-purge draft losses can be determined by testing the air flow, inlet, and outlet temperatures, and the amount of operating time.

Shell losses are radiant losses that continue to occur during the off cycle. Natural draft losses are losses that occur during the boiler off cycle, and are associated with the air flow through the boiler created by the difference in temperature between the boiler and outside ambient conditions. Natural draft loss can also be tested during the boiler off cycle.

Commercial building heating systems typically have a wide range of heating demands throughout the year. To prevent cycle load losses, many buildings use multiple small boilers.

Energy-Survey Example

Figure 1 shows an example of a mass balance energy survey that accounts for all the energy flow Btu and all mass flows into and out of the entire plant system. The energy analysis involves a combination psychrometrics and thermodynamics computer program, a boiler efficiency program, and a flue gas Btu analysis program, that an associate and I developed for these surveys. This boiler and plant analysis procedure provides the business owner with an easy-to-understand energy analysis, provides a greater degree of accuracy in the Btu energy flows, and reduces the engineering time because the calculations are computerized.

In this particular survey, the combustion efficiency is 88.1 percent, the boiler efficiency is 85.5 percent, and the overall plant efficiency is 81.9 percent. Overall plant efficiency for use in this article is the Btu of energy consumed by the plant processes divided by the Btu of fuel consumed to produce the steam.

Plants with many steam leaks, little condensate return, poor pipe insulation, and poor maintenance of steam traps tend to have a plant efficiency that is well below the boiler efficiency. The computer program provides nine data sheets for each boiler covering all the losses, flue gas analysis including SO_2, SO_3, acid dew point, Btu, and particulate emissions. The flue gas program allows the engineer to change the leaving flue gas temperature (for the same mass flow) to check for potential heat recovery. Through the reduction of excess air, the program can also calculate the energy savings associated with the combustion air reduction.

To develop an energy balancing procedure, it was necessary to choose enthalpy-calculating procedures with the same zero-energy starting point for dry air, water vapor, and dry flue gases. Table 4 shows some of the procedures reviewed for the combustion air. The gas table procedure by Keenan, Chao, and Kaye is used in a number of gas turbine energy analysis programs. This procedure eliminates negative enthalpies because the zero enthalpy level is set really low. I chose the Zimmerman and Lavine procedure, which also allowed the use of the Keenan and Keyes steam tables. This was so engineers could see enthalpies they are most familiar with. Also, Zimmerman and Lavine utilize procedures that allow for analysis of air and water vapor up to very high temperatures.

The author would like to thank his associate, Nels Strand, for his assistance in the development of the computer programs.

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Boiler Energy Balance – Btu's Into Equal Btu's Out & Boiler Efficiency

A. Energy Entering The Boiler

1. Combustion Air	3,508,176 Btu/hour
2. Fuel	134,469,741 Btu/hour
3. Boiler Feedwater	24,991,642 Btu/hour
4. Total Energy Entering	162,969,559 Btu/hour

B. Energy Leaving The Boiler

1. Flue Gas Flow	19,465,094 Btu/hour
2. Steam Output	137,898,800 Btu/hour
3. Radiant Loss	591,667 Btu/hour
4. Unaccounted Loss	2,017,046 Btu/hour
5. Blowdown	2,890,586 Btu/hour
6. Unburned Carbon	106,366 Btu/hour
7. Total Energy Leaving	162,969,559 Btu/hour

C. Boiler Losses

1. Dry Gas Heat Loss	9,085,245 Btu/hour
2. Evaporation Of Hydrogen Formed Water	5,388,834 Btu/hour
3. Evaporation Of Fuel Moisture	1,028,209 Btu/hour
4. Water Vapor In Combustion Air	217,152 Btu/hour
5. Carbon Monoxide	0 Btu/hour
6. Unburned Carbon In Flue Gas	106,366 Btu/hour
7. Radiant Loss	591,667 Btu/hour
8. Unaccounted Loss	2,017,046 Btu/hour
9. Blowdown Loss	1,707,766 Btu/hour
10. Total Losses	20,141,985 Btu/hour

D. Boiler Efficiency

$$1.\ \text{Boiler Eff.} = \frac{\text{Fuel Input (Btu/hour)} - \text{Losses (Btu/hour)}}{\text{Fuel Input (Btu/hour)}} \times 100$$

$$= \frac{134{,}469741\ \text{(Btu/hr)} - 20{,}141{,}985\ \text{(Btu/hr)}}{134{,}469{,}741\ \text{(Btu/hr)}} \times 100$$

$$= 85.02\%$$

Boiler Losses = 100% – 85.02% = 14.98 %

$$2.\ \text{Boiler Eff.} = \frac{\text{Steam Flow (lbs/hr) x (Steam h} - \text{Feedwater h) Btu/lb}}{\text{Fuel Input (Btu/hr)}} \times 100$$

$$= \frac{100{,}000\ \text{lbs/hr x } (1378.9880 - 235.7702)\ \text{Btu/lb}}{134{,}469{,}741\ \text{Btu/hr}} \times 100$$

$$= 85.02\ \%$$