CHAPTER 3
BENEFITS OF BETTER BURNING

Combustion Fundamentals

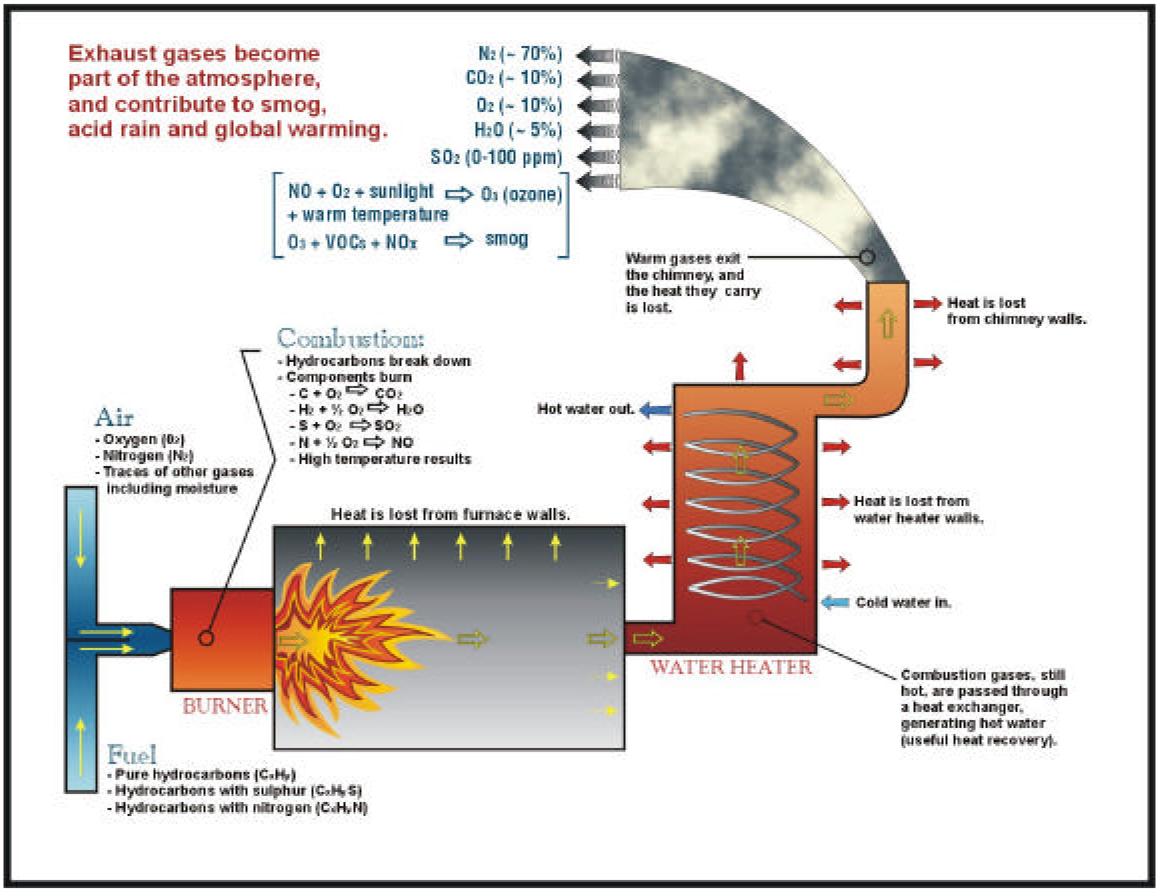
As every stationary engineer knows, conventional fuels are made up of two elements: carbon and hydrogen, which combine with oxygen, in a process we call combustion, to produce heat. Fuels may contain additional materials, such as sulphur, which also produces some heat when burned, mineral matter (ash), water, and traces of metallic elements. These are viewed as impurities; the fuel value lies in the carbon and hydrogen. In fossil fuels these two elements are usually combined in hydrocarbon molecules. They range from the simplest form, methane (CH_4), which is the major constituent of natural gas, through more complex hydrocarbons contained in petroleum fuels such as gasoline and heavy oil, to complex hydrocarbons mixed with uncombined carbon in coal. The proportion of carbon to hydrogen increases from the gaseous fuels to the solid fuels. Non-fossil fuels such as biomass and alcohol also depend on carbon and hydrogen for their energy content, but in molecular combinations that usually include oxygen.

Ideally, in the process of combustion the molecular structure of the fuel is completely broken down; the carbon oxidizes to carbon dioxide (CO_2) and the hydrogen oxidizes to water vapour (H_2O). Incomplete combustion results in a variety of additional products, most of them harmful even in small quantities. They are discussed in Chapter 5. Fortunately for natural gas and light fuel oil, the premium-quality fuels used for most heating and industrial purposes in Canada, modern, well-equipped combustion equipment can eliminate products of incomplete combustion.

However, as shown in Poster 3-1, even complete combustion has many effects beyond the desired one of providing thermal energy.

Oxygen for combustion is normally provided by atmospheric air, which contains about 21% oxygen, by volume. This is fortuitous since higher concentrations would result in higher flame temperatures, making it harder to avoid damage to the furnace and burners. A lower oxygen concentration would result in slower mixing, larger flames and lower temperatures, and while this is a technique used to reduce NO_x emissions, as will be discussed in Chapter 5, more furnace volume is often required.

Stationary combustion systems almost always operate with excess air; that is, more air is passed through the burner than is chemically required for complete combustion. This is done to speed up the process of mixing fuel and air, to ensure that substantially all the fuel is provided with the oxygen necessary for combustion before it is chilled below combustion temperatures by contact with heat exchange surfaces. Safety and the range of equipment control are additional considerations in setting excess air levels. Insufficient air can quickly lead to a furnace full of explosive gas, so the margin of excess air must be set to provide a surplus as the fuel and air controls modulate to accommodate changing load conditions.



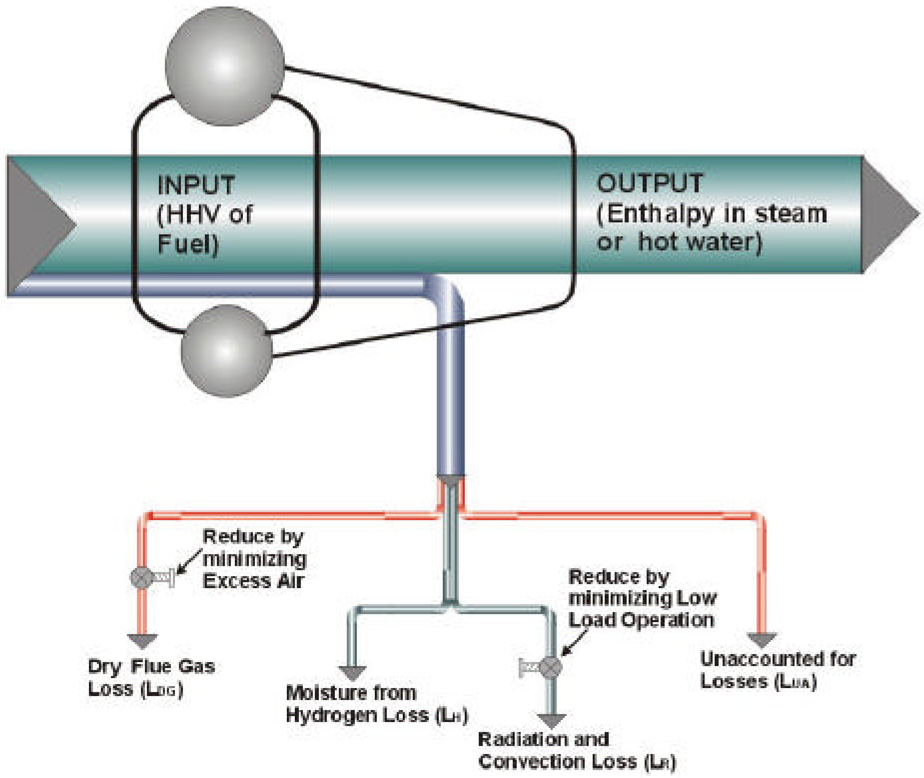
Poster 3-1 The Combustion Process

However, excess air incurs a penalty in the unused heat it carries away, and it is the heat loss that can be controlled through regular adjustment of the combustion system.

Major Boiler Losses

The standard for determining boiler efficiency in North America is the ASME Power Test Code (ASME PTC 4.1 – 1964, reaffirmed 1973). As discussed in Appendix 1, taking full account of all the inputs, outputs and losses that affect the efficiency of a boiler or other combustion system can become quite involved. However, for systems fired with natural gas and fuel oil many of the losses listed do not apply, and others are small enough to be rolled into an "unaccounted for" category, for which a value can be assumed. Boiler efficiency can then be determined by evaluating four losses, which are described below. A simplified method for quantifying them is presented in Poster 3-2.

SIMPLIFIED BOILER EFFICIENCY



L_{DG} **(%)** = [24 x DG x (FGT - CAT)] / HHV

- **DG (lb/lb fuel)** = (11 CO_2 + 8 O_2 + 7 N_2) x (C + 0.3755) / 3 CO_2
- **FGT** = Flue Gas Temp., °F
- **CAT** = Combustion Air Temp., °F
- **HHV** = Higher Heating Value of fuel, Btu/lb
- **CO_2 and O_2** = % by volume in the flue gas
- **N_2** = 100 - CO_2 - O_2
- **C and S** = Weight fractions in fuel analysis

L_H **(%)** = [900 x H_2 x (hg - hf)] / HHV

- **H_2** = weight fractions in fuel analysis
- **hg** = 1055 + (0.467 X FGT), Btu/lb
- **hf** = CAT - 32, Btu/lb

L_R **(%)** = see Radiation and Convection Losses Chart

L_{UA} **(%)** = assume 0.1% for natural gas
0.2% for light oil

Poster 3-2 Simplified Efficiency

Dry Flue Gas Loss

Air and fuel enter the burner at close to ambient temperature, but the products of combustion leave the stack at much higher temperatures. The dry flue gas loss accounts for the heat thus lost in the "dry" products of combustion, that is, carbon dioxide (CO_2), oxygen (O_2), nitrogen (N_2), carbon monoxide (CO) and sulphur dioxide (SO_2). They are called dry products because they carry only sensible heat. There has been no change of state, so no latent heat is involved. Normally concentrations of CO and SO_2 are in the parts per million (ppm) range, so they can be ignored from the viewpoint of heat loss (although not from the viewpoint of emissions).

The dry flue gas loss can be minimized by reducing flue gas temperature, using supplementary heat recovery as discussed in Chapter 2, and by reducing excess air, as discussed in Chapter 4 and Appendix 1.

Loss Due to Moisture From the Combustion of Hydrogen

Unlike the "dry" gases, the hydrogen component of fuel leaves the boiler as water vapour, taking with it the enthalpy, or heat content, corresponding to its conditions of temperature and pressure. It is steam at very low pressure but fairly high temperature, the stack temperature, and most of its enthalpy is in the heat of vapourization. This makes it a significant loss, commonly about 11% for natural gas and 7% for fuel oil. The difference reflects the relative hydrogen content of these two fuels. Some fuels, like coal and biomass, contain water which also carries latent heat in the flue gas and can be a significant efficiency loss.

Reducing flue gas temperature has only a small effect on this loss, unless a condensing heat exchanger is employed, as discussed in Chapter 2.

Loss Due to Radiation and Convection

The external surface of an operating boiler is hotter than its surroundings and therefore loses heat by both radiation and convection. For any given boiler at operating temperature the amount of heat lost is more or less constant, which means that, expressed as a percentage of the boiler's heat output, the loss increases as boiler output is reduced. Also, on a percentage-of-output basis, larger boilers have a lower loss due to radiation and convection than smaller boilers.

Actual measurement of radiation and convection loss is tedious, difficult and seldom undertaken. Instead, the American Boiler Manufacturers Association's (ABMA) standard radiation loss chart is widely used as a convenient shortcut. It is quite satisfactory for boilers of conventional configuration such as package or field-erected boilers and water heaters having the furnace and heat exchange surface enclosed in a single housing. In any case it provides a standardized method that is useful for comparative purposes.

Figure 3-1 gives radiation and convection losses for some common sizes of boilers, extracted from the ABMA chart for boilers having all walls watercooled and operating at low to medium pressures. It shows that for most boilers the loss is less than 1% except at low loads; only boilers rated at less than 30,000 lb/h have radiation and convection losses greater than 1% across the load range. However, Figure 3-1 also shows that for boilers in the middle and lower size ranges, operating at low load incurs a significant efficiency penalty. In plants with more than one boiler, shutting boilers down as necessary to keep the operating ones in the upper load range minimizes this efficiency loss.

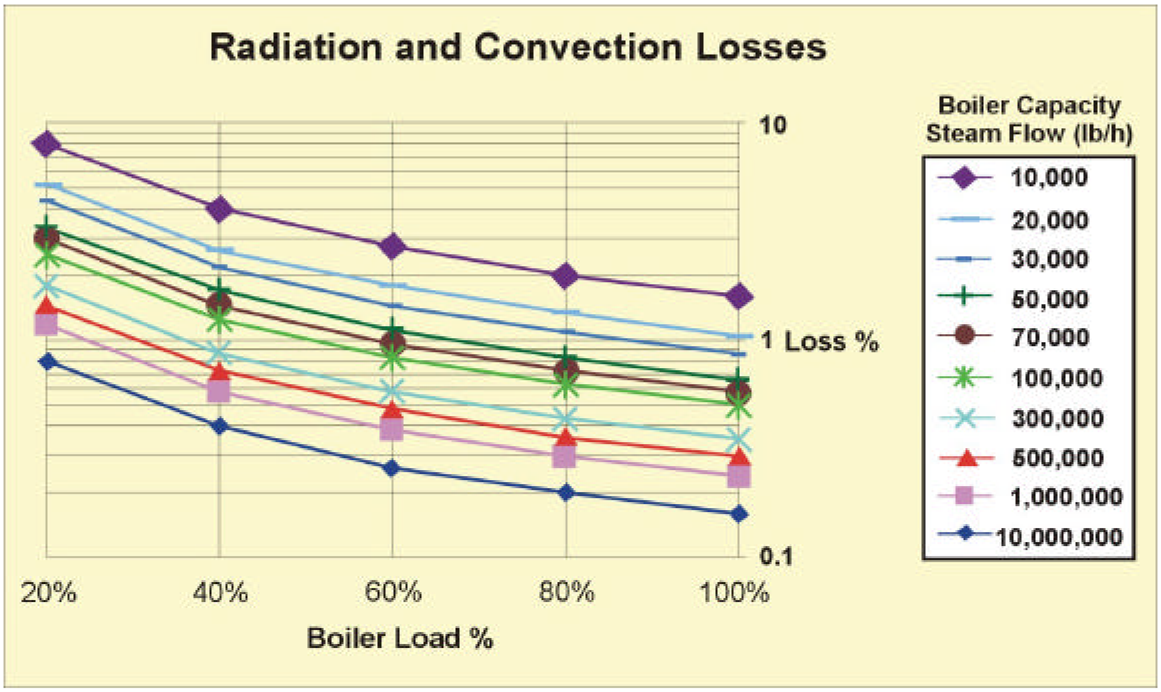


Figure 3-1 Radiation and Convection Losses

<u>"Unaccounted For" Losses</u>

For combustion systems fired with natural gas or fuel oil, many of the losses such as unburned fuel, moisture in fuel, moisture in air, heat loss in ash, etc. are either non-existent or very small. They can be handled conveniently, and usually with sufficient accuracy, by assuming a value for the total as "unaccounted for" losses. Commonly used figures are 0.1% for natural-gas-fired systems and 0.2% for oil-fired systems.