EMISSION FACTORS AND EFFICIENCIES FOR SMALL-SCALE OPEN BIOMASS COMBUSTION: TOWARD STANDARD MEASUREMENT TECHNIQUES

S. S. Butcher,* U. Rao,** K. R. Smith, J. F. Osborn,*** P. Azuma, and H. Fields

Resource Systems Institute, East-West Center, Honolulu, Hawaii, 96848
*Department of Chemistry, Bowdoin College, Brunswick, Maine, 04011
**Tata Energy Research Institute, Pondicherry, India 605002
***Civil Engineering, Carnegie-Mellon University, Pittsburgh, PA, 15213

Introduction

A large fraction of the population of the earth is served by the preparation of food and space heating by small fires. In many cases the cooking is done indoors and the combustion products are not vented out of the building, but simply escape through windows, doors, and porous walls and roofing. This report describes a preliminary step in defining a test protocol for the simultaneous measurement of efficiency and emissions of open biomass cooking/heating stoves as they are used in many developing countries. This study is part of a larger study of the health impacts of these combustion sources [Smith and others (1)].

Previous studies of total suspended particulates by Smith et al.(2), and carbon monoxide concentrations in village houses by Dary et al.(3) show that exposures are significant and may approach or even exceed those experienced by cigarette smokers (4). Another aspect of biomass fuel use which is of considerable importance in some areas is the availability of fuel and ways in which the efficiency of fuel use might be increased [de Montelembert and Clement (5)].

There have been many studies of efficiencies and emissions for metal wood-fired spaceheaters [Cooper & Malek, (6)] and there have also been several studies of the efficiencies of fuel use for undeveloped countries [Prasad (7)]. The test protocol described here attempts to combine two important objectives:

1) The burn conditions in the tests should simulate as closely as possible those expected in the field;

2) The testing should combine efficiency and emission measurements.

The combustion region in a village house is defined by the stove, which confines the fire and supports the cooking utensil, and also by the cooking utensil itself. An important benefit of combining efficiency and emissions tests is that future work on the design of improved stoves can evaluate changes and potential compromises between emissions and efficiency goals.

Another objective of this study is the design of a measurement system that could be replicated at a reasonably low cost and operated by individuals with limited experience with emissions and efficiency testing. Such easily assembled systems might then be made available at field locations in the relevant countries, where local institutions familiar with local customs and fuel types could examine ways of improving the performance of the combustion systems. While perhaps not satisfying the requirements for accuracy necessary for showing compliance to regulatory requirements, such a system could be very useful for designing and testing improved stove/fuel combinations.

Apparatus and Materials

The tests were conducted in a small ($17 m^3$) utility building of the type often used for equipment storage. The building had a concrete floor, a sliding entrance door, and sliding windows on two sides. This building was also used to stimulate a village hut (8). The cookfire was built in a stove in the corner of the building and the emissions were collected by a hood that is a quarter section of a cone and could be raised and lowered over the fire. The hood fitted into a corner of the building. Air in the hood was exhausted from the building at a rate of about 10 m^3/min through a 0.2 m diameter duct with a 1/3 hp blower located just outside.

Such an arrangement is quite different from those typically used to measure emissions from the types of woodfired stoves in common use in industrial countries (6). Such stoves have flues and emissions measurements can be made by insertion of probes into the flue-gas stream. The stoves of interest here, which are the most common stoves in the world, have no flues. The emissions testing equipment must capture all the emissions without significantly altering the combustion characteristics of the stove.

The movable hood met these specifications in our tests. The hood was raised to about 0.6 m in order to change stoves and clean up after tests. Most types of simple biomass-fueled cookstoves (8,9) without flues could be placed or constructed on the floor under this hood. The hood was then lowered to about 0.3 m. This allowed all the emissions from the fire to be captured by the hood exhaust, but is not so close to the stove that it creates a greatly increased air flow through the combustion region.

TSP and CO were sampled just upstream of the blower. The air flowrate through the exhaust duct was inferred from the pressure drop across an orifice plate in a section of 0.15 m diameter duct downstream of the blower. The flowrate was calibrated to the pressure drop by making an absolute measurement of the flowrate with a pitot transverse in a straight section of the duct downstream from the orifice plate. The calibration was performed on two occasions. Although the blower capacity was degraded somewhat by the buildup of particles on the blower vanes, the orifice calibration was not significantly affected. The air was exhausted at a location about three meters from the building. The entrainment of the exhaust gases was not a problem during these experiments.

Stainless steel and copper probes (¼" I.D.) facing into the air flow removed aliquots of the total emissions. These were passed through filter cassettes (for TSP) or through a damping volume and then taken through an Ecolyzer CO monitor (Model 2100; modified to a detection range of 0-500 ppm). The CO stream was drawn by the pump in the Ecolyzer which operated at about 1.2 liter/min. The Ecolyzer was calibrated with a 203 ppm CO standard (span gas). The sensitivity of the instrument was such that the measurement error of the CO concentration ranged from 4 to 8 ppm.

The particulate matter sample stream was drawn by a battery powered personal sampler (Gilian model HFS113) at rates ranging from 1.5 to 4 liter/min. The personal sampler was operated in the constant flowrate mode and this rate was monitored by the rotameter on the sampler. The rotameters were calibrated by volume displacement. Several types of 37mm filters were used depending on the desired end-point (glass fiber for TSP, Teflon for TSP and trace metals, quartz for elemental carbon determination).

The temperature in the duct at the sampling probes was generally 30-40^{o} C. The collection method is more similar to that used by Butcher and Ellenbecker (10) in a study of residential heaters than it is to EPA Method 5, which has been used to study emissions from a wide range of combustion sources, including residential heaters (11).

Biomass fuels for these tests should be chosen to represent those in common use in developing countries, which are mainly in tropical areas. Anecdotal accounts by villagers (2) and measurements of emissions from wood species from temperate climates indicate that emissions vary by tree species (6,12). Emissions from various kinds of crop residues vary even more significantly because of greatly varying ash contents and physical characteristics (1). Emissions from animal dung also vary somewhat according to the content of dirt incorporated during the collection process. The emissions from all biomass fuels can be expected to vary by moisture content.

In these preliminary tests, six tropical tree species, cow dung, coconut husks, and charcoal were used. Collection, drying, and storage procedures were designed to result in a range of moisture contents typical of what would be expected in the field.

Test Procedure

The heat utilization measurements were based on the provisional international standards developed by Volunteers for International Technical Assistance (13). The temperature of two liters of tap water was determined and then placed in a covered cooking pot. The fire was started under the pot with the aid of a small measured amount of kerosene to help insure that each test began in a consistent manner. The particulate samplers were started as the fire was lit. The fire was actively tended by adding fuel, rearranging fuel, and blowing on the fire through a blowpipe, as needed. Fires in real field situations usually receive similar attention. A fairly vigorous fire was maintained to raise the water to the boiling point and to boil it for 15 minutes. When the water boiled, the time was noted. After boiling for 15 minutes the fire was reduced to keep the water at a simmer (>95^{o}) for 30 minutes. At the end of this period the fire was extinguished and the samplers were turned off.

The amount of fuel added and the fuel residue were determined by a pan balance to an accuracy of 1g. Charcoal and unpyrolyzed wood residues were weighed separately. The amount of kerosene added was recorded and the amount of water remaining in the pot was determined.

Two types of "efficiency" of the cooking process were determined. The first was the "overall heat utilization," which is the ratio of the heat output (sensible + latent heat of the water) to the heat input in terms of the heats of combustion of fuels used (the "low heat value," corrected for moisture content and charcoal residues). The kerosene used for lighting accounted for only a small fraction of energy used. The second was the "net heat utilization" and is the ratio of sensible heat output to heat input. Both measures of heat utilization are useful, depending on the type of cooking being considered. A third "power" measure is sometimes important as well: it is the average stove power during the heat-to-boil phase of the test cycle. This was not determined in these tests because the power test required stopping the fire to weigh the fuel. Starting and stopping the fire, unfortunately, greatly affects emissions. Joint power and emissions tests would require some other technique, perhaps placement of the entire stove on a large scale.

During the burn, the air sampling equipment was monitored more or less continuously and critical values were recorded at 5-minute intervals. These values included orifice-plate pressure drop, sampler flow rates, duct temperature at the sample probes, ambient temperature, and Ecolyzer reading.

The filters were placed in a dessicator for 24 hours before the tare and sampled weights were taken. Weights were then measured to within 0.01 mg. In most cases, each filter represented an integrated sample over the entire burn. The total particle emissions were determined as the product of the filtered weight and the ratio of the total duct flow to the particle sampler flow. The emission factor for particulate matter was then calculated as the ratio of total particle emissions to net fuel consumed. These particulates could be expected to have mass median aerodynamic diameters of about 0.6 μm or less based on wood and dung smoke measurements in open and closed stoves (8,14). This means that essentially all TSP is within the respirable range (<2.5 μm).

The carbon monoxide concentration in the duct was obtained from the Ecolyzer reading (corrected for temperature). The duct concentration was then integrated over the time of the burn and multiplied by the flow rate through the duct to obtain the total carbon monoxide emissions. The emission factor was obtained by dividing by the fuel consumed, as described above.

Results and Discussion

The results of seventeen test burns are summarized in Table 1. These results are sorted by stove type. The chulas were constructed of firebrick or of large stones. The conventional chula is U-shaped and open at the top to support the cooking utensil. It is constructed of clay or similar indigenous materials. The C.P.R.I. stove is a cylindrical metal stove designed for increased heating efficiency. The fuel use rate ranged from 0.2-1.6 kg/hr. A number of different fuels were tested, but these results are aggregated for present purposes. The large variations in emissions factors very likely resulted from variations in the burning conditions from one burn to the next and also from errors of measurement. Variations in the burning conditions occur naturally and have also been observed in other stove tests (8,10). These variations can only be minimized by conducting many tests. Key among the measurement errors are those which arise from weighing the 37 mm filters. For some cases the particulate weight was less than 0.10 mg and near the limit of sensitivity of the available balance. There may also be problems associated with the adsorption of gases such as SO_2 on glass fiber filters.

Other problems may arise from the configuration of the duct near the sampling probes. The sampling probes were located fairly close to a right angle bend in the ductwork and just upstream of the blower inlet. Substantial inhomogeneity of the flow field was observed in this region and the particle collection efficiency may have depended on the sample probe location and orientation. Particle losses in the duct upstream of the sampler were estimated by measuring the deposition on weighed aluminum foil. For a series of burns in which the total emissions were 62 grams, about 5 grams were estimated to have been deposited in the duct.

The emissions factors in Table 1 may be compared with factors obtained by others for fireplaces. Fireplaces, although usually not tended continuously like chulas, are more similar to chulas than are closed metal stoves. Dasch (14), in a fireplace study using EPA Method 5, obtained an average of 5.4 g/kg for filterable particulates with a range of 2.4-12 g/kg. The condensible organic fraction averaged 6.9 g/kg with a range of 2.3-22 g/kg. DeAngelis, et al. (11), obtained averages of 2.4 g/kg particulates and 6.7 g/kg condensible organics for fireplaces. The results obtained here tend to fall between values for particulates only, and those for particulates plus condensibles from these other studies. Further work is needed to define the sampling method most appropriate for assessing the health effects of these low temperature combustion sources.

Dasch (15,16), Lips (17), and DeAngelis, et al. (11,18) obtained average carbon monoxide emission factors which ranged from 16 to 110 g/kg in fireplace studies. This range includes several burns carried out at much higher combustion rates than we have used. Smith, et al. (8), in a study of concentrations in a simulated village hut which allowed the determination of emission factors by indirect means obtained the results at the low end of the range. Additional research is being conducted to explain this discrepancy.

Table 1

Summary of Results
Mean Values (range)

Stove	Overall Efficiency	Particle Emission Factor	Carbon Monoxide Emission Factor
Small Chula 9 burns	13.3% (9.0-16.6)	9.1 g/kg (4.2-21.3)	84 g/kg (72-92)
Large Chula 2 burns	14.2	12.3 (9.1-15.5)	>88 (76->101)
Three Rock Chula 3 burns	11.6 (6.7-14.3)	7.7 (4.2-10.2)	63 (39-81)
C.P.R.I. Stove 3 burns	15.5 (11.8-18.0)	5.2 (0.3-8.3)	182 (86-360)

The current system using personal samplers offers the advantage of simple and stable pumps usable in other applications such as personal sampling. A disadvantage is that the small sample volumes result in particle masses than can only be determined with a sub-milligram level analytical balance. In many cases the filtered masses of 1-5 mg were easily measured, but for some fuels these masses were less than 0.1 mg. The advantages of using the present system will be compared with those using a large volume of air and less demanding weighing procedure in future work.

Some aspects of the sampling method are bound to affect the operation of the fire somewhat and one can only try to minimize these effects. As mentioned, the 0.3 m distance from the hood to the floor means that the hood opening is about 0.54 m^2 for these studies. At an average flowrate of 10 m^3/min, this gives an average face velocity of about 19 m/min. It is difficult to say how much of an effect this airflow has on the fire. We do know that fugitive emissions to the interior of the hut was a minor factor for these tests. Generally speaking, very little smoke was apparent in the hut. The CO concentration was measured at the edge of the hood on three occasions. Two of these measurements were less than the detection limit of the system as set up (less than 2 ppm), and one measurement was about 4 ppm.

Although there are several remaining problems to be solved in this system, it seems that it can be useful as an inexpensive approach to measuring thermal efficiency and air emissions from simple open biomass-fired stoves.

References

(1) Smith, K.R., and others. Rural biomass fuels and air pollution: a global review. World Health Organization, Geneva (forthcoming), 1984.

(2) Smith, K.R., Aggarwal, A.L., and Dave, R.M. Atmos. Environ. 1983, 17(11):2343-2362.

(3) Dary, O., Pineda, O., and Belizan, J.M. Bull. Environ. Contam. Toxicol. 1982, 26:24-30.

(4) Smith, K.R. Air pollutant emissions, concentrations, and exposures from biomass combustion: the cigarette analogy. To be presented at the Annual Meeting of the Fuel Chemistry Division, American Chemical Society, August 26-31, 1984, Philadelphia, PA.

(5) deMontalembert, M.R., and Clement, J. Fuelwood Supplies in the Developing Countries. FAO Forestry Paper 42, Food and Agriculture Organization of the United Nations, Rome, 1983.

(6) Cooper, J.A. and Malek D., eds. Proceedings of the 1981 International Conference on Residential Solid Fuels: Environmental Impacts and Solutions. Beaverton, Oregon, Oregon Graduate Center, 1982.

(7) Prasad, K.K., ed. Some Studies on Open Fires, Shielded Fires and Heavy Stoves. Woodburning Stove Group, Eindhoven University of Technology, and Division of Technology for Society, TNO, Apeldoorn, Netherlands, 1981.

(8) Volunteers in Technical Assistance. Wood Conserving Cook Stoves Bibliography. VITA, Arlington, VA, 1983.

(9) Smith, K.R., Apte, M., Menon P., and Shrestha, M. Carbon monoxide and particulates from cooking stoves: results from a simulated village kitchen. To be presented at the Third International Conference on Indoor Air Quality and Climate, August 20-24, 1984, Stockholm, Sweden, 1984.

(10) Butcher, S.S. and Ellenbecker, M.J. J. Air. Pollut. Contr. Assoc. 1982, 32:380-384.

(11) DeAngelis, D.G., Ruffin, D.S., and Reznik, R.B. Preliminary characterization of emissions from wood-fired residential combustion equipment (Monsanto report), EPA-600/7-80-040, USEPA, Research Triangle Park, NC, 1980.

(12) Ayer, F.A., ed. Proceedings of Conference on Wood Combustion Environmental Assessment. NTIS, New Orleans, LA, 1981.

(13) Volunteers in Technical Assistance. Testing the Efficiency of Wood-burning Cookstoves; Provisional International Standards. VITA, Arlington, VA, 1982.

(14) Rau, J.A., and Huntzicker, J.J. Carbonaceous aerosol from residential wood combustion. To be presented at the Annual Meeting of the Fuel Chemistry division, American Chemical Society, August 26-31, 1984, Philadelphia, PA.

(15) Dasch, J.M. Environ. Sci. Technol. 1982, 16:635-645.

(16) Dasch, J.M. Particulate and gaseous emissions from residential fireplaces. GMR-3588 ENV #101, General Motors Research Laboratories, Warren, MICH, 1981.

(17) Lips, H.I., and Lim, K.J. Assessment of emissions from residential and industrial wood combustion, Acurex Draft Report Fr-81-85/EE, EPA Contract 68-02-3188, 1981.

(18) DeAngelis, D.G., Ruffin, D.S., and Reznik, R.B. Source assessment: residential combustion of wood, EPA-600/2-80-042b, USEPA, Research Triangle Park, NC, 1980.