So you finally bought a Combustion Analyser!

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The goal of many household energy projects is to develop an improved stove with a good combustion and heat transfer performance. This article describes how with a basic combustion analyser, along with a few mathematical tools, a stove developer is well equipped to work wonders in improving a stove's performance.

Developing an improved stove is the primary goal of many domestic energy projects. Most developers know it is not easy to produce a clean burning stove without using emissions measuring equipment like a combustion analyser. But along with having the correct equipment you also need to know how to extract useful information from the raw numbers. A stove developer is looking for better combustion and better heat transfer. A basic combustion analyser along with a few mathematical tools will produce useful information from a surprisingly small number of measurements.

Analysing combustion

Improving combustion has two aspects: burning the fuel completely and minimizing harmful emissions. Similarly, a better heat transfer also has two main factors: getting the heat into the pot or the room, and limiting the amount that is wasted either up the chimney or into the air. The combustion analyser will help with all of these.

First you need to find the level of carbon monoxide (CO) in the emissions, the oxygen (O_2) level and the temperature. These three measurements are key. If you have a scale you can also determine the mass of fuel being burned at the time the measurements were taken and from this calculate the quantity of CO produced when burning a kilogram of fuel.

Carbon monoxide (CO)

If CO or CO_2 is found in the gas flowing from a stove, there is combustion taking place. Detecting CO_2 is more difficult than CO, so simple gas analysers will only measure the latter. It is normally reported in parts per million (ppm) or milligrams per cubic metre of gases (mg/m^3). To convert mg/m^3 to ppm, multiply mg/m^3 by 0.81075. To convert CO ppm to CO%, divide by 10,000.

Example

$$\frac{500\text{ ppm CO}}{10{,}000} = 0.05\%\text{ CO}$$

Oxygen (O_2)

Oxygen is also easy to detect and is usually reported in percent (%). The air entering a stove can be thought of in two components, the amount required for combustion (the air demand) and the air not theoretically needed to burn the fuel (excess air)

Excess air (EA) is calculated as follows:

$$\text{EA }(\%) = \frac{[\,O_2\% - (CO\%/2)]\times 100}{20.95 - [O_2\% - (CO\%/2)]}$$

Summing the combustion and excess air gives the total air supplied, also called the Air Factor, represented by the symbol Lambda, λ. Lambda is excess air plus one.

$$\lambda = \frac{EA\%}{100} + 1$$

Example

If EA = 160%, $\lambda = 160/100 + 1.00 = 2.60$

i.e. the total air entering the stove is 2.6 times greater than that required for combustion.

Calculating CO_2

Because the composition of fuels like coal or wood is usually known, the amount of CO_2 in the stack (chimney) sample can be calculated from the O_2 and CO. If there is 20.95% oxygen in the air going into a stove, and 10% in the gases that come out, then approximately half of it has been used during combustion. Some of it will have reacted with hydrogen in the fuel to make H_2O (water). This happens easily so analysers usually assume that all the hydrogen has been burned. Another portion of the oxygen combines with carbon to make CO. So based on the fuel composition, the initial and post-combustion oxygen levels, and the CO level, the rest of the oxygen can be assumed to have been burned to CO_2. Using this logic, a reasonable calculation of the CO_2 level, expressed in %, can be made without measuring it directly, useful if you have that simple gas analyser.

Figure1 *A TSI CA-6203 Combustion Analyser*

$$CO_2\% = CO_2\,Max\,\%\times\left[\frac{20.95 - (O_2\% + \frac{CO\%}{2})}{20.95}\right]$$

Note: CO_2 Max for Wood is 19.4%

The CO/CO_2 Ratio (CO_R)

A measure of how completely the fuel is being burned can be determined by dividing the CO by the CO_2. Fully combusted carbon emerges as CO_2, partially burned carbon as CO. The better the combustion, the lower the proportion of CO. This calculation can be made with any level of dilution, provided both are determined from readings taken at the same time. As the CO is usually given in ppm and the CO_2 in %, a conversion factor is needed to determine their relative abundance.

$$CO_R = \frac{CO}{CO_2}$$

Example

Suppose the levels are 500 ppm CO, and 10% CO_2

First convert the CO ppm to CO%

$$\frac{500\text{ppm CO}}{10{,}000} = 0.05\%\text{ CO}$$

Then divide the CO by the CO_2

$$CO_R = \frac{0.05\%\text{ CO}}{10\%\text{ }CO_2} = 0.005 = 0.5\%$$

The target of a stove developer is to achieve a CO_R of 2% or less. Very low readings are possible in modern stoves.

Correcting the CO reading undiluted gas concentration

The CO_R is calculated using the readings taken directly from the analyser and can compare the combustion efficiency of different stoves. However it is not correct to make comparisons between stoves using uncorrected CO readings alone. The presence of excess air, as indicated by the oxygen level, means that the CO measurements will be incorrect, with valid comparisons for individual gases only being made using EA-corrected figures.

Example: Compare these measurements from the stack and determine which version of the stove has lowest CO level:

Test 1 CO = 2561 ppm, O_2 = 8.00%
Test 2 CO = 1981 ppm, O_2 = 10.60%
Test 3 CO = 2144 ppm, O_2 = 11.25%

Test 1 shows the EA is 60.19%, so λ is 1.6019. The undiluted CO level is 1.6019 x 2561 = 4301 ppm.

Test 2 shows the EA is 100.50%, so λ is 2.0050. The undiluted CO level is 2.0050 x 1981 = 3972 ppm.

Test 3 shows the EA is 113.62%, so λ is 2.1362. The undiluted CO level is 2.1362 x 2144 = 4580 ppm.

The stove in Test 2 is the cleanest burning, and Test 3 is the dirtiest, something not obvious from the CO reading alone. It is very important to make this correction to obtain the undiluted gas concentration. It makes meaningful comparisons between different stoves and fuels possible.

Particulates

Suppose we want to know the PM 2.5 particulate emission level and how clean the burn is when a stove is used with two different fuels.

Example:
Test 1 CO = 3566 ppm, O_2 = 13.05%, PM 2.5 = 135 $\mu g/m^3$
Test 2 CO = 2911 ppm, O_2 = 11.40%, PM 2.5 = 161 $\mu g/m^3$

The calculated EA, λ, CO_2 and CO_R levels for the tests are:

Test 1 EA = 159.34%, λ = 2.5934, CO_2 7.15%, CO_R = 4.99%
Test 2 EA = 116.08%, λ = 2.1608, CO_2 8.71%, CO_R = 3.34%

The undiluted PM 2.5 concentrations are:
Test 1 135 x 2.5934 = 350 $\mu g/m^3$
Test 2 161 x 2.1608 = 348 $\mu g/m^3$

The fuel in Test 2 has a better combustion efficiency indicated by a lower CO_R but they have the same level of PM 2.5 emissions.

Analysing heat transfer efficiency

A combustion analyser can measure the chimney gas temperature and calculate the amount of heat lost up the 'chimney stack'.

The air feeding a stove has to be drawn from outdoors. The initial temperature (T_1) is the outdoor temperature and the final temperature (T_2) is the temperature inside the chimney.

T_2-T_1 = Delta T = ΔT

Stack losses are a combination of gas volume and ΔT.

Recording the temperature in the chimney will not, alone, tell you what the loss is. You need to know, as before, the amount of excess air that is diluting and expanding the volume of emissions from the fire. The combustion analyser will calculate the amount of heat contained in the gases and combine this with the quantity of excess air to produce a percentage heat loss. If the exit temperature was the same as the outdoor temperature, the loss would be 0%.

To determine the loss in Watts, you have to weigh the fuel being burned and determine the heat generated, then multiply that times the percentage of heat being lost. This heat loss feature is helpful even if you are working on stoves without a chimney. Take a sample of gases from the point at which they exit past the pot and you get the percentage of heat being lost at that point. The inputs used are the room temperature, the exit temperature and the Excess Air level. Care must be taken to ensure no air from the room enters the sample being drawn or you will get an inflated Excess Air figure.

For small stoves with a short gas path, the exit temperature will give a general indication of losses: the higher the temperature, the greater the loss. Unfortunately, this is only true in certain cases. For example, if you increase the excess air supply significantly, you may see a drop in temperature but a large increase in heat loss because the extra air is cooling the fire and rushing the heat past the pot in a larger volume of cooler gas.

The thermal efficiency of a small stove is usually lower than a space heating chimney stove. Exceptions to this are some institutional stoves with pots sunk completely into an all-enclosing, insulated body. In such a stove, decreasing the excess air can show a constant or even a decreasing exit temperature and a substantial increase in efficiency.

Figure 2 *A Testo 350 XL Combustion Analyser*

Figure 3 *A Lufft temperature logger*

Using a combustion analyser to track the undiluted gas and particulate levels, the heat loss and the CO_R a stove developer is well equipped to work wonders improving a stove's performance.

Profile of the Author

Crispin Pemberton-Pigott has worked with Appropriate Technologies for 30 years, largely in rural water and manual production equipment. A stove maker for 25 years, he won the Design Institute of South Africa Chairman's Award 2004 for the 'Vesto', a semi-gasifing stove now manufactured in Swaziland at New Dawn Engineering, a producer of labour-based manufacturing systems for rural employment. He is a co-founder of the Eastern Cape Appropriate Technology Unit (RSA), the Renewable Energy Association of Swaziland and the Industrial Designers Association of South Africa. Presently the Regional Technical Advisor for GTZ/ProBEC he is also on the Board of the Sustainable Energy Society of Southern Africa (SESSA) and chairs its daughter organisation, the Association for Renewable Energy Cooking Appliances (AFRECA). He is a member of the South African Bureau of Standards technical committees writing national standards and test protocols for coal, paraffin and gel fuel stoves.

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