Review of Emissions Testing Hood at Aprovecho

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How it works

The blower applies a suction to the top of the orifice which is in the top of the hood. Currently, the orifice is 1.07 inch diameter, and is by far the greatest flow restriction in the system. The pressure meter measures the difference between the outside air pressure and the pressure downstream of the orifice. This creates a narrow jet of gas flowing through the orifice at high speed (over 100 ft/sec).

One must measure the temperature of this jet. Normally, this can be done with the same probe as the one used to sample the concentrations of the pollutants. From the temperature, the density of the flowing gas can be calculated. From this density, and from the pressure drop across the orifice, one can calculate the speed of the flow through the orifice. By knowing the area of the orifice, one can calculate the volume flow through the orifice. By knowing this, and the density (previously calculated) and the approximate composition of the flowing gas, once can calculate the mass flow through the orifice, and the number of molecules flowing through the orifice.

The probe measures what fraction of the molecules is CO2, what fraction is CO, what fraction is O2, etc. (If particulate measurement is done, this may be somewhat different.) We therefore know the CO molecular flow rate. We know the mass of a molecule of CO, so we know the mass flow rate of CO, in g/sec or whatever units. We can record all these measurements every minute or so, or faster if you do it by computer, and we can total up all the CO, in grams, during a cooking event. Or, if the production of CO is greatest while the stove is warming up we can tell that too.

The rate at which CO2 is being produced is approximately proportional to the rate at which the wood is being burned. Since wood burns in stages, this relationship is only approximately true. Wood is about 50% carbon by weight[1]. Of this amount, the vast majority of it goes into CO2. A little will appear as charcoal at the end of the process. Even for a very dirty stove only a tiny amount of carbon leaves the stove as CO, or soot, or smoke.

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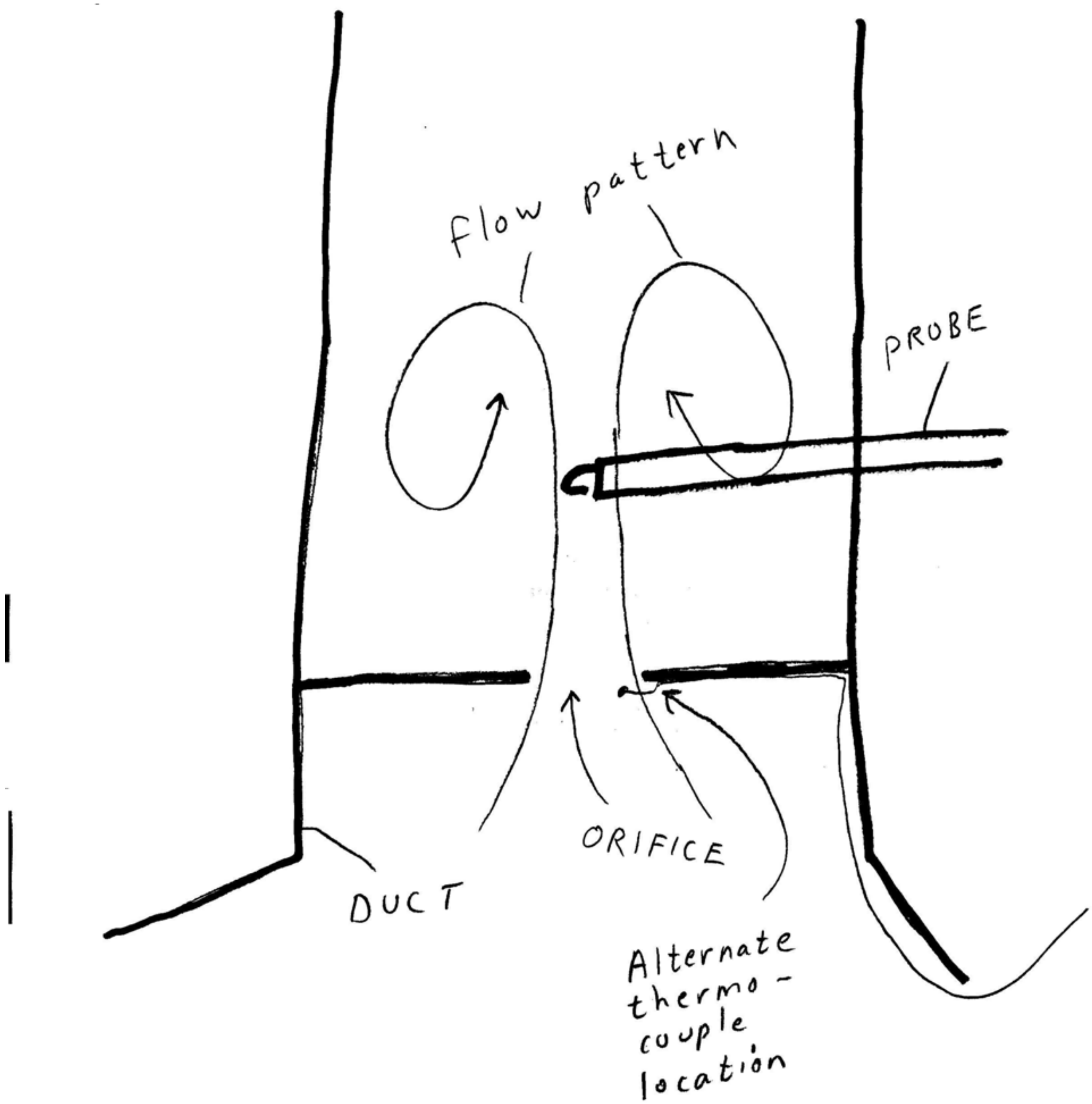
1 See Appendix D, Table 3, Biomass Stoves, by Samuel F. Baldwin. He states that Douglas Fir wood (not including the bark) is 52.3% carbon by weight for dry wood. I've estimated 50% by weight of the fairly dry wood that we often use. Data is probably available for other types of wood, and one can add a correction for the moisture in the wood as well.



Sketch of probe section of hood

How to use the hood

If you are using an actual pot of water, one will need to worry about the steam from the pot once it gets boiling. This is partly because the steam may damage the pollution analyzer (consult the manufacturer about this) and partly because analysis of the gas flow assumes there is no water vapor aside from that created by the burning wood. A steam venting system like that used at the June workshop in the simulated kitchen should be good.

Currently, the hood has some aluminum foil sheets hanging down to form sort of an enclosure. At the start, the height of the stove or hood should be adjusted so that the top of the stove is about even with the bottom of these sheets. While using the hood, especially the first few times, keep an eye on whether or not any smoke escapes from under the hood. As a rule of thumb, the amount of smoke that escapes is equal to the amount of pollutants that escape being accounted for. If a small amount of smoke escapes, it's not a big deal, if a large amount escapes it is. You may need to tinker with the height of the hood and the sheets around the sides to keep the smoke in while still being able to see what's happening at the stove. You may be able to lower the stove such that you can better see what's happening. You might be able to remove some of the aluminum foil. Try it and see. The smoke loss should always be a good indicator of what you need to do.

The fan that cools the blower motor sets up a good bit of wind. I don't think this is affecting the hood as it is currently designed, but on the other hand, if you think a draft might be influencing the test, blocking the draft is never a bad idea. As long as the stove is not completely enclosed, the stove should not be affected.

The hood was designed to be used indoors, under the big hood at Apro so that the smoke blows up and out of the building. The blower stand is 49 inches tall, I hope it's not too tall to fit under the hood. The height was selected so that a fairly tall stove with pot would fit under the hood. Of course, you can always raise the stove or the hood. The hood can also be used outdoors if the wind is light. Another option is to rig a loose duct from the top of the blower to either the outdoors or the big hood.

At the start of a test, the blower on the hood should be turned on, followed by the pollution analyzer. The analyzer may have a warmup time, so allow this to expire before starting a fire. The analyzer needs to have an accurate zero point, and this needs to be pure air. Then start the fire under the hood.

The hood is set up so that you can take all data by hand, perhaps every minute or so. The analyzer probably has a data port also, so this might be prefered. Probably also take data by hand the first few times to make sure they agree.

Some pollution analyzers also take a pressure or "draft" reading. This may be the same as the analog pressure mounted to the hood. Check this to confirm. If the probe is the type that has the thermocouple and is in the jet, it is more likely to disagree with the analog gauge, since the fast flow of gas past the probe will affect the pressure it sees. If the readings agree, then either gauge can be used. If the 2 measurements disagree, the analog gauge should be the correct one. Of course, if the analyzer has a built in pressure measurement, and this measurement can be used, this can be output directly to the computer.

The pressure measurement can be used to give a running estimate of the heat the fire is putting out. The pressure (actually a negative pressure) developed by the blower is proportional to the density of the gas in the blower, if this gas is hotter, the air is less dense and the pressure difference is lower. With room temperature air, the pressure is about 3.4 inches of water. With about 3.5 kW of heat going through the blower the pressure is about 2.9. More power gives a lower pressure. Tests have been done as low as 2.6 inches. This would be about 6 kW. Remember this is the heat going up the stack, the actual firepower will be higher.

At one time I had though it would be possible to estimate instantaneous firepower by measuring the temperature and flow going through the hood. It turns out there is so much heat loss before the hood that this is impossible.

It is possible to estimate (more accurately, it turns out) the firepower by measuring the CO2. The equations section of this document gives the formulas for doing this. The spreadsheet also has columns for this as well.

Once the data has been gathered, it can be turned into graphs of CO2 and CO production per unit time and total CO2 and CO production by using either the equations in the equation section or the spreadsheet which will accompany this document. (Particulates will require a separate calculation based on how the particulate measurement is done-I don't know anything about this.)

Features of the hood

The hood is sized to be used with stoves releasing something on the order of 5-10 kW of firepower. With the hood as it is, this will give a reasonable high concentration of CO, CO2, etc. but yet the hood won't get so hot that it damages itself. At least, this is the intention, it should be monitored while being used to check for this. Also see the section on potential problems.

If lower power stoves are being used, the gas temperatures and pollutant concentrations might get close to ambient values and the accuracy of the system suffers. Again see the section on potential problems.

The blower is a type that is advertised as being good for hot particle laden flows. The rubber hose leading to the analog pressure gauge is a type that is heat resistant. If either item of the hood needs to be replaced, it should be replaced with a similar item.

Formulas for use

If gas flow temperature is measured in °C it must be converted to degrees Kelvin by the formula:

$$T_{Kelvin} = T_{Centigrade} + 273$$

If temperature is measured in °F it must be converted by the formula:

$$T_{Kelvin} = \frac{T_{Fahrenheit} + 460}{1.8}$$

Once temperature at the orifice is known, the density, ρ, can be calculated from:

$$\rho = \frac{100{,}000 * 29}{8.314 T_{Kelvin}}$$

The ambient pressure is assumed to be 100,000 Pa, which should be good in Oregon and Ohio, both of which are a little above sea level. If the hood is ever used in Colorado, a lower number should be used. The molecular mass of the flow is assumed to be 29. The density calculated is in grams per cubic meter. Typically this is about 700 grams per cubic meter.

The speed of flow through the orifice is calculated from:

$$V = \sqrt{\frac{2 * 249 * 1000 * \Delta P}{\rho}}$$

ΔP is the pressure drop measured across the orifice, in inches of water. The 249 is the conversion from inches of water to Pa. The speed calculated is in meters per second. This number is typically around 40 meters per second.

The mass flow rate is calculated from:

$$\dot{m} = \left(\frac{\pi D^2}{4}\right) * 0.61 * V * \rho$$

D is the orifice diameter, in meters. The 0.61 is the discharge coefficient. This is the number that would change if a non-round orifice were used (but then, we're not going to do this, are we?). The discharge coefficient will vary slightly over a range of conditions, but the variation is not large, and 0.61 is a good average value. The mass flow measured is in grams/second, typically this will be about 13 g/sec.

The molecular flow rate is calculated from:

$$\dot{N} = \dot{m} / 29$$

Again, the molecular mass of the effluent is assumed to be 29. The molecular flow rate is in gram-moles per second, and is typically about 0.4 gram-moles per second.

Finally, the mass flow rate of the 2 gases of interest can be found by multiplying by the fraction of gas that is CO2 or CO (these are read directly from the pollution measuring equipment) and then multiplying by the molecular mass of each gas (44 for CO2 and 28 for CO):

$$\dot{m}_{CO2} = 44 * (\%CO2) / 100 * \dot{N}$$

$$\dot{m}_{CO} = 28*(ppmCO)/1{,}000{,}000*\dot{N}$$

The rate at which wood is burned is about equal to (neglecting the fact that wood burns in stages, which makes this strictly an approximation):

$$\dot{m}_{wood} = 12/44*2*\dot{m}_{CO2}$$

CO2 is 12/44 carbon by weight, for every 1 gram of carbon released, about 2 grams of wood are consumed, assuming the wood is fairly dry. This would be grams of wood per second.

Finally, the energy release rate of wood can be estimated from:

$$\dot{Q} = 18{,}000\dot{m}_{wood}$$

which comes from the fact that 1 gram of fairly dry wood releases about 18,000 Joules of energy when burned.

You can total up the amount of wood burned by totaling the wood burning rate, and this should be about equal to the amount of wood burned by direct measurement, assuming not a lot is left over as charcoal.

Potential upgrades

At some point some sort of particulate measuring system will be added. This was intended to be added near the place where the probe goes, but someone who knows more about particulate measurement will need to decide this. If the particulate measurement is farther downstream, you may have the problem of particulates accumulating in the ducts and not being measured. Again, someone who knows more about particulates will need to decide this.

We've talked about adding a stove flow measurement system, measuring the quantity of air that goes through the stove. I believe this could be estimated by making an accurate measurement of the gas temperature just above the fire (this would need a shielded thermocouple) and using the estimate of firepower that comes from the CO2 concentration. It would also be possible to do this more directly using various anemometers.