

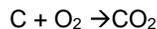
Combustion of fuel Oil

By E. O. Olson

COMBUSTION as we normally think of it is generally described as "rapid oxidation" of any material, which is classified as combustible material. By oxidation we mean simply the adding of oxygen in a chemical reaction. By combustible we mean any substance which combines readily and rapidly with oxygen under favorable conditions. We normally consider combustion only in connection with the fuels such as wood, coal, gas and oil, and in this particular case we shall concern ourselves primarily with fuel oil.

Fuel oil is classified as a hydrocarbon fuel. It is called that because it is composed principally of carbon and hydrogen. Combustion of fuel oil then, according to our previous definition, would be the rapid combining of carbon and hydrogen with oxygen.

For purposes of this discussion we shall abbreviate by using the common chemical symbols for these elements which make up the fuel and other elements which enter into the combustion process or are by-products of it. With these symbols we can write the equations which we have defined above. If we had pure carbon for fuel and an atmosphere of pure oxygen, our reaction would be



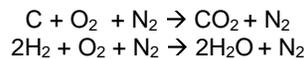
This is a chemical reaction, which produces an entirely new product and the reaction gives off heat. Chemical reactions take place on the basis of weight of the combining elements. All calculations, therefore, must be on that basis unless otherwise specified. So we could say 1 pound C + 2.66 pounds O₂ produces 3.66 pounds CO₂. The end product of flue gas is 100% CO₂. It is simpler to think of air and gases in terms of volume, however, and therefore we shall convert to volumes at "Standard Conditions," 60°F. and atmospheric pressure except for calculating.

In normal combustion we do not supply pure oxygen as the atmosphere in which combustion

takes place, but the oxygen is supplied as one of the components of the air we breathe. The air is composed of approximately 21% oxygen and 79% nitrogen and other inert gases by volume. We shall not bother with the inert gases mixed in very small quantities with the nitrogen but shall call it all nitrogen.

That means that if we have combustion involving pure carbon and air, the products of combustion would not be 100% CO₂ as above but would be approximately 21% (by volume) CO₂ and the balance would be nitrogen, because the nitrogen has no part in the combustion process.

As we stated above, oil is composed of carbon and hydrogen. A typical No. 2 oil shows approximately 86% C and 14% H₂ by weight. Therefore, the air which is supplied to burn oil gives up its oxygen to form not only CO₂ but also a compound with the hydrogen and the equation looks like this:



The combustion of hydrogen also gives off heat and, as is noted by this equation, the product is water. If exactly the right amount of air were supplied for complete combustion of the carbon and hydrogen in the fuel, the products of combustion would be as indicated in Fig. 1. With practical equipment, however, it is generally not possible to get a perfect mixture

in which all of the combustible elements are supplied with the exactly correct quantity of oxygen, and therefore it is necessary to supply what is known as excess air. This excess air is simply air over and above the theoretical requirement for the burning of the fuel. It must be supplied because the equipment which mixes the air with the fuel is not capable of bringing oxygen into intimate enough contact with the molecules of fuel to produce complete combustion without some excess being present. The efficiency of the particular burner is indicated by the amount of excess air required to produce clean combustion. When more excess air is required to do the job, the efficiency of the unit is lower. This excess air takes no part in the combustion process but enters the heating unit at room temperature and is discharged at the temperature of the exit gases and carries away that much heat. It is therefore a source of heat loss. If we introduce 50% excess air, we have the situation shown in Fig. 2.

The percentage of excess air required indicates the efficiency of the equipment. Complex and expensive instruments are required to measure excess air directly, however, and it is customary to use another device to indicate the amount of excess air present. It has been found that a measure of the excess air can be obtained by measuring the degree to which it

FIGURE 1

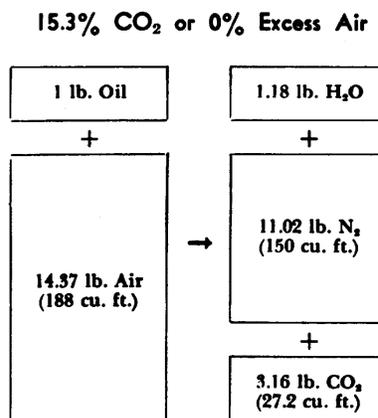
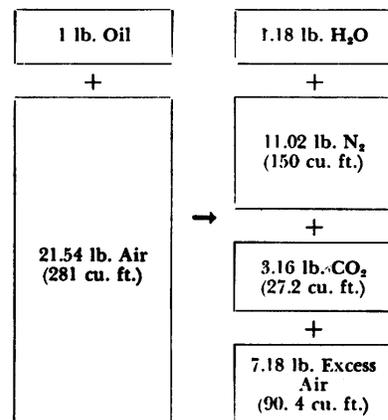


FIGURE 2

10.6% CO₂ or 50% Excess Air



dilutes the other products of combustion. When more excess air is introduced, the percentage of CO₂, for example in the total gaseous products of combustion, is reduced. Therefore, instead of getting 15.3% CO₂ in the flue gas, such as we would normally get with zero excess air with the fuel oil described, an increase of air to 50% excess would reduce the CO₂ reading to 10.6%.

In Fig. 2 it would be correct to show the excess air in its components of nitrogen and oxygen, but we have shown it as excess air for purposes of discussion.

The curve in Fig. 3 shows how excess air dilutes the products of combustion and reduces the percent CO₂ in the flue gas (again by volume).

The various factors contributing to the amount of excess air required for clean combustion will be treated later.

The above discussion is an over-simplification of the actual combustion process. The chemical reactions by which carbon, hydrogen, and oxygen are changed into CO₂ and water should include a number of very complex intermediate steps which might include the "cranking" of the hydrocarbon molecule and the uniting with oxygen to form intermediate products. In the case of blue flames such as occur in vaporizing burners the term "aldehydous combustion" is sometimes used to describe the process. In this process the vaporizing and cracking of the oil and mixing of the air with the gaseous products thus formed takes place before combustion begins. This type of combustion

carbon on heating surfaces, but gaseous combustibles are frequently found in the flue gases unless some excess air is supplied.

In yellow flames such as found in gun type burners the combustion process is spoken of as "carbonic combustion." In this type of flame the reduction of oil droplets to gas and the combustion process are not definitely separated as in a blue flame. The two processes are intermingled and continuous throughout the flame. Because of the much higher temperatures in the vaporizing zone, much of the fuel does not go through the intermediate reactions but carbon is burned directly to CO₂, hence the term carbonic combustion. The principal intermediate reaction is $2C + O_2 \rightarrow 2CO$ (carbon monoxide). CO is an odorless gas which is completely burned unless the process is interrupted: $2CO + O_2 \rightarrow 2CO_2$. Other reactions are also taking place involving intermediate products. In this type of combustion gaseous combustibles are seldom found in the flue gases, even with smoky fires.

In either type of combustion the presence of the intermediate products such as formaldehyde can be detected by their sharp odor if the flame is chilled before combustion is complete. Some of these products can also be drawn off experimentally by means of a sampling tube.

It is important in the combustion process that the temperature be maintained at a high enough level to make the combustion process continuous so that the end result will be the products of combustion shown in Figures 1 and 2. These intermediate products when present

called "combustibles," and may be detected by various means. If they are present, they constitute a loss of fuel because of what we commonly term incomplete combustion.

It will be noted from Figure 2 that the products of combustion are water, nitrogen, CO₂, and excess air. The fact that these gases entered the combustion chamber at room temperature, say 70°F., and leave the furnace at a temperature much higher than that, say 500°F., indicates that heat is being carried up the stack and all of the heat generated by the chemical reaction of combustion is not available as useful heat. Some of these losses are not avoidable. For example, nitrogen is present in the air but takes no part in the combustion process except that it is heated from room temperature to the exit gas temperature. The water, which is the product of combustion, is present in the flue gas in the form of super-heated steam.

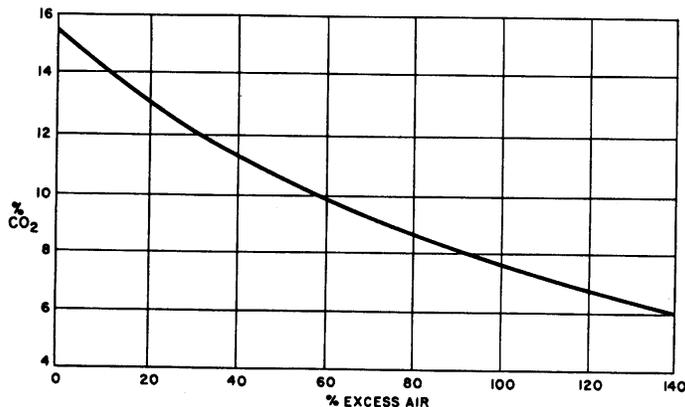
Measurement of Heat Loss

In order to determine the magnitude of these losses, it is necessary to establish standards and a method for measuring heat. The unit of heat measurement in the English system is the Btu (British thermal unit). The Btu is defined as the quantity of heat required to raise the temperature of one pound of water one degree F. This value will vary slightly depending upon the temperature of the water and for that reason the Btu is based on water at 39°F. With the aid of a "measuring stick" such as the Btu, it is possible to evaluate the effectiveness and efficiency of the combustion process as it actually occurs as compared with the theoretical performance.

For example, it is a known fact that one pound of air when heated one degree F. absorbs .24 Btu. The water vapor, which is a product of combustion, contains approximately 1,150 Btu per pound at 212° and 1,204 Btu per pounds at a temperature of 400° to 500°. The net heat gain above, water at 70° is 1,166 Btu. The nitrogen, which appears in the flue gas after the oxygen has been separated from it, may be assumed to have the same heat content as an equivalent amount of air.

If we know that one pound of fueloil has a heating value of approximately 19,500 Btu, it is

FIGURE 3



EXCESS AIR REDUCES CO₂

does not readily deposit soot or in the products of combustion are

possible then to calculate the heat losses under the conditions which exist. The following calculations will give an idea of how percentage stack losses can be determined if an analysis of the products of combustion is available.

Referring to Figure 1, assume air enters the combustion chamber at 70°F. and the stack temperature is 470°F.

Since we assume no excess air and no combustibles in the products of combustion, we can say that the losses will be at the minimum if the exit temperature is reasonable, say 400° net (flue gas temp. - room temp.). The heat losses then would be:

Water (1.18) (1166)	=1376 Btu
N ₂ (11.02) (.24) (400)	=1060 Btu
CO ₂ (3.16) (.24) (400)	= <u>303 Btu</u>
Total Loss	2739 Btu

If we assume the heat value of the fuel at 19,500 Btu/lb., the loss is

$$\frac{(2739)(100)}{19,500} = 14.1\%$$

The only way to reduce this loss is to reduce the exit temperature.

If we now use the values in Figure 2, our total loss would be increased by excess air:

$$(7.18)(.24)(400) = 688 \text{ Btu or } 3,427 \text{ Btu Total Loss}$$

The loss would then be

$$\frac{(3427)(100)}{19,500} = 17.6\%$$

It is evident that we cannot ever utilize 100% of the heat given off by the combustion process.

Stack loss is increased by increasing excess air and stack temperature. Take, for example, excess air of 100% and net stack temp. of 600°.

Total stack loss
 (14.37) (.24) (600) + 3422
 =5492 Btu per lb. of fuel or 28.0%
 The loss thus calculated makes several assumptions:

1. No combustibles in the flue gas.
2. No dissolved water in the fuel.
3. No smoke.

As mentioned above, the percent CO₂ in the flue gas indicates the amount of dilution by excess air. CO₂ may be accurately measured by a rather simple instrument that traps a specified volume of flue gas, absorbs the CO₂ and thus shows the percent reduction in gas volume. The absorbing reagent is a solution of potassium hydroxide. The most common instruments for this type of testing are the Orsat, Bacharach CO₂ tester, and the Dwyer CO₂ tester.

If CO₂ percentage is to be meaningful, it is necessary to know the amount of smoke being formed. A high CO₂ reading can be obtained with a smoky fire. If the fire is set for zero smoke, it is entirely possible to provide too much excess air for good efficiency.

The most common smoke tester is known as the "Shell-Bacharach" smoke meter which passes a measured quantity of flue gas through a prescribed area of filter paper. The smoke number is graduated from 0 to 10. Zero smoke indicates a perfectly white spot on the filter paper with 100% reflectance on a photometer. No. 10 smoke indicates a very black spot on the filter paper showing zero reflectance on the photometer. The gradations of blackness between these two points are graduated 0, 1, 2, 3, etc. For testing purposes it is customary to set a specified smoke number as a point of reference. A No. 1 smoke reading is used by many laboratories as this reference point

Over-fire draft is the negative pressure in the combustion chamber as measured with a draft gauge. Readings are given in hundredths of an inch of water column. Only enough draft is required to remove the products of combustion and on a small size job this may be as low as .02". Larger jobs need more draft.

Stack temperature is the temperature of the flue gas at the furnace or boiler exit. The gross temperature is as measured. The net temperature is the measured temperature minus the room temperature. For accurate work it is necessary to shield the thermometer or thermocouple to avoid radiation losses. For field test work, however, the readings obtained with the thermocouple or a suitable thermometer are satisfactory if sufficient time is

allowed for equilibrium to be reached.

Following are a few of the conditions, which contribute to low CO₂ or high excess air:

1. Inefficient burner not capable of giving an intimate and turbulent mixture of air and atomized oil.
2. Overfire draft too high.
3. Improper choice of nozzle or contaminated nozzle. A spray pattern that does not fit the burner or an off-center pattern may require high excess air to clean up the smoke.
4. Air leaks in the furnace or boiler.

High stack temperature may be caused by any of the following:

1. Overfiring due to the burner putting too much fuel into the combustion chamber.
2. Furnace or boiler too small for the job, thus necessitating overfiring.
3. High excess air. An increase in excess air increases stack temperature. Reducing excess air reduces stack temperature.
4. High draft.
5. Heat exchange surfaces covered with soot.

10% or higher CO₂ is regarded as reasonably good settings with smoke readings of 1 or lower. Stack temperatures ideally should not exceed approximately 500°F. but some modern boilers are designed to operate with stack temperatures as high as 700° gross. With 700° stack temperatures it is practically impossible with reasonable burner settings to get stack losses below 25%.

The table below shows approximate heat losses based on the type of calculations given above.

**Stack Losses (Approximate)
No. 2 Fuel Oil
% CO₂ in Flue Gas**

Figure 4

Net Stack Temp	6	7	8	9	10	11	12	13	14	15
300	20.2	18.5	17.0	16.0	15.0	14.2	13.7	13.2	12.7	12.5
350	22.7	20.5	19.0	17.7	16.5	15.5	15.0	14.5	14.0	13.5
400	25.0	22.7	20.7	19.2	18.0	17.0	16.2	15.7	15.2	14.7
450	27.5	24.7	22.1	21.0	19.5	18.5	17.5	16.7	16.2	15.7
500	30.0	26.7	24.5	22.7	21.2	19.7	18.7	18.0	17.2	16.7
550	32.2	29.0	26.2	24.2	22.7	21.2	20.2	19.2	18.5	18.0
600	34.7	31.0	28.2	26.0	24.2	22.7	21.5	20.5	19.7	19.0
650	37.0	33.0	30.0	27.7	25.7	24.2	22.7	21.7	21.0	20.2
700	40.0	35.2	32.0	29.2	27.2	25.5	24.2	23.0	22.0	21.2
750	42.5	37.5	34.0	31.2	29.0	27.0	25.5	24.2	23.2	22.5
800	45.0	40.0	36.0	33.0	30.5	28.5	27.0	25.5	24.5	23.5

