Lesson 2

Combustion Efficiency

Lesson Goal and Objectives

Goal

To familiarize you with combustion principles and with the factors that affect combustion efficiency in boilers.

Objectives

Upon completing this lesson, you should be able to—

1. describe the three conditions that are necessary for complete combustion and their relationship to each other,
2. define *stoichiometric amount of oxygen,*
3. define the terms *lower explosive limit, upper explosive limit, excess air, higher heating value,* and *net heating value,*
4. estimate combustion efficiency using charts, figures, and calculation forms, and
5. list areas of potential heat loss in a boiler.

Combustion Variables

Combustion is a chemical process occurring from the rapid combination of oxygen with combustible materials, or fuel, that produces heat. In a boiler, fuel such as coal oil, gas, or wood is mixed with air at elevated temperatures producing heat and the oxides of many of the elements contained in the fuel.

Most fuels used in boilers are composed of essentially carbon and hydrogen, but can also contain other elements such as nitrogen and sulfur. The products resulting from complete combustion of hydrocarbon, or organic fuels are carbon dioxide and water vapor. However, if the fuel contains oxygen, the resulting flue gas may contain aldehydes and organic acids creating an air pollution problem. The simplified reactions of carbon and hydrogen are given as:

(Eq. 2-1) $$C + O_2 \rightarrow CO_2 + \text{energy}$$

(Eq. 2-2) $$2\ H_2 + O_2 \rightarrow 2\ H_2O + \text{energy}$$

Equations 2-1 and 2-2 show that the final products resulting from complete combustion of organic fuels are carbon dioxide, water, and energy in the form of heat. This is the ideal condition that all boiler operators strive to achieve. However, incomplete combustion can occur if combustion conditions are not adequate. When combustion is incomplete, smoke (unburned fuel), carbon monoxide, and other partially oxidized products will be formed. These are air pollutants or undesired products. In addition, less heat will be produced when combustion is incomplete.

If the fuel should contain elements such as sulfur and nitrogen, the flue gas produced will contain the oxides of these elements **even when** combustion is complete. Sulfur oxides and nitrogen oxides are air pollutants that can be harmful if emitted in significant amounts. Air pollution control techniques will be discussed in Lesson 6.

To achieve complete combustion once the air (oxygen) and fuel have been brought into contact, the following conditions are necessary:

- temperature high enough to ignite the fuel and air mixture
- turbulent mixing of the fuel and air, and
- sufficient residence time for the reaction to occur.

Called the "three T's of combustion," turbulence, temperature, and time, these conditions govern the speed and completeness of a reaction. They depend on each other, because changing one affects the other two.

Air Supply

The amount of air needed for combustion in a boiler depends on the fuel, the equipment used, and the operating conditions of the unit. If there is too much air, an excessive amount of hot gases will be discharged from the boiler as well as a correspondingly high heat loss. If there is not enough air, unburned fuel will be discharged from the boiler. Therefore, it is important to design and operate the boiler with the appropriate amount of air to completely combust the fuel fed to the furnace.

Turbulence

Turbulent mixing of the air (oxygen) and fuel is essential for efficient combustion. Each combustible particle must contact oxygen before it will burn. If the air and fuel mixing in the combustion chamber or in the fuel bed is poor, there will be too much combustion air in some places and not enough in others. Inadequate mixing can result in incomplete combustion products and unburned fuel being emitted from the boiler.

Temperature

The rate at which a combustible material is oxidized is greatly affected by the temperature. The higher the temperature, the faster the oxidation reaction will proceed. The chemical reaction of fuel and oxygen can occur even at ambient temperatures. For this reason, a pile of coal can be a fire hazard. Small amounts of heat are given off as the coal slowly oxidizes. This in turn raises the temperature of the coal pile and increases the oxidation rate, liberating more heat. Eventually, a full-fledged fire can break out.

In boilers, when the combustible material reaches its ignition temperature, the rate of oxidation is accelerated to the combustion point. Once the fuel is ignited, the heat released during combustion will be high enough to sustain the continual oxidation of the fuel.

Time

Air supply, turbulence, and temperature determine the rate at which combustion proceeds. However, a sufficient amount of time is required to ensure that the fuel completely burns. If the residence time is not high enough, unburned fuel or partially oxidized compounds will be emitted from the boiler. This causes an appreciable heat loss in the boiler and pollutants to be emitted into the atmosphere. The residence time is directly related to the volume of the furnace chamber. The larger the chamber volume for a set flow rate, the longer the residence time will be.

Combustion Calculations

Stoichiometric Amount of Oxygen

Oxygen is necessary for combustion to occur. To achieve complete combustion of an organic compound, a sufficient supply of oxygen must be present to convert all of the carbon to CO_2. This quantity of oxygen is referred to as the *stoichiometric* or *theoretical amount*. The stoichiometric amount of oxygen is determined from a balanced chemical equation summarizing the oxidation reactions. Consider a generalized fuel with a chemical formula $C_xH_yS_zO_w$ where the indices x, y, z, and w represent the relative number of atoms of carbon, hydrogen, sulfur, and oxygen respectively. Balancing the chemical reaction for the complete oxidation (combustion) of this fuel with oxygen from air gives:

(Eq. 2-3)

$$C_xH_yS_zO_w + \left(x + \frac{y}{4} + z - \frac{w}{2}\right)O_2 + \frac{0.79}{0.21}\left(x + \frac{y}{4} + z - \frac{w}{2}\right)N_2 \rightarrow$$

$$\rightarrow xCO_2 + \frac{y}{2}H_2O + zSO_2 + \frac{0.79}{0.21}\left(x + \frac{y}{4} + z - \frac{w}{2}\right)N_2 + Q$$

Where: Q = heat of combustion

The above reaction assumes that:

- air consists of 21% by volume of oxygen with the remaining 79% made up of nitrogen and other inert gases;
- combined oxygen in fuel is available for combustion, thus reducing air requirements;
- fuel contains no combined nitrogen, so no "fuel NO_x" is produced;
- "thermal NO_x" via the nitrogen fixation is small, so that it is neglected in stoichiometric air calculations;
- sulfur in fuel is oxidized to SO_2 with negligible SO_3 formation.

For example, to combust methane (CH_4) Equation 2-3 reduces to:

(Eq. 2-4) $$CH_4 + 2\ O_2 + 7.53\ N_2 \rightarrow CO_2 + 2\ H_2O + 7.53\ N_2 + Q$$

$$\text{Moles or relative volumes}$$
$$\underbrace{1 + 2 + 7.53}_{\text{Total air required}} \rightarrow \underbrace{1 + 2 + 7.53}_{\text{Total flue gases}}$$

For every mole or standard cubic foot of CH_4 burned, the reaction requires 9.53 moles or standard cubic feet of air for complete combustion. A listing of the theoretical air requirements for a number of fuels are given in Table 2-1.

Excess Air

In boilers, more than the stoichiometric amount of air is used to ensure complete combustion. This extra volume is referred to as *excess air*. If ideal mixing were achievable, no excess air would be necessary. However, most combustion devices are not capable of achieving ideal mixing of the fuel and air streams. The amount of excess air is held to a minimum in order to reduce heat losses. Excess air takes no part in the reaction but does absorb some of the heat produced. To raise the excess air to the combustion temperature, additional fuel must be used to make up for this loss of heat. Operating at a high volume of excess air can be very costly in terms of the added fuel required.

Depending on the amount of excess air, different concentrations of CO_2 and O_2 in the stack gas will result, as shown in Figure 2-1.

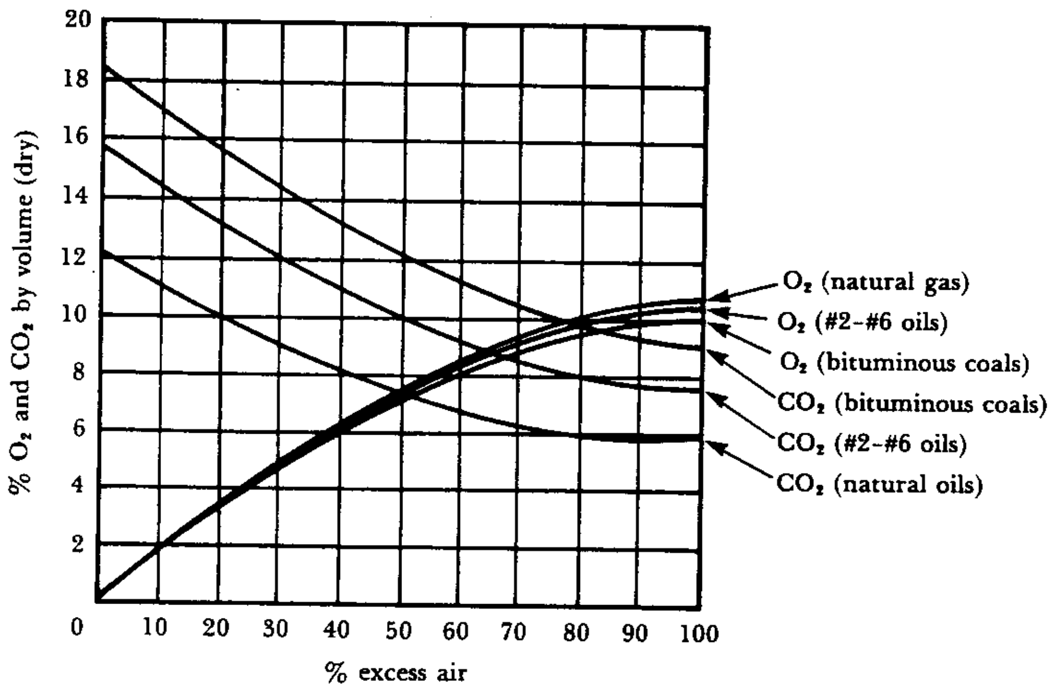


Figure 2-1. Excess air concentrations of CO_2 and O_2 in stack.

Table 2-1. Combustion constants and approximate limits of flammability of gases and vapors in air.

Substance	Lb/ft³	Ft³/lb	Heat of combustion				For 100% total air (mol/mol of combustible) (ft³/ft³ of combustible)						For 100% total air (lb/lb of combustible)						Flammability limits (% by volume)	
			(Btu/ft³)		(Btu/lb)		Required for combustion			Flue products			Required for combustion			Flue products				
			Gross (high)	Net (low)	Gross (high)	Net (low)	O_2	N_2	Air	CO_2	H_2O	N_2	O_2	N_2	Air	CO_2	H_2O	N_2	LEL	UEL
Carbon, C*	—	—	—	—	14,093	14,093	1.0	3.76	4.76	1.0	—	3.76	2.66	8.86	11.53	3.66	—	8.86	—	—
Hydrogen, H_2	0.0053	187.723	325	275	61,100	51,623	0.5	1.88	2.38	—	1.0	1.88	7.94	26.41	34.34	—	8.94	26.41	4.00	74.20
Oxygen, O_2	0.0846	11.819	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Nitrogen (atm), N_2	0.0744	13.443	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Carbon monoxide, CO	0.0740	13.506	322	322	4,347	4,347	0.5	1.88	2.38	1.0	—	1.88	0.57	1.90	2.47	1.57	—	1.90	12.50	74.20
Carbon dioxide, CO_2	0.1170	8.548	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Paraffin series																				
Methane, CH_4	0.0424	23.565	1013	913	23,879	21,520	2.0	7.53	9.53	1.0	2.0	7.53	3.99	13.28	17.27	2.74	2.25	13.28	5.00	15.00
Ethane, C_2H_6	0.0803	12.455	1792	1641	22,320	20,432	3.5	13.18	16.68	2.0	3.0	13.18	3.73	12.39	16.12	2.93	1.80	12.39	3.00	12.50
Propane, C_3H_8	0.1196	8.365	2590	2385	21,661	19,944	5.0	18.82	23.82	3.0	4.0	18.82	3.63	12.07	15.70	2.99	1.68	12.07	2.12	9.35
n-Butane, C_4H_{10}	0.1582	6.321	3370	3113	21,308	19,680	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91	1.86	8.41
Isobutane, C_4H_{10}	0.1582	6.321	3363	3105	21,257	19,629	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91	1.80	8.44
n-Pentane, C_5H_{12}	0.1904	5.252	4016	3709	21,091	19,517	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81	—	—
Isopentane, C_5H_{12}	0.1904	5.252	4008	3716	21,052	19,478	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81	—	—
Neopentane, C_5H_{12}	0.1904	5.252	3993	3693	20,970	19,396	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81	—	—
n-Hexane, C_6H_{14}	0.2274	4.398	4762	4412	20,940	19,403	9.5	35.76	45.26	6.0	7.0	35.76	3.53	11.74	15.27	3.06	1.46	11.74	1.18	7.40
Olefin series																				
Ethylene, C_2H_4	0.0746	13.412	1614	1513	21,644	20,295	3.0	11.29	14.29	2.0	2.0	11.29	3.42	11.39	14.81	3.14	1.29	11.39	2.75	28.60
Propylene, C_3H_6	0.1110	9.007	2336	2186	21,041	19,691	4.5	16.94	21.44	3.0	3.0	16.94	3.42	11.39	14.81	3.14	1.29	11.39	2.00	11.10
n-Butene, C_4H_8	0.1480	6.756	3084	2885	20,840	19,496	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39	1.75	9.70
Isobutene, C_4H_8	0.1480	6.756	3068	2869	20,730	19,382	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39	—	—
n-Pentene, C_5H_{10}	0.1852	5.400	3836	3586	20,712	19,363	7.5	28.23	35.73	5.0	5.0	28.23	3.42	11.39	14.81	3.14	1.29	11.39	—	—
Aromatic series																				
Benzene, C_6H_6	0.2060	4.852	3751	3601	18,210	17,480	7.5	28.23	35.73	6.0	3.0	28.23	3.07	10.22	13.30	3.38	0.69	10.22	1.40	7.10
Toluene, C_7H_8	0.2431	4.113	4484	4284	18,440	17,620	9.0	33.88	42.88	7.0	4.0	33.88	3.13	10.40	13.53	3.34	0.78	10.40	1.27	6.75
Xylene, C_8H_{10}	0.2803	3.567	5230	4980	18,650	17,760	10.5	39.52	50.02	8.0	5.0	39.52	3.17	10.53	13.70	3.32	0.85	10.53	1.00	6.00
Miscellaneous gases																				
Acetylene, C_2H_2	0.0697	14.344	1499	1448	21,500	20,776	2.5	9.41	11.91	2.0	1.0	9.41	3.07	10.22	13.30	3.38	0.69	10.22	—	—
Napthalene, $C_{10}H_8$	0.3384	2.955	5854	5654	17,298	16,708	12.0	45.17	57.17	10.0	4.0	45.17	3.00	9.97	12.96	3.43	0.56	9.97	—	—
Methyl alcohol, CH_3OH	0.0846	11.820	868	768	10,259	9,078	1.5	5.65	7.15	1.0	2.0	5.65	1.50	4.98	6.48	1.37	1.13	4.98	6.72	36.50
Ethyl alcohol, C_2H_5OH	0.1216	8.221	1600	1451	13,161	11,929	3.0	11.29	14.29	2.0	3.0	11.29	2.08	6.93	9.02	1.92	1.17	6.93	3.28	18.95
Ammonia, NH_3	0.0456	21.914	441	365	9,668	8,001	0.75	2.82	3.57	—	1.5	3.32	1.41	4.69	6.10	—	1.59	5.51	15.50	27.00
	—	—								SO_2						SO_2				
Sulfur, S*	0.0911	10.979			3,983	3,983	1.0	3.76	4.76	1.0	—	3.76	1.00	3.29	4.29	2.00	—	3.29	—	—
Hydrogen sulfide, H_2S	0.1733	5.770	647	596	7,100	6,545	1.5	5.65	7.15	1.0	1.0	5.65	1.41	4.69	6.10	1.88	0.53	4.69	4.30	45.50
Sulfur dioxide, SO_2	0.0476	21.017	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Water vapor, H_2O	0.0766	13.063	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Air	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Gasoline	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.40	7.60

*Carbon and sulfur are considered as gases for molal calculations only.

Sources: Adapted from *Fuel Flue Gases*, American Gas Association.
Combustion Flame and Explosions of Gases, 1951.

Figure 2-1 shows how the amount of excess air is indicated by the amount of CO_2 or O_2 measured in the flue gas. Flue gas can be analyzed for the percentage of CO_2, O_2, and CO by using an orsat apparatus or continuous monitors. As can be seen from Figure 2-1, when excess air is kept low, the concentration of CO_2 in the flue gas is high, while that of O_2 remains relatively low. The boiler should be operated with a minimal amount of excess air to promote good combustion and to prevent high heat loss.

Excess air can be calculated using Equation 2-5.

(Eq. 2-5)

$$\%\ EA = \frac{\%\ O_2 - 0.5\%\ CO}{0.264\%\ N_2 - (\%\ O_2 - 0.5\%\ CO)} \times 100$$

Example 2-1 will illustrate how to calculate excess air when the flue gas concentrations are known.

Example 2-1

Assume the flue gas from a boiler was analyzed with an orsat apparatus and found to contain the following concentrations:

Gas	Percent
CO_2	17.0
O_2	3.5
CO	0.02
N_2	79.0

Using Equation 2-5, the percent excess air is:

$$\%\ EA = \frac{3.5 - 0.5\ (0.02)}{0.264(79.0) - [3.5 - 0.05(0.02)]} \times 100$$

$$= \frac{3.5 - 0.01}{20.86 - 3.49} \times 100$$

$$= 0.201 \times 100$$

$$= 20.1\%$$

Combustion Limits

Not all mixtures of fuel and air are able to support combustion. The flammable, or explosive limits, for a mixture are the maximum and minimum concentrations of fuel in air that will support combustion. The *lower explosive limit* (LEL) is defined as the concentration of fuel **below which** combustion will not be self-sustaining. The *upper explosive limit* (UEL) is defined as the concentration of fuel mixture that will not burn because of a lack of oxygen. Table 2-1 listed the flammability limits (LEL and UEL) for common fuels and solvents.

For example, consider that a mixture of gasoline vapors and air is at atmospheric conditions. From Table 2-1 the LEL is 1.4% by volume of gasoline vapors and the UEL is 7.6%. Any concentration of gasoline in air within these limits will support combustion. That is, once a flame has been ignited it will continue to burn. Concentrations of gasoline in air below or above these limits will not burn and can quench the flame.

Thermodynamic and Combustion Terms

In describing any combustion process, many terms are used to define heat. These terms can be divided into two categories: thermodynamic and combustion. Thermodynamic terms, applying to all systems, define the energy level, or potential heat, present in any substance. Combustion terms, initiated to aid in standardizing fuel usage calculations, are applied to heat produced by combustion methods. Because the combustion terms are specific examples of the thermodynamic terms, some overlap is involved in defining them. The following are important terms describing heat thermodynamically:

Sensible heat (H_s): Heat that causes a change in temperature when added or removed.

Latent heat (H_v): Heat given off by a vapor condensing to a liquid or gained by a liquid evaporating to a vapor, without a change in temperature. The latent heat of vaporization of water at 212°F is 970.3 Btu/lb.

Heat content or **enthalpy (H):** The sum total of latent and sensible heat present in a substance (gas, liquid, or solid) **minus** that contained at an arbitrary set of conditions chosen as the base or zero point. Values for various gases are listed in Table 2-2.

Table 2-2. Heat contents of various gases.

Temp (°F)	Heat content, H (Btu/lb at 1 atm)								
	O_2	N_2	Air	CO	CO_2	SO_2	H_2	CH_4	H_2O
60	0	0	0	0	0	0	0	0	0
100	8.8	9.9	9.6	10.0	8.0	5.9	137	21.0	–
200	30.9	34.8	33.6	34.9	29.3	21.4	484	76.1	–
300	53.3	59.9	57.7	59.9	52.0	37.5	832	136.4	1165
400	76.2	85.0	81.8	85.0	75.3	54.4	1182	202.1	1212
500	99.4	110.3	106.0	110.6	99.8	71.8	1532	272.6	1259
600	123.1	136.1	130.2	136.3	125.1	89.8	1882	347.8	1307
700	147.2	161.7	154.5	162.4	149.6	108.2	2233	427.4	1355
800	171.7	187.7	178.9	188.7	177.8	127.0	2584	511.2	1404
900	196.6	213.9	203.4	215.6	205.6	146.1	2935	599.2	1454
1000	221.7	240.7	235.0	242.7	233.6	165.5	3291	691.1	1505
1200	272.5	294.7	288.5	297.8	290.9	205.1	4007	886.2	1609
1400	324.3	350.8	343.0	354.3	349.7	245.4	4729	1094.1	1717
1600	377.3	407.3	398.0	407.5	416.3	286.4	5460	1313.0	1829
1800	430.7	465.0	455.0	465.3	470.9	327.8	6198	1542.6	–
2000	484.0	523.8	513.0	523.8	532.8	369.1	6952	–	–
2200	539.3	583.2	570.7	583.3	596.1	411.1	7717	–	–
2400	594.4	642.3	628.5	643.0	659.2	452.7	8490	–	–
2600	649.0	702.8	687.3	703.2	723.2	495.2	9272	–	–
2800	702.8	763.1	746.6	771.3	787.4	557.5	10060	–	–
3000	758.6	824.1	806.3	832.6	852.0	580.0	10870	–	–
3200	816.4	885.8	866.0	894.0	916.7	622.5	11680	–	–
3400	873.4	947.6	925.9	956.0	981.6	665.0	12510	–	–
3600	931.0	1010.3	986.1	1018.3	1047.3	707.5	13330	–	–

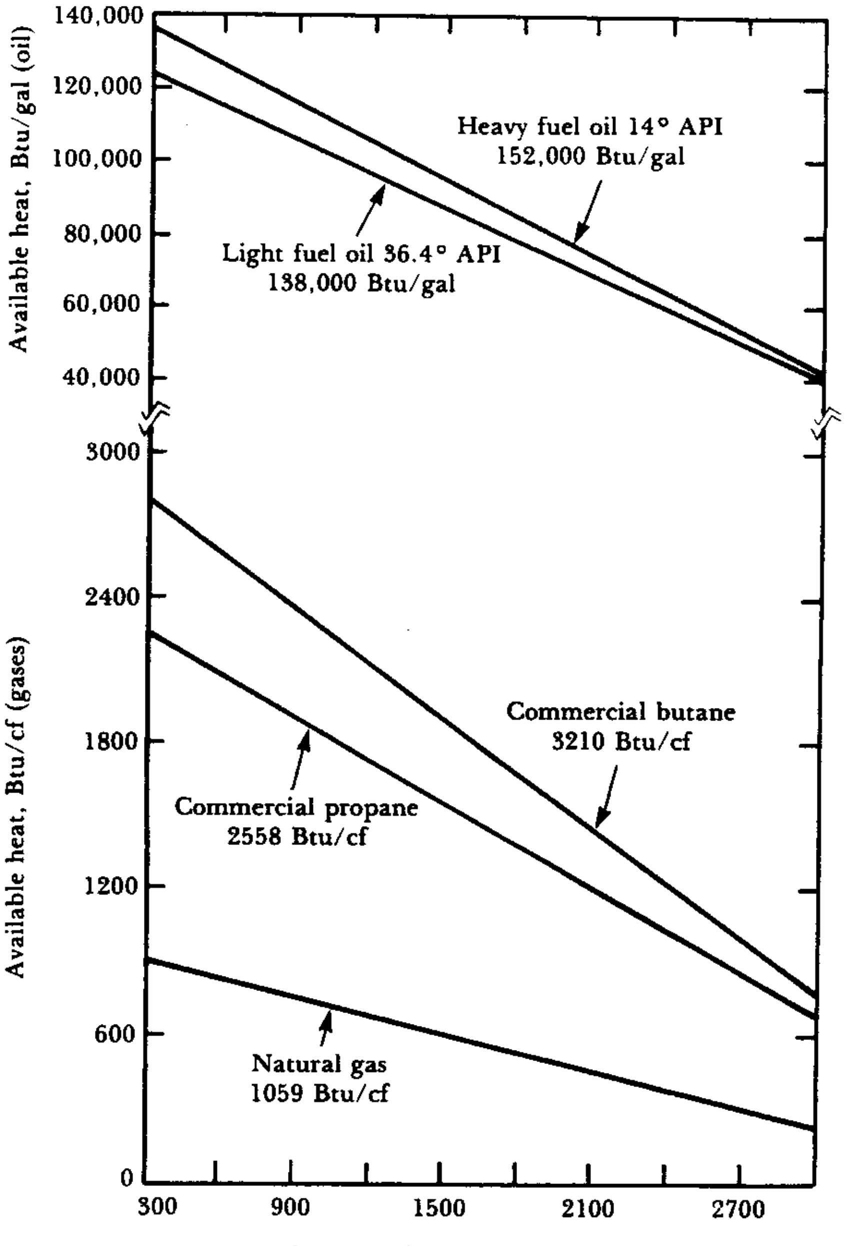
Source: North American Combustion Handbook, 1952.

Some useful terms describing heat produced by combustion of a fuel are:

Gross heating value (HV_G): The total heat obtained from the complete combustion of a fuel that is at 60°F when combustion starts, and the combustion products of which are cooled to 60°F before the quantity of heat released is measured. Constant pressure, normally 101.3 kPa (1 atmosphere) is maintained throughout the entire combustion process. Gross heating values are also referred to as *total,* or *higher, heating values* (HHV).

Net heating value (HV_N): The gross heating value minus the latent heat of vaporization of the water formed by the combustion of the hydrogen in the fuel. For a fuel containing no hydrogen, the net and gross heating values are the same.

Available heat (H_A): The gross quantity of heat released within a combustion chamber minus (1) the sensible heat carried away from the dry flue gases and, (2) the latent heat and sensible heat carried away in water vapor contained in the flue gases. The available heat represents the net quantity of heat remaining for useful heating. Figure 2-2 shows the available heat from the complete combustion (no excess air) of various fuels at various flue gas temperatures.



Source: North American Combustion Handbook, 1965.

Figure 2-2. Available heat for some typical fuels (referred to 60°F).

Since all of the previous terms describe heat, they all are expressed in units of lb/Btu. Figure 2-3 illustrates the interrelation of these terms.

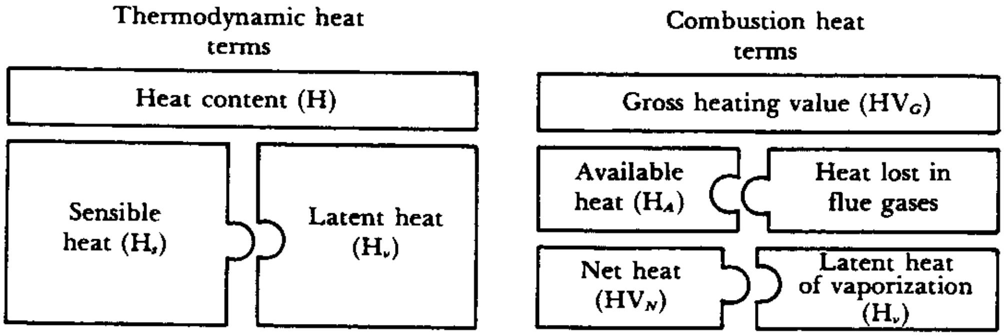


Figure 2-3. Heat terms.

Depending on the user, the above terms can also have more than one definition. For example, a laboratory chemist may describe latent heat as the energy used in the chemical combustion of a fuel to carbon dioxide and water; while a boiler operator may describe latent heat as the difference between the gross and net heating values.

Another important term used in performing combustion calculations is the ***specific heat***, C_p, of a substance. Specific heat is defined as the amount of heat required to raise 1 pound of a substance 1 degree fahrenheit. Specific heat is given as Btu/lb • °F in English units. Specific heat depends on temperature.

Heat Balance

To design or review the operating performance of a boiler, a heat balance of the system is usually determined. The first law of thermodynamics states that energy entering a system must leave the system or be stored in some manner. In a boiler the heat energy into the system is therefore equal to the heat energy out of the system.

Heat in (sensible + HHV) = heat out (sensible + latent + available)

In order to compute a heat balance, a number of parameters must be measured including fuel heat content and quantity burned, air quantity, flue gas losses, and boiler losses.

Fuel Characteristics

The chemical makeup and heat content of the common fuels burned in boilers vary depending on the type of fuel used. Fossil fuels—natural gas, fuel oil, and coal—are most often used in boilers. Natural gas consists of varying amounts of methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), oxygen (O_2), nitrogen (N_2), and hydrogen sulfide (H_2S), depending on where the gas comes from.

The heat content of natural gas varies from approximately 950 to 1150 Btu/ft^3 of gas. The analyses and heat contents of various samples of natural gas are given in Table 2-3.

Table 2-3. Various samples of natural gas.

Sample no. source of gas		1 Pa.	2 So. Cal.	3 Ohio	4 La.	5 Okla.
Analyses						
Constituents, % by vol						
H_2	Hydrogen	—	—	1.82	—	—
CH_4	Methane	83.40	84.00	93.33	90.00	84.10
C_2H_4	Ethylene	—	—	0.25	—	—
C_2H_6	Ethane	15.80	14.80	—	5.00	6.70
CO	Carbon monoxide	—	—	0.45	—	—
CO_2	Carbon dioxide	—	0.70	0.22	—	0.80
N_2	Nitrogen	0.80	0.50	3.40	5.00	8.40
O_2	Oxygen	—	—	0.35	—	—
H_2S	Hydrogen sulfide	—	—	0.18	—	—
Ultimate, % by wt						
S	Sulfur	—	—	0.34	—	—
H_2	Hydrogen	23.53	23.30	23.20	22.68	20.85
C	Carbon	75.25	74.72	69.12	69.26	64.84
N_2	Nitrogen	1.22	0.76	5.76	8.06	12.90
O_2	Oxygen	—	1.22	1.58	—	1.41
Specific gravity (rel to air)		0.636	0.636	0.567	0.600	0.630
Higher heat value						
Btu/cu ft@60°F and 30 in. Hg		1,129	1,116	964	1,002	974
Btu/lb of fuel		23,170	22,904	22,077	21,824	20,160

Source: Babcock and Wilcox, 1978.

Fuel oils, refined from crude oil, contain varying amounts of carbon, hydrogen, nitrogen, oxygen, ash, and sulfur. Fuel oils are graded according to gravity and viscosity, the lightest being No. 1 and the heaviest No. 6. Grades 5 and 6 usually need to be heated before they can be adequately pumped to and burned in the burner. The heat content of fuel oil varies from approximately 18,000 to 20,000 Btu/gal. The analyses and heat contents of some fuel oils are listed in Table 2-4.

It is common practice to report the components of coal using either a *proximate* analysis or an *ultimate* analysis. In the proximate analysis, the amount of moisture, volatile matter, fixed carbon, and ash in the coal are determined. In the ultimate analysis, the amount of carbon, hydrogen, oxygen, nitrogen, sulfur, and ash are determined. The ultimate analysis is useful in computing the stoichiometric, or theoretical, air requirements by using Equation 2-6.

$$\text{(Eq. 2-6)} \qquad \text{Theoretical air} = 11.53\ \text{C} + 34.34\left(\text{H}_2 - \frac{\text{O}_2}{8}\right) + 4.29\ \text{S}$$

Coal is ranked by the amount of fixed carbon, the hardness, and the calorific value, or heat content. Peat and lignite are the softest coals, sub-bituminous and bituminous are harder, and anthracite is the hardest. The analyses and calorific values of some selected coals are given in Table 2-5.

Table 2-4. Analyses of typical fuel oils.

Grade of fuel oil	Sample no. 1	Sample no. 2	Sample no. 4	Sample no. 5	Sample no. 6
Weight, percent					
Sulfur	0.01-0.5	0.05-1.0	0.2-2.0	0.5-3.0	0.7-3.5
Hydrogen	13.3-14.1	11.8-13.9	(10.6-13.0)*	(10.5-12.0)*	(9.5-12.0)*
Carbon	85.9-86.7	86.1-88.2	(86.5-89.2)*	(86.5-89.2)*	(86.5-90.2)*
Nitrogen	Nil-0.1	Nil-0.1	—	—	—
Oxygen	—	—	—	—	—
Ash	—	—	0-0.1	0-0.01	0.01-0.5
Gravity					
Deg API[1]	40-44	28-40	15-30	14-22	7-22
Specific	0.825-0.806	0.887-0.825	0.966-0.876	0.972-0.922	1.022-0.922
Lb per gal	6.87-6.71	7.39-6.87	8.04-7.30	8.10-7.68	8.51-7.68
Pour point, °F	0 to −50	0 to −40	−10 to +50	−10 to +80	+15 to +85
Viscosity					
Centistokes@100°F	1.4-2.2	1.9-3.0	10.5-65	65-200	260-750
Saybolt Universal Scale@100°F	—	32-38	60-300	—	—
Saybolt Furol Scale@122°F	—	—	—	20-40	45-300
Water and sediment, vol %	—	0-0.1	tr to 1.0	0.05-1.0	0.05-2.0
Heating value					
Btu per lb, gross (calculated)	19,670-19,860	19,170-19,750	18,280-19,400	18,100-19,020	17,410-18,990

*Estimated.

[1] The API degree scale is commonly used in specifying various grades of oil. It is inversely related to the specific gravity at 60°F:

$$\text{Degrees API} = \frac{141.5}{\text{Sp. gr.}@60°\text{F}} - 131.5$$

Source: Babcock and Wilcox, 1978.

Table 2-5. Typical analyses of wood, peat, and coal.

Kind of fuel	Proximate analysis				Ultimate analysis					Calorific value (Btu/lb)
	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Hydrogen	Carbon	Nitrogen	Oxygen	
Wood	—	—	—	—	—	6.25	49.50	1.10	43.15	5,800
Peat	56.70	26.14	11.17	5.99	0.64	8.33	21.03	1.10	62.91	3,586
Lignite	34.55	35.34	22.91	7.20	1.10	6.60	42.40	0.57	42.13	7,090
Subbituminous	24.28	27.63	44.84	3.25	0.36	6.14	55.28	1.07	33.90	9,376
Bituminous	3.24	27.13	62.52	7.11	0.95	5.24	78.00	1.23	7.47	13,919
Semibituminous	2.03	14.47	75.31	8.19	2.26	4.14	79.97	1.26	4.18	14,081
Semianthracite	3.38	8.47	76.65	11.50	0.63	3.58	78.43	1.00	4.86	13,156
Anthracite	2.80	1.16	88.21	7.83	0.89	1.89	84.36	0.63	4.40	13,298

Source: Woodruff and Lammer, 1977.

Boiler Efficiency

Boiler efficiency is defined as the amount of heat absorbed by the water divided by the amount of heat contained in the fuel being burned. In equation form, this is

$$\text{(Eq. 2-7)}\quad \text{Boiler efficiency} = \frac{\text{heat absorbed by boiler fluid}}{\text{heat contained in fuel}} \times 100\%$$

$$= \frac{\text{steam flow rate (heat of steam} - \text{heat of feedwater)}}{\text{(weight of fuel)(HHV of fuel)}} \times 100$$

$$= \frac{\dot{m}_s(h_s - h_{fw})}{\dot{m}_f(\text{HHV})} \times 100$$

Where: $\dot{m}_s$ = mass flow rate of steam, lb/hr
$\dot{m}_f$ = mass flow rate of fuel, lb/hr
h_s = enthalpy of steam leaving boiler, Btu/lb
h_{fw} = enthalpy of water entering the boiler, Btu/lb
HHV = higher heating value of fuel, Btu/lb

To calculate boiler efficiency using Equation 2-7, the quantity of energy input to the boiler and output from the boiler are measured. These measurements can be taken by using flowmeters, thermometers, or thermocouples, and pressure gauges. Calculation inaccuracies can occur because of inaccuracies of the measuring devices. All instruments should be calibrated frequently. The results are usually checked by calculating a heat balance for the system. Measurements to be taken are:

Feedwater entering the boiler
  $\dot{m}_{fw}$ = boiler feedwater flow rate
  T_{fw} = feedwater temperature
  p_{fw} = feedwater pressure

Steam leaving the boiler
  $\dot{m}_s$ = steam flow rate
    $= \dot{m}_{fw} - m_b$ (feedwater flow rate – blowdown flow rate)
  T_s = steam temperature
  p_s = steam pressure

Fuel entering boiler
  $\dot{m}_f$ = fuel flow rate
  T_f = fuel temperature
  p_f = fuel pressure
  HHV = fuel higher heating value

Heat Losses

Not all of the energy contained in fuel is converted to heat and absorbed by the boiler equipment. Some of this energy is lost. Some fuel may leave as unburned carbon if combustion is not complete. Moisture in the fuel accounts for some heat loss. Hydrogen in the fuel is converted to water when burned, making this another heat loss. Moisture in the air also contributes to heat loss. One of the largest heat losses is from the dry flue gas because the stack temperature is much higher than the temperature of air (ambient) used for combustion. Stack temperature is usually maintained at greater than 300°F to prevent moisture and acids in the flue gas from condensing on ductwork, fans, or stack walls.

One method to calculate boiler efficiency is the *Btu method* (Babcock and Wilcox, 1978). The amount of air required per pound of fuel burned is calculated using the theoretical air required per 10,000 Btu heat value of the fuel. Values of theoretical air (lb of air/lb of fuel) can be obtained by multiplying the heat content of the fuel as fired, (Btu/10,000)/lb of fuel, by the theoretical air required per 10,000 Btu, lb air/(Btu/10,000).

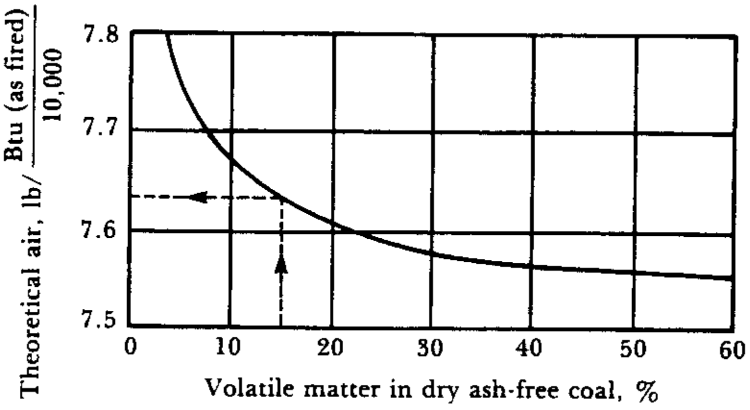
If the ultimate analysis of a fuel is known, the value of theoretical dry air expressed as lb air/(Btu/10,000) is calculated using Equation 2-8.

(Eq. 2-8)

$$\text{Theoretical dry air} = 144\left(\frac{8\,C + 24\left(H_2 - \frac{O_2}{8}\right) + 3\,S}{\text{Btu/lb}}\right)$$

Where: C = carbon, % by weight
H_2 = hydrogen, % by weight
O_2 = oxygen, % by weight
S = sulfur, % by weight
Btu/lb = heat value of the fuel.

Equation 2-8 should only be used when the ultimate analysis of the fuel is given and when the correct heating value of the fuel is known. When the proximate analysis of coal is known, Figure 2-4 can be used to obtain the theoretical air in lb per 10,000 Btu.



Source: Babcock and Wilcox, 1978.

Figure 2-4. Theoretical air in lb per 10,000 Btu heat value of coal with a range of volatile matter.

Example 2-2

From the proximate analysis of a type of coal given below, calculate theoretical air in units of lb of air/lb of fuel. The excess air is 20%. (Source: Babcock and Wilcox, 1978.)

Bituminous coal
proximate analysis as fired, % by weight

Moisture	12.0
Volatile matter	25.8
Fixed carbon	46.2
Ash	16.0
Btu/lb	10,900

Solution:

1. The volatile matter on a dry ash free basis is:

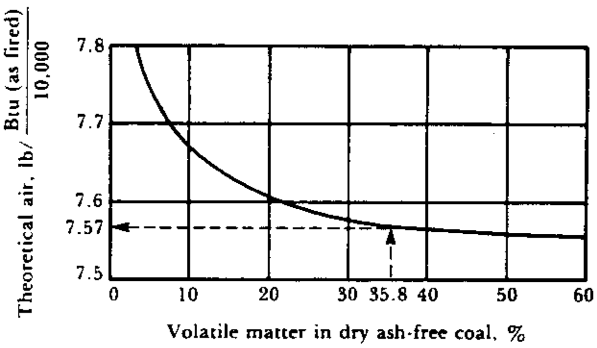
$$\frac{\text{volatile matter}}{\text{volatile matter} + \text{carbon}} \times 100\% \qquad \frac{25.8}{25.8 + 46.2} \times 100\%$$

$$= 35.8\%$$

2. Using Figure 2-4, and the abscissa of 35.8, move up to the line and read the value on the ordinate.

$$\text{lb of air}\big/10{,}000$$

$$= 7.57$$



3. The required total dry air including 20% excess air is:

$$7.5 \text{ lb of air} \times \frac{\text{excess air} + 100}{100} \times \frac{\text{heating value of fuel}}{10{,}000 \text{ Btu}} \qquad 7.5 \times \frac{120}{100} \times \frac{10{,}900}{10{,}000}$$

$$= 9.81 \text{ lb of air/lb of fuel}$$

Table 2-6 is an example of combustion calculations using the Btu method. This table is taken from *Steam/Its Generation and Use* by Babcock and Wilcox. Bituminous coal is the fuel used in the calculations in Table 2-6. Examples for fuel oil and natural gas can be found in *Steam/Its Generation and Use.*

Table 2-6. Combustion calculations.

Based on quantities per 10,000 Btu fuel input

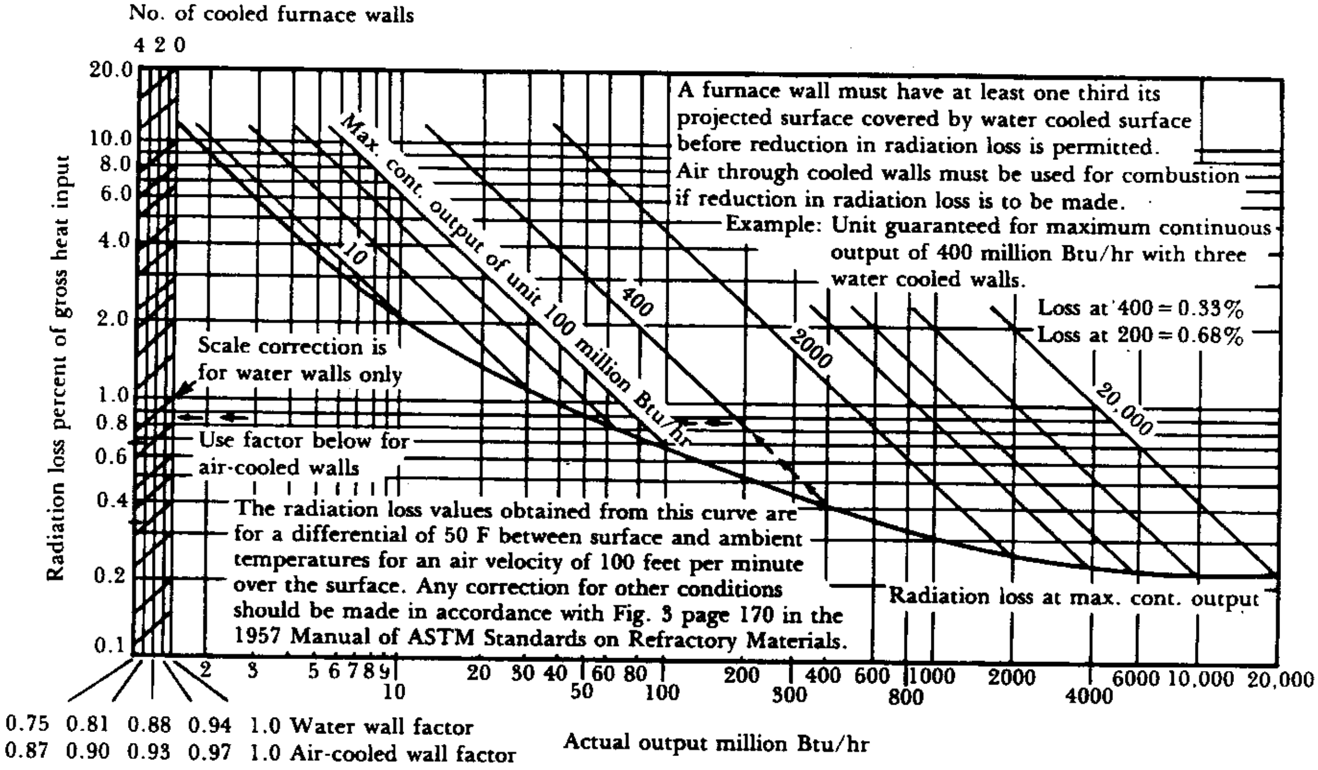
LINE				
1	Fuel—*Bituminous Coal, Virginia*			
2	Analysis As Fired			
3	Ultimate, % by Wt		Proximate, % by Wt	
4	C	*80.31*	Moisture	*2.90*
5	H_2	*4.47*	Volatile	*22.05*
6	S	*1.54*	Fixed carbon	*68.50*
7	O_2	*2.85*	Ash	*6.55*
8	N_2	*1.38*		*100.00*
9	H_2O	*2.90*		
10	Ash	*6.55*		
11		*100.00*		
12	Btu per lb, as fired, *14,100*			

Conditions by test or specification		Date	LINE
			a
Total air	%	*120*	b
Air temperature to heater	F	*80*	c
Air temperature from heater	F	*350*	d
Flue gas temperature leaving unit	F	*280*	e
H_2O per lb dry air	lb	*0.013*	f
			g
Unburned fuel loss	%	*0.4*	h
Unaccounted loss	%	*1.5*	i
Radiation loss (ABMA), Figure 2-5	%	*0.8*	j
			k

LINE						LINE
13	**Quantities per 10,000 Btu Fuel Input**					13
14	Fuel burned, [100 (100 − line 10) ÷ line 12] − .007 × line h			lb	*0.66*	14
15	Dry air, line b [(value from Fig. 4, Table 11 or Eq. 6) − .08 × line h]			lb	*9.11*	15
16	H_2O in air, line 15 × line f = *9.11* × *0.013*			lb	*0.12*	16
17	Wet gas, total, lines (14 + 15 + 16)			lb	*9.89*	17
18	H_2O in fuel, 100 (8.94 × line 5 + line 9) ÷ line 12, or Table 11			lb	*0.30*	18
19	H_2O in flue gas, total, line 16 + line 18			lb	*0.42*	19
20	H_2O in flue gas, total, in percent, (line 19 ÷ line 17) × 100			%	*4.31*	20
21	Dry gas, total, line 17 − line 19			lb	*9.47*	21
22	**Losses per 10,000 Btu Fuel Input**					22
23	Unburned fuel, 10,000 × line h ÷ 100			Btu	*40*	23
24	Unaccounted, 10,000 × line i ÷ 100			Btu	*150*	24
25	Radiation, 10,000 × line j ÷ 100			Btu	*80*	25
26	Latent Heat, H_2O in fuel, 1040 × line 18			Btu	*312*	26
27	Sensible heat, flue gas, line 17 × Btu from Fig. 1 @ line e and line 20 = *9.89* × *50*			Btu	*495*	27
28	Total losses, lines (23 + 24 + 25 + 26 + 27)			Btu	*1077*	28
29	Total losses in percent, (line 28 ÷ 10,000) × 100			%	*10.8*	29
30	Efficiency, by difference, 100 − line 29			%	*89.2*	30
31	**Quantities per 10,000 Btu Fuel Input** Combustion temperature, adiabatic					31
32	Heat input from fuel			Btu	*10,000*	32
33	Heat input from air, lines (15 + 16) × Btu from Fig. 8 @ line d temp			Btu	*612*	33
34	Heat input, total, lines 32 + 33			Btu	*10,612*	34
35	Less latent heat loss, H_2O in fuel, line 26			Btu	*−312*	35
36	Heat available, maximum			Btu	*10,300*	36
37	Less (lines 24 + 25) × 0.5*			Btu	*−115*	37
38	Heat available, line 36 − line 37			Btu	*10,185*	38
39	Heat available per lb of flue gas, line 38 ÷ line 17	Btu	*1021*			39
40	Adiabatic temperature, from Fig. 1 for lines 20 & 39	F	*3513*			40

*Note: It is customary to reduce the maximum heat available, line 36, by from ⅓ to ½ of the unaccounted plus radiation losses, on the assumption that a portion of these losses occurs in the combustion zone.

Source: Babcock and Wilcox, 1978.



A furnace wall must have at least one third its projected surface covered by water cooled surface before reduction in radiation loss is permitted.

Air through cooled walls must be used for combustion if reduction in radiation loss is to be made.

Example: Unit guaranteed for maximum continuous output of 400 million Btu/hr with three water cooled walls.

Loss at 400 = 0.33%
Loss at 200 = 0.68%

Scale correction is for water walls only

Use factor below for air-cooled walls

The radiation loss values obtained from this curve are for a differential of 50 F between surface and ambient temperatures for an air velocity of 100 feet per minute over the surface. Any correction for other conditions should be made in accordance with Fig. 3 page 170 in the 1957 Manual of ASTM Standards on Refractory Materials.

Source: Babcock and Wilcox, 1978.

Figure 2-5. Radiation losses.

Review Exercise	
1. To achieve complete combustion of an organic compound, a sufficient supply of oxygen must be present to convert all of the carbon to CO_2. The quantity of oxygen is called ________.	
2. In boilers, more than the stoichiometric amount of air is required to ensure complete combustion. This volume of air is referred to as ________.	1. stoichiometric or theoretical amount
3. An orsat apparatus is used to measure the concentration of ________ in the flue gas. a. particulate matter b. CO_2 and O_2 only c. CO_2, H_2O, and O_2 d. CO_2, O_2, and CO	2. excess air
	3. d. CO_2, O_2, and CO

4. The __________ is defined as the concentration of fuel mixture that will not burn because of a lack of oxygen. a. low amount of excess air b. lower explosive limit (LEL) c. upper explosive limit (UEL) d. sensible heat factor	
5. The amount of heat given off when a vapor condenses to a liquid or gained when a liquid evaporates to a vapor without a change in temperature is called a. sensible heat. b. latent heat. c. enthalpy. d. gross heating value.	4. c. upper explosive limit (UEL)
6. The __________ is equal to the gross heating value minus the latent heat of vaporization of water formed by the combustion of hydrogen contained in a fuel. a. sensible heat (H_s) b. enthalpy (H) c. net heating value (HV_n)	5. b. latent heat.
7. True or False? Natural gas consists of varying amounts of methane, ethane, ethylene, hydrogen, and other gases.	6. c. net heating value (HV_n)
8. Fuel oil(s) __________ usually need to be heated before they can be adequately pumped to and burned in a burner. a. No. 1 and No. 2 b. No. 1 c. No. 5 and No. 6 d. No. 6	7. True
9. In the __________, the amount of moisture, volatile matter, fixed carbon, and ash in the coal are determined. a. proximate analysis b. ultimate analysis c. heat balance	8. c. Nos. 5 and 6
10. True or False? Bituminous coal is harder, has a higher heat content and contains more volatile matter than does anthracite coal.	9. a. proximate analysis
	10. False. The reverse is true for each criteria.

11. In a boiler, which of the following are heat losses?
    a. unburned carbon
    b. moisture in the fuel
    c. hydrogen in the fuel
    d. moisture in the combustion air
    e. dry flue gas
    f. a., b., and d. only
    g. all of the above

11. g. all of the above

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