Development of an Emissions/Efficiency Standard for Wood-Fired Appliances

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Introduction

The Canadian Combustion Research Laboratory (CCRL) has been carrying out a detailed research program on domestic bulk-fuel-fired equipment. One of the goals of this program has been to develop a straightforward test procedure to determine the efficiency of controlled-combustion wood-fired space heaters (1). A parallel goal has been the characterization of the combustion of these appliances.

Such a procedure would allow all Canadian stoves to be measured and compared in the marketplace, on the same equitable basis.

At the same time, consumers would be presented with information by which they could choose between two stoves of the same nominal efficiency, on the basis of the amount of incomplete combustion products and, hence, on the potential for chimney fires from creosote and on the pollutant emissions to the environment.

It also presents regulators with the possibility of placing minimum levels of emissions in certain applications, such as high population areas, areas with poor fumigation such as the West coast, sub-arctic or river valleys, or as criteria for eligibility for assistance under government programs, such as the Canadian Oil Substitution Program (COSP).

A simplified version of this procedure could be used by manufacturers with inexpensive test equipment to carry out development of efficient, clean-burning appliances in their own plant.

Because of the nature of the burning process in these units, combustion is normally incomplete, due to poor mixing, low temperatures and the bulk and compositional nature of the fuel itself.

Currently, the techniques generally proposed in the United States to measure efficiency require either the use of a calorimeter room or a simplified stack loss method (1), (2). For the former, emissions can only be determined by additional instrumentation and measurement. For the latter, the efficiency is determined by measuring the combustion products in the flue gas and using an inferential carbon balance to determine the heat losses. If one wishes to determine emissions as well as efficiency, the stack loss method is preferable. As it now stands, the technique assumes a constant fuel composition, a recognizably incorrect assumption for bulk wood-fired equipment.

To correct this, CCRL has carried out a specific set of experiments to characterize the changes in fuel composition which occur over the cycle, in terms of ultimate analysis, energy content and moisture level.

This paper presents results of these experiments, as well as a description of the proposed standard itself.

Experimental Methods

Several effectively identical fuel charges were prepared, carefully weighed and burned, one at a time, in a typical wood stove. At a series of points in the burning cycle, the fire was extinguished rapidly, and the fuel composition analyzed. The difference in composition for a change in per cent charged consumed showed the ultimate analysis of the fuel lost.

Experimental Apparatus

Test Stove. A well-built, cast iron horizontal baffle stove, with a 3 combustion chamber lined with firebrick and having a volume of 0.05 m^3 was used for the experiments.

Test Fuel. Fuel used was commercially available Douglas Fir construction grade lumber of 5 cm x 10 cm nominal dimensions arranged in two lattice arrangements, with both the wide and narrow side of the wood as base, arrangements "A" and "B", respectively. The moisture content of the fuel, as-fired, averaged 12%.

Fuel Weight. Wood was weighed before and after each burn by means of a triple beam balance with accuracy of 0.1 g. During the test burn, weight was monitored by continuous digital weigh scale to allow extinguishing of the fuel charge after the desired per cent weight loss.

Stove Installation. The stove was located in the standard CCRL test setup (3), mounted on a continuous digital weigh scale, with 1.3m of single wall flue pipe connecting the appliance to a 6 m high Class A chimney to generate consistent draft. A draft hood type collector then gathered the flue gas with dilution room air and exhausted the products to the outside. Continous analyzers were used to measure all flue gas components, monitor the burn and assure typical operating conditions.

Test Procedure

A metal tray was installed on the floor of the stove to allow removal of the fuel remaining. A small initial charge of Douglas Fir kindling was first fired to heat the system and provide a coal bed. When this charge was 85% consumed, the test wood charge, previously weighed, was placed in the stove and the experiment begun. With the desired per cent weight change reached, the fire was rapidly smothered using a CO_2 extinguisher; the charge on its metal tray was removed and placed in a container surrounded by water, fitted with an air-tight lid. The charge was allowed to cool while ensuring that no re-ignition would occur. The charge was then weighed again, ground up, thoroughly mixed and analyzed for elemental composition, moisture and heating value.

Tests were repeated with varying weights-per-cent-consumed to develop a profile of wood consumption over the entire cycle.

The experiments were carried out at high and low burning rates, typically 2.8 kg/h and 0.6 kg/h, respectively.

Experimental Results

Table I presents the analyses of the composition of the remaining, unburned fuel, for a number of combustion trials. While the composition of the fuel remaining at any point in the burn is provided directly from a chemical analysis of the burned charge, what is of interest is that for the fuel which has just been consumed. This is obtained by determination of the fraction of initial weight represented by each component at the beginning and end of a burn interval, then subtracting to obtain the amount actually lost. Summing for all components gives the total loss, with the loss of any one component being expressed as a percentage of this total, as shown in Table II.

In accordance with normal convention, the per cent by weight of components lost is reported on a total basis for moisture and on a dry basis for the chemical elements and the calorific value. The ultimate composition determined is assumed to apply at the mid-point of the two weights.

After determining the compositions of the fuel consumed, a least-squares procedure was used to compute equations for the moisture loss, the ultimate analysis and the calorific value (HHV).

Equations developed for moisture loss and change in ultimate analysis are as follows:

(1) % original $H_2O = 204\ e^{-.02125x}$

where x is the % total weight lost.

(2) % carbon = $29.77 + .6799y - .0169y^2 + .000174y^3$

(3) % oxygen = $62.96 - .7033y + .0172y^2 - .0001699y^3$

(4) % hydrogen = $7.269 + .0274y - .0009y^2$

(5) Calorific Value (HHV) (J/g) = $12136 + 189y - 3.488y^2 + .03988y^3$

where y is the % dry weight burned.

Draft Efficiency-Emissions Standard

The following is a draft standard for the measurement of the efficiency and emissions of domestic wood-fired appliances, in the format it has been submitted to the Canadian Standards Association.

This procedure requires the measurement of carbon dioxide, carbon monoxide, oxygen and hydrocarbons in the flue gas and uses a fuel composition which varies throughout the burning cycle, based on the above described experiments to accurately determine performance.

1.1 Scope

1.1.1 This document describes the method of obtaining heating capacities, energy efficiencies, emissions levels and air consumption rates for wood-fired appliances with a closed fire chamber.

1.1.2 For the purpose of this standard, a wood-fired appliance with a closed fire-chamber meets the following requirement: the air/fuel mass ratio is less than 30 during the burning of at least 80% of the fuel mass consumed in the low firing cycle defined in 6.1.1.

1.1.3 This standard is not intended to test appliances which release a significant proportion of their energy output to an area other than that intended to be heated or to the stack.

1.2 Purpose

1.2.1 The purpose of this standard is to:

1. establish a uniform method of testing for obtaining test results.
2. specify types of test equipment for performing such tests.
3. specify data required and calculations to be used.
4. list and define the terms used in testing.

2.1 General

2.1.1 The requirements of the appropriate safety standards shall not be violated by any of the test stove installation requirements for this standard.

3. Test Facilities

3.1 Test Room

3.1.1 The test shall be conducted in a room with a height for discharge of flue products of at least 4.6 m above floor level. The room shall be free of drafts such that air velocities shall be less than 10 cm/sec within one meter of the appliance when the appliance is not operating. The flue shall discharge into the same space or into a space freely communicating with the test room. Any draft hood or similar device used for final venting of the combustion products shall not impose a draft greater than 1.25 Pa on the appliance flue when the appliance is not operating.

3.1.2 The temperature in the test room shall be maintained between 16 degrees C and 25 degrees C during the tests. Any ventilation required to acheive this requirement shall not violate the draft conditions of 3.1.1.
3.1.2.1 The air temperature in the test room shall be measured by means of a 24 gauge, type J thermocouple, or equivalent. The thermocouple shall be located centrally within a vertically oriented 150 mm steel pipe open at both ends. The thermocouple and shield shall be located on the horizontal plane with the primary air intake openings of the heater. The thermocouple shall not be closer than 1 metre from the heater and it shall not be further than 2 metres from the heater.
3.1.2.2 The accuracy of the temperature measurement equipment shall be within +/-0.6 degrees C.

3.2 Appliance Installation

3.2.1 The flue pipe for the appliance shall be made of no. 24 gauge black steel and shall extend 1.2 metres above the platform of the scale on which the heater is located. The flue pipe shall be constructed such that any cracks or joints are sealed with furnace cement or equivalent. Flue pipe diameter shall be as specified by the manufacturer.

3.2.2 The flue pipe shall vent into a vertical factory-built chimney conforming to ULC S629 and extending 4.5 metres above the platform of the scale on which the heater is located. The inside diameter of the factory built chimney shall be 200 mm, unless a larger diameter is specified by the applicance manufacturer.

3.2.3 If the flue pipe and chimney are of different diameter, the diameter of the flue pipe shall be brought to that of the chimney by a gradually tapered section 0.5 to 1 metre in length.

4. Test Instrumentation

4.1 Required Instrumentation

4.1.1 Test instrumentation required for these tests are as described below.

4.2 Wood Weight

4.2.1 The appliance to be tested shall be placed on a scale so that the weight of wood consumed can be recorded. Weight changes of the fuel in the appliance shall be determined to within +/- 1% of the total amount of fuel burned during the cycles of record as defined in 6.2.5.

4.3 Flue Gas Temperature

4.3.1 The flue gas temperature shall be determined by means of an array of five 24 gauge type K themocouples or equivalent, located within 15 cm of the appliance flue collar. The thermocouples shall be connected in parallel to provide an average flue gas temperature reading.

4.3.2 The accuracy of the temperature measuring equipment shall be within +/- 0.6 degrees C.

4.4 Flue Gas Composition

4.4.1 The following flue gas constituents shall be measured: Oxygen, Carbon Monoxide, Carbon Dioxide, and Hydrocarbons. The percentage of CO2 and CO in the flue gas shall be measured by means of continuous infared analyzers, Orsat analyzer, or equivalent analysis equipment, providing a measurement of the percentage of dry flue gas volume with an accuracy of at least +/- 0.2%. Oxygen shall be measured using paramagnetic analyzer, thermomagnetic analyzer, Orsat analyzer, or equivalent analysis equipment providing a measurement of percent of dry flue gas volume with an accuracy of at least +/- 0.2%. (Note: zirconium oxide-type oxygen analyzers shall not be used, because of their sensitivity to incomplete combustion products.) Hydrocarbons are to be measured using a flame ionization detector type analyzer equipped with a cooled sampling train (3). Hydrocarbon readings shall be reported in ppm methane equivalent, with an instrument accuracy of +/- 1%.

4.4.2 Gas samples shall be taken by means of a slotted probe inserted within 1 metre of the stove flue collar. The probe shall be fabricated from 1 cm tubing of inert material.

4.5 Elapsed Time

4.5.1 Elapsed time shall be measured with a device capable of accurately measuring to +/- 30 seconds per 24 hr period.

5. Fueling Requirements

5.1 Test Fuel

5.1.1 The test fuel shall be Douglas Fir lumber with nominal dimensions of 5 cm x 10 cm with a dry density between .50 and .60 g/cm3.

5.1.2 The fuel shall have a moisture content between 10% and 15% when tested according to ASTM 2016, and calculated as:

(6) $R = 100\,(Ww - Wd)/Ww$

where:

Ww = wet weight of the wood sample (kg)
Wd = dry weight of the wood sample (kg)
R = wood moisture content (total basis)

5.1.3 Wetting of previously dried wood is prohibited.

5.1.4 The higher heating value (HHV) of the fuel shall be determined according to ASTM 3286-77 or ASTM 2015-77.

5.1.5 Wood pieces with significant knots, discolourations, rot, or other defects shall not be used for test purposes.

5.2 Fuelwood Charge

5.2.1 The fuelwood shall be assembled in a lattice arrangement of two 5 cm x 10 cm pieces fastened together with the base 2 x 5cm, height 10 cm and air space between each set of pieces of 2 cm.

5.2.2 The pieces shall have a length 5/6 the length of the longest firebox dimension, with as many pieces as can be fitted into the available width.

5.2.3 These lengths shall be held together by two 5cm by 10 cm pieces across either end with the 10 cm face down.

5.2.4 Rows shall continue in this manner to reach as close as possible to the maximum recommended fueling height, or the top of the highest loading opening if no maximum height is indicated.

5.2.5 The complete fuel charge shall be held together by nails or staples for fueling. These fasteners shall be counted and their weight recorded.

5.2.6 The fuel charge may be built up from smaller dimensions to facilitate loading. If this is done, all the subsections to make up a complete charge must be added at the same time during refueling.

5.2.7 Appliances with combustion chambers of other than simple box shape shall have fuel charges providing equivalent loading to the charge described above.

6. Test Procedure

6.1 Burn Rates

6.1.1 A minimum of three tests shall be conducted, one at each of the burn rates as defined in Table III. The different burn rates are to be achieved via different settings of the controls in a manner consistent with the manufacturer's instructions. If an appliance is designed to operate at a single firing rate only, or over a very limited range of firing rates, the burn rate requirement shall be adjusted as appropriate.

6.1.2 A bed of coals shall be established whose mass is 15%, +/- 1% of the test fuel weight. The appliance is then fueled with the test charge and the controls are set. Sucessive test charges are added when the coal bed returns to 15%, +/- 1% of the test fuel weight.

6.1.3 Coals shall be raked or levelled before each test charge is added. If the manufacturer specifies a specific procedure for the raking of coals, this procedure shall be followed.

6.2 Data Collection

6.2.1 Computations of heat output, energy efficiency, and air consumption shall be based on data taken throughout the test cycles.

6.2.2 Data shall be taken at intervals at least corresponding to the consumption of 5%, 15%, 25%, ..., of the weight of the initial wood charge. A minimum of nine sets of data will be taken for each test and the time interval between taking data may vary with the rate of wood consumption.

7. Results

7.1 Ultimate Analysis, Moisture Content, and Calorific Value of the Fuel:

7.1.1 The ultimate analysis, moisture content, and calorific value of the fuel will vary as the fuel charge is consumed. For test purposes, equations based on experimental results have been developed to model changes in the main constituents of the wood, as described previously.

7.1.2 Because a fresh charge of wood is added when 80% of the fuel mass is lost, the previous charge will still be burning. Thus it is necessary to calculate the burn rate of each charge independently. This is done by fitting a curve of the form y=ae**bx to the wood burnt in order to predict the remaining burn rate, and subtracting this from the measured burn rate to get the new charge burn rate.

7.2 Hydrocarbon Measurement

7.2.1 The hydrocarbons measured by the FID are less than those actually present, due to condensation of some hydrocarbons in the cooling bath and to failure of the instrument to detect all hydrocarbons present. However, the reading approximates a fixed fraction of those hydrocarbons actually present, including the heavier molecular weight components, so that the total hydrocarbons can be determined by multiplying the HC reading in ppm by xxxx to obtain the % methane equivalent in the flue gas.

7.3 Combustion Equation

7.3.1 Results for average heat input, average efficiency, average heat output, and average air flow are calculated based on the following chemical equation modelling the wood combustion:

$$wCaHbOc + wpH2O + uO2 + 3.77uN2 = dCO2 + eCO + gO2 + hN2 + jH2O + kCH4$$

where

- w = moles of dry fuel/100 moles dry flue gas
- a = fraction of carbon atoms in the fuel
- b = fraction of hydrogen atoms in the fuel
- c = fraction of oxygen atoms in the fuel
- p = moles of water/mole of dry fuel
- u = moles of oxygen entering/100 moles dry flue gas
- d = moles of CO2/100 moles dry flue gas
- e = moles of CO/100 moles dry flue gas
- g = moles of O2/100 moles dry flue gas
- h = moles of N2/100 moles dry flue gas
- j = moles of H2O/100 moles dry flue gas
- k = moles of CH4/100 moles dry flue gas

7.3.2 Fuel Constituents Ratio

a,b,and c are determined from the equations:

a = CR/12.011
b = HD/1.008
c = OX/16

where:

CR = weight percent carbon in the unburnt fuel
HD = weight percent hydrogen in the unburnt fuel
O2 = weight percent oxygen in the unburnt fuel

while p is determined from:

p = MWw/(18.016(100-M))

where:

M = .125R (% by weight of water in the wet wood)
Ww = the molecular weight of wood (assumed to be 100 g/mole)

7.3.2 Mass Balances:

Balancing the masses of elemental constituents present, the following equations are obtained:

Carbon balance:	wa = d + e + k
Hydrogen balance:	(2p + b)w = 2j + 4k
Oxygen balance:	(p + c)w + 2u = 2d + e + 2g + j
Nitrogen balance:	3.77u = h
Sum of dry products:	d + e + g + h + k = 100

Solving these equations yields values for the unknowns w, u, j, and h.

7.4 Heat Output

7.4.1 Given the weight of fuel consumed over any time interval, the number of moles of product can be calculated using the values found above. If the moles of product are determined for the fuel input over the interval, then the instantaneous stack losses can be calculated as:

li= sigma(moles of product x (enthalpy of product at stack temperature minus enthalpy of product at ambient temperature))

Enthalpies in Joules/litre are calculated from the following equations:

Product	Equation
Oxygen	1.323(Ts-Ta)+.000161(Ts-Ta)**2
Nitrogen	1.253(Ts-Ta)+.000136(Ts-Ta)**2
Carbon dioxide	1.843(Ts-Ta)+.000411(Ts-Ta)**2
Carbon monoxide	12640+1.262(Ts-Ta)+.000152(Ts-Ta)**2
Water	1.432(Ts-Ta)+.000276(Ts-Ta)**2
Methane	37706+1.6493(Ts-Ta)+.001064(Ts-Ta)**2

Total losses are thus L= sigma(li)

Total input I = wt of fuel times calorific value of fuel per unit weight.
Therefore, heat output of the appliance is (I-L)/T
where
T is the burn time in hours

7.5 Efficiency

$n = 100*(I-L)/I$
where
n is the efficiency in percent

8. Emission Control Requirements

8.1 Carbon Monoxide

8.1.1 The carbon monoxide emissions per unit of heat output shall be determined for each of the required firing rates.

8.1.2 An equation relating carbon monoxide emissions to heat output shall be developed from these results using a least-squares fit polynomial regression.

8.1.3 The minimum labelled burn rate of the appliance shall be that providing a carbon monoxide emission level not greater than xxx g/MJ according to the equation of 8.1.2.

8.1.4 No stove shall be certified by this agency for domestic use which has an average emission level for the three test burns greater than yyy g/MJ.

8.2 Hydrocarbons

8.2.1 The hydrocarbon emissions per unit of heat output shall be determined for each of the firing rates, in accordance with 7.2.1.

8.2.2 An equation relating hydrocarbon emissions to heat output shall be developed from these results using a least-squares fit polynomial regression.

8.2.3 The minimum labelled burn rate of the appliance shall be that providing a hydrocarbon emission level not greater than zzz gm/MJ according to the equation of 8.2.2.

8.2.4 No stove shall be certified by this agency for domestic use which has an average emission level for the three test burns greater than qqq g/MJ.

9. Labelling

9.1 A label shall be affixed to any rated appliance providing all of the following information:

1. Appliance manufacturer
2. Appliance name
3. Maximum firing rate (kg/hr) with corresponding heat output (MJ/kg), efficiency (%), and burn time (hr).
4. Minimum firing rate (kg/hr) with corresponding heat output (MJ/kg), efficiency (%), and burn time (hr).
5. Level of emissions of incomplete combustion products: carbon monoxide and hydrocarbons.

9.2 At the option of the manufacturer, the information as shown in items 3 or 4 above may be provided at one other firing rate tested, provided this rate falls between the permitted minimum and maximum rates.

9.3 The label may be incorporated as part of a safety certification label, if so desired by the testing agency.

Conclusions

1. Generalized equations now exist to characterize the variation in fuel composition over the burning cycle of a domestic wood-fired appliance, irrespective of the fuel orientation or firing rate.

2. These equations have been incorporated into an indirect stack loss method to determine efficiency and emissions.

3. A draft standard now exists which may be used by testing agencies, manufacturers, regulatory authorities and the public to measure efficiency and emissions of domestic wood-fired appliances on an equitable basis, and to provide guidance and direction for future designs.

4. A series of experiments is now underway to provide guidelines for specific emission levels of carbon monoxide and hydrocarbons as required by various agencies.

References

1. A.C.S. Hayden, "Efficiency of Wood-Burning Appliances", ERP/ERL Report 78-82, CANMET, Ottawa, 1978.

2. T.T. Maxwell, D.F. Dyer, G. Maples, "Efficiency and Heat Output Measurements for Residential Wood Heating Appliances", Proceedings, Wood HEating Seminar VI, Wood Energy Institute, Atlanta, February 1980.

3. A.C.S. Hayden and R.W. Braaten, "Effect of Firing Rate and Design on Domestic Wood Stove Performance", Proceedings, APCA Specialty Conference on Residential Coal Combustion, Louisville, March 1982.

Table I. Ultimate analysis of wood remaining after varying amounts consumed.

% Burned	% H_2O Wet	Ultimate Analysis, Dry Basis C	H	S	N	Ash	O	HHV (J/kg)
0	7.54	50.58	5.62	0.16	0.23	0.06	43.34	19810
CONFIGURATION "B" - HIGH FIRE								
19.4	3.16	55.27	5.92	0.09	0.17	0.12	38.43	21690
33.5	2.92	57.89	5.64	0.06	0.23	0.16	36.02	22560
58.4	2.16	65.62	4.50	0.01	0.44	0.20	29.23	25730
76.3	1.64	86.33	2.71	-	0.29	0.40	10.27	32450
96.3	2.28	83.68	1.77	-	0.32	2.37	11.84	28870
38.7	5.18	59.90	4.85	0.01	0.63	0.24	34.37	23280
76.9	2.53	83.29	2.74	-	1.56	0.14	12.27	31130
CONFIGURATION "A" - LOW FIRE								
15.9	4.71	52.66	5.00	0.12	0.14	0.12	41.96	20750
32.6	4.70	54.71	4.86	0.08	0.04	0.07	40.24	21600
47.0	3.98	58.49	4.61	0.07	0.05	0.51	36.27	22580
56.4	4.33	57.30	4.53	0.06	0.07	0.13	37.91	22400
63.2	4.55	59.18	4.39	0.06	0.09	0.21	36.07	22630
42.9	4.00	55.94	4.73	0.06	0.04	0.10	39.13	21640
CONFIGURATION "A" - HIGH FIRE								
17.9	6.28	54.20	5.95	0.04	-	0.14	39.67	21050
35.5	5.30	57.46	5.46	0.01	-	0.12	36.95	22300
52.9	4.07	64.03	4.98	-	-	0.18	30.81	24880
63.8	4.54	71.36	4.37	-	-	0.30	23.97	27630
80.5	3.01	92.15	2.06	-	-	0.37	5.42	34080
93.6	4.03	90.44	1.31	-	-	1.18	7.07	32340

Table II. Ultimate analysis of wood burned.

% Burned			Ultimate Analysis, %			
Dry	Wet	Water	C	H	O	HHV, J/kg
CONFIGURATION "B" - HIGH FIRE						
7.78	9.68	341.1	25.1	4.00	69.83	9558
22.9	26.5	56.8	42.7	7.24	49.81	17543
43.1	46.0	55.5	44.6	7.58	47.55	17130
65.4	67.3	37.8	37.8	6.90	54.64	16695
85.4	86.3	20.2	86.8	2.88	9.98	33113
98.0	98.1	30.3	83.7	1.77	11.84	28868
26.4	29.0	-	41.2	8.91	49.54	16854
46.6	48.6	153.4	46.5	5.67	46.38	17554
65.8	67.6	22.3	43.2	6.63	49.88	18817
85.8	86.6	34.1	83.0	2.92	12.32	31480
CONFIGURATION "A" - HIGH FIRE						
8.41	8.96	175.9	32.6	3.99	61.30	13633
25.4	26.7	131.1	41.6	7.84	50.18	16242
42.5	44.2	114.5	38.7	6.82	54.41	14933
56.9	58.3	33.4	40.3	6.93	52.76	15961
71.1	72.2	84.0	46.1	7.18	46.50	19801
86.4	87.0	33.4	92.9	2.42	4.63	34897
96.7	96.8	53.5	90.4	1.31	7.07	32345
CONFIGURATION "A" - LOW FIRE						
6.68	7.97	297.2	37.0	9.64	52.13	13661
21.9	24.2	63.0	44.3	5.57	48.94	17308
37.7	39.8	96.0	39.7	5.72	54.48	17000
72.5	73.5	52.8	58.5	4.61	36.27	22500

Table III. Burn rates for emissions/efficiency test.

Burn rate	Definition
High	The maximum burn rate achievable
Mid	Halfway between high and low burn rate, +/- 0.15
Minimum	<25% of the high burn rate, or the minimum burn achievable.