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ROUND ROBIN TEST OF A WOOD STOVE: THE INFLUENCE OF STANDARDS, TEST PROCEDURES AND CALCULATION PROCEDURES ON THE EMISSION LEVEL

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Abstract—As a part of the IEA Bioenergy, Task X-Conversion, Combustion activity, an international round robin test of a wood stove supplied with a catalytic afterburner (JØTUL 3TDCI-2) has been performed to investigate and compare the emission level of CO, particles/tar, hydrocarbons and NO_x. The participating countries were Austria, Canada, Denmark, Finland, the Netherlands, Norway, Sweden, U.K. and U.S.A. The wood stove was tested according to national standards and test procedures. In addition, a comparison of the calculation procedures used to convert measured transient volumetric emission levels into average emission levels in g/kg dry fuel was performed, based on both arithmetic and weighted averaging. The results uncovered significant differences in ways of doing environmental evaluation. Particle emission measurements were found to be the best method to evaluate the environmental acceptability of the tested stove, since the particle emission level was least dependent of the national standards, test procedures and calculation procedures used. Finally, transient particle emission measurements are presented, which reveal a close relationship between particle and hydrocarbon emissions. © 1997 Elsevier Science Ltd

Keywords—Combustion; biomass; wood; particles; CO; hydrocarbons; NO_x

1. INTRODUCTION

Several researchers have investigated the emission level of various air pollution compounds from wood-fired appliances in recent years,[1-9] and effective methods of reducing the emission level of unburned compounds, such as particles, CO and hydrocarbons have been introduced.

Standards for testing of emission levels from wood-fired appliances have been introduced in several countries. These standards are, however, based on different sources and philosophy. This may result in different evaluation and conclusions regarding emission levels. A stove evaluated in one country as environmentally acceptable will not necessarily get the same evaluation in another country, even if the restrictions are the same. It is, therefore, important to investigate and compare measurements and evaluations of stoves done in different countries to see if links exist between the standards, test procedures, calculation procedures, measurements and evaluations.

This work has been carried out as an IEA Bioenergy activity and was established by the activity leader and participants of the Combustion activity. The work has been funded nationally, grants raised by the participant in each of the countries.

2. ROUND ROBIN EXPERIMENTS

The selected wood stove used in the round robin test was a JØTUL 3TDCI-2 stove equipped with a catalytic afterburner. A schematic drawing of the stove is given in Fig. 1. If properly ignited, the catalytic afterburner will oxidise unburned flue-gas compounds leaving the combustion chamber at flue-gas temperatures down to about 400K. This was established by measuring the flue-gas temperature before and after the catalytic afterburner. The by-pass is kept open if the stove is loaded in cold condition until the

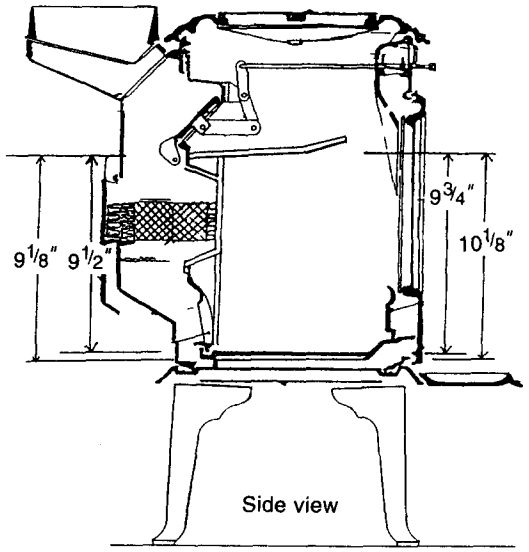

Fig. 1. Schematic drawing of the tested stove, JØTUL 3TDCI-2.

flue-gas temperature is high enough to ignite the catalytic afterburner, and the draft is high enough to prevent smoke from flowing into the room when the additional pressure drop due to the catalytic afterburner is introduced. The by-pass is then closed. The flue gases are mixed with secondary air before entering the catalytic afterburner. The catalytic afterburner used in this work was a honeycomb design, delivered by Corning Glass Works and installed by the stove manufacturer, and is an oxidising catalytic afterburner.

The most important test conditions are given in Table 1. The emission levels reported from the respective countries were given in different units and are based on national standards, test procedures and calculation procedures used in the respective countries. In order to directly compare the emission levels, the reported emission levels were re-calculated by the respective countries to g/kg dry fuel. National emission limits and reported emission levels in g/kg from this work are given for CO in Table 2, particles in Table 3, hydrocarbons in Table 4 and NO_x in Table 5.

2.1. *CO emissions*

All countries, except U.S.A., have reported CO emission levels. The U.S.A. has standards for measuring CO emissions, but the test is a commercial test where restrictions are given only on the particle emission level. U.K. measured the transient volumetric CO emission level in the flue gas, however, they did not

Table 1. Test conditions

	Norway	Netherlands	Sweden	Finland	Austria	Canada	U.K.	U.S.A.	Denmark
Having national emission standards	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Fuel	Spruce	Lariks	Fuel wood	Birch	White beech	Douglas fir	Beech	Douglas fir	Birch
Fuel density in combustion chamber after loading (kg/m³)	112 ± 11	112 ± 11				112 ± 11		112 ± 11	
Continuous firing with several small loads during the test			X	X	X		X		X
Testing over one big load	X	X				X		X	
Natural draught	X	X	X	X		X	X	X	X
Chimney height (m)	4.5	4.5	5.0	4.5		4.5	5.5	4.5	4.5
Forced draught (Pa)					15				
Using a dilution tunnel	X	X			X	X		X	
CO measurements	X	X	X	X	X	X	X	X	X
Particle/tar measurements	X	X	X			X	X	X	
C_xH_y measurements	X	X		X	X				
NO_x measurements	X	X		X	X				
Efficiency measurements		X		X			X		X
Tests done at several average wood consumptions	X	X		X	X	X	X		
Test done at one average wood consumption			X	X					X
Moisture in fuel (weight %)	15	16	18	13	12	17	12–16/31.5	17	15–21

Table 2. CO emission limit and reported CO emissions

Country	National level	Recalculated reported values to g/kg fuel (dry basis)	Recalculated national level to g/kg fuel (dry basis)
Norway	[a]	21.8–32.3	[a]
Netherlands	[a]	8–27	[a]
Sweden	[a]	15.9	[a]
Finland (birch)	[a]	36.2	[a]
Finland (peat briquettes)	[a]	47.6	[a]
Austria	1100 mg/MJ[b]	8.69–18.78	19.4
Canada	[a]	10–23.8	[a]
U.K.	[a]	[c]	[a]
U.S.A.	[a]	[c]	[a]
Denmark	0.3% CO at 7.5% CO_2	7.9	32

[a]No national levels.
[b]From 1 January 1995 in the Styria area and from the beginning of 1997 for Austria as a whole.
[c]No reported values.

measure the flue-gas flow and it was, therefore, not possible to calculate the CO emission level in g/kg dry fuel.

Canada, the Netherlands and Norway have nearly the same standards and test procedures, but the fuel is different. The transient volumetric CO emission level is measured in the dilution tunnel in Norway, and in the chimney in Canada and the Netherlands. The procedure for calculating the emission level is, therefore, different. Figure 2 shows that there is a difference between the reported CO emission levels from these three countries. The results from the Netherlands and Norway show decreasing emission levels with increasing average fuel consumption, while the trend is opposite for Canada.

Denmark has restrictions on the CO emission level. The limit is 3000 ppm CO at 7.5 vol% CO_2. The reported level from Denmark was calculated to 7.9 g/kg dry fuel, which is below the CO emission limit in Denmark. In Austria there are regional standards for the Styria area. These standards are expected to be adopted nationally at the beginning of 1997, with a CO emission limit of 1100 mg/MJ. With the test fuel used in the Austrian test, this limit corresponds to 19.4 g/kg dry fuel. In Fig. 2 it can be seen that none of the three tests performed in Austria exceeded the desired national limit.

In Fig. 2 it can be seen that the smallest difference in the emission level is at an average fuel consumption of approximately 2 kg dry fuel/h. At lower average fuel consumptions, the difference in the reported levels increases. The CO emission level is below 50 g/kg dry fuel for all experiments performed or 2.5 g/MJ if 19.8 MJ/kg dry fuel is used as calorific heating value for wood. Finland and Sweden have performed their measurements at one average fuel consumption only. Finland has

Table 3. Particle emission limit and reported particle emissions

Country	National level	Recalculated reported values to g/kg fuel (dry basis)	Recalculated national level to g/kg fuel (dry basis)
Norway	5 g/kg and 10 g/kg[b]	1.5–5.6	5, catalytic; 10, non-catalytic
Netherlands	[a]	2–5	[a]
Sweden	40 mg/MJ	3.9	0.75
Finland	[a]	[d]	[a]
Austria	[a]	[d]	[a]
Canada	4.1 g/h and 7.5 g/h[c]	3.0–23.8	[e]
U.K. (12–16% H_2O in fuel)	5 g/h + 0.1 g/h per 0.3 kW	1.5–16	[5/(average fuel consumption)] + 1.89815
U.K. (31.5% H_2O in fuel)	[a]	3.3–5.3	[a]
U.S.A.	4.1 g/h and 7.5 g/h[c]	1.6–3.6	[e]
Denmark	[a]	[d]	[a]

[a]No national levels.
[b]5 g/kg (dry basis) for catalytic stoves, 10 g/kg (dry basis) for non-catalytic stoves.
[c]4.1 g/h (dry basis) for catalytic stoves, 7.5 g/h (dry basis) for non-catalytic stoves.
[d]No reported values.
[e]Not possible to re-calculate.

Table 4. C_xH_y emission limit and reported C_xH_y emissions

Country	National level	Recalculated reported values to g/kg fuel (dry basis)	Recalculated national level to g/kg fuel (dry basis)
Norway	[a]	4.6–6.1	[a]
Netherlands	[a]	1–4	[a]
Sweden	[a]	[b]	[a]
Finland (birch)	[a]	4.2	[a]
Finland (peat briquettes)	[a]	9.6	[a]
Austria	80 mg/MJ[c]	2.8–7.1	1.4
Canada	[a]	[b]	[a]
U.K.	[a]	[b]	[a]
U.S.A.	[a]	[b]	[a]
Denmark	[a]	[b]	[a]

[a]No national levels.
[b]No reported values.
[c]From 1 January 1995 in the Styria area and from the beginning of 1997 for Austria as a whole.

in addition reported CO emission levels using peat briquettes as fuel. While the CO emission level reported from Sweden is at the same level as for the other countries, the CO emission level reported from Finland is approximately twice as high.

2.2. *Particle/tar emissions*

Particle and tar emissions are reported from Canada, the Netherlands, Norway, Sweden, U.K. and U.S.A., and are shown in Fig. 3. Canada, the Netherlands, Norway and U.S.A. use nearly the same procedure for measuring the particle emission level: the filter system collecting the particles in a dilution tunnel. The Swedish standard demands that the particles have to be separated into tar and particles when they are reporting. The values reported in this work are the sum of these two. Sweden collects the tar and particles from the chimney using a glass-fibre filter, while U.K. uses an electrostatic precipitator at the top of the chimney.

The trends for Canada, the Netherlands, Norway and U.S.A. are similar. However, the particle emission level reported from Canada is higher than the particle emission level reported from the other three countries. Canada, Norway, Sweden and U.K. have introduced restrictions to the particle/tar emission level. In Sweden the emission limit is 40 mg/MJ, which corresponds to 0.75 g/kg dry fuel, using the reported calorific value of 18.63 MJ/kg. In Fig. 3 it can be seen that the reported tar emission level is about five times higher than the emission limit in Sweden.

In Canada, Norway and U.S.A., the particle emission limit is based on a weighted value from four runs. The particle emission level reported from Norway is 2.9 g/kg dry fuel, which is lower than the emission limit of 5 g/kg for stoves equipped with a catalytic afterburner. The particle emission level reported from Canada is 10 g/h, which is higher than the emission limit of 4.1 g/h for stoves equipped with a catalytic afterburner. Finally, the emission limit in U.S.A. is the same as the Canadian limit. The reported particle emission level from U.S.A. is 3.6 g/h and, therefore, below the emission limit.

Table 5. NO_x emission limit and reported NO_x emissions

Country	National level	Recalculated reported values to g/kg fuel (dry basis)	Recalculated national level to g/kg fuel (dry basis)
Norway	[a]	0.4–0.6	[a]
Netherlands	[a]	0.4–0.6	[a]
Sweden	[a]	[b]	[a]
Finland (birch)	[a]	1.4	[a]
Finland (peat briquettes)	[a]	3.7	[a]
Austria	150 mg/MJ[c]	2	2.6
Canada	[a]	[b]	[a]
U.K.	[a]	[b]	[a]
U.S.A.	[a]	[b]	[a]
Denmark	[a]	[b]	[a]

[a]No national levels.
[b]No reported values.
[c]From 1 January 1995 in the Styria area and from the beginning of 1997 for Austria as a whole.

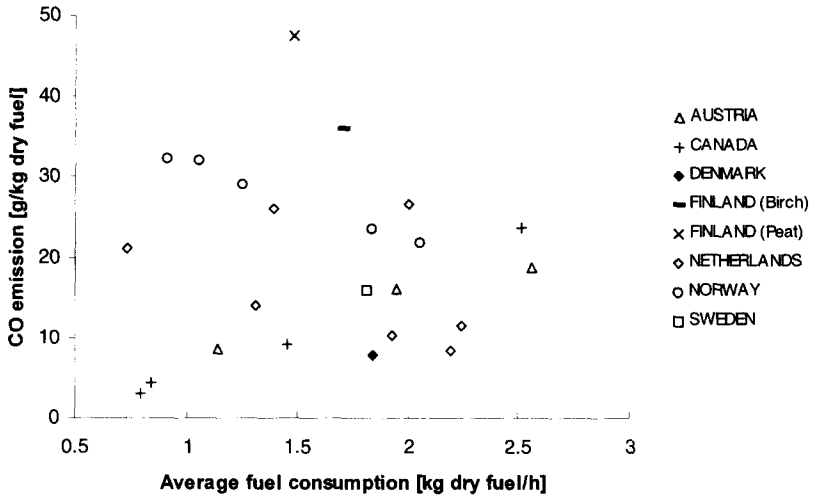

Fig. 2. CO emission levels reported from the round robin test.

The U.K. has restrictions if an appliance is submitted for consideration for acceptance for use in smoke-controlled areas under section 11 of the Clean Air Act, 1956. The Department of the Environment requires it to lie within the smoke emission limit set out in the British Standards document PD6434. The scope of this document is to provide guidance on domestic solid-fuel appliances designed to burn bituminous coal with reduced smoke emission. The document states that combustion of other solid fuels, including wood, should be included in its basic principles, while expecting that some details might not be applicable. PD6434 sets a smoke emission limit that can be expressed as 5 g/h + 0.1 g/h per 0.3 kW of the corresponding heat output. Using the reported calorific heating value of 20.5 MJ/kg dry fuel, we find that the emission level is higher than the emission limit below an average fuel consumption of approximately 1.5 kg/h using wood with a moisture content of 12–16 w%. When using wood with a moisture content of 31.5 w%, the reported particle emission level is around the emission limit, with some scatter in the results.

From Fig. 3 it can be seen that, with the exception of some reported values from U.K. and Canada, the reported emission values are below 6 g/kg dry fuel.

2.3. *Hydrocarbon emissions*

Hydrocarbon emissions are reported from Austria, Finland, the Netherlands and Norway, and can be seen in Fig. 4. Only Austria reports use of a written standard (VDI 3481). The other countries use common test procedures normally used for this type of measurement in their laboratories. With the exception of Finland, all

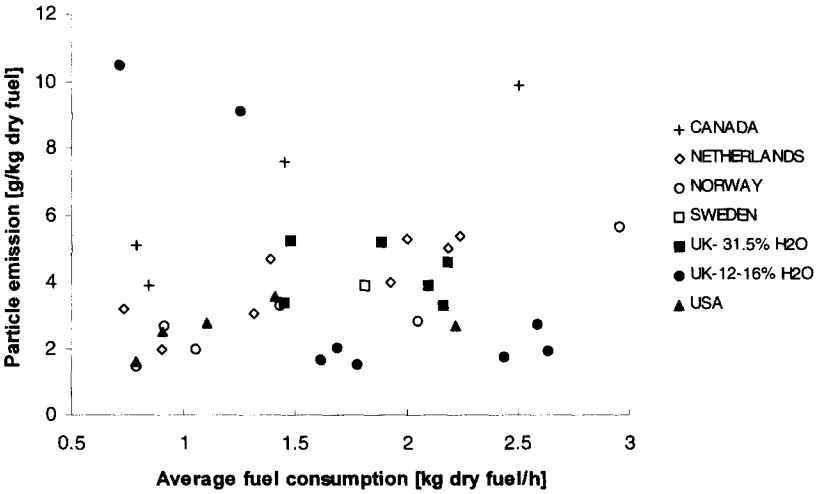

Fig. 3. Particle emission levels reported from the round robin test.