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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

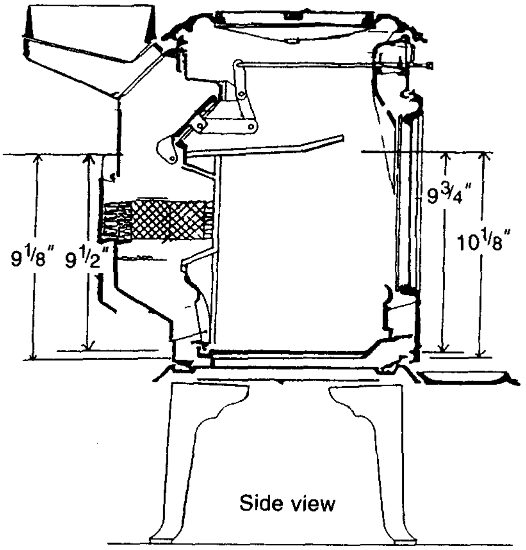

Fig. 1. Schematic drawing of the tested stove, JØTUL 3TDCI-2.

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/m^3)	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	
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.
[a] From 1 January 1995 in the Styria area and from the beginning of 1997 for Austria as a whole.

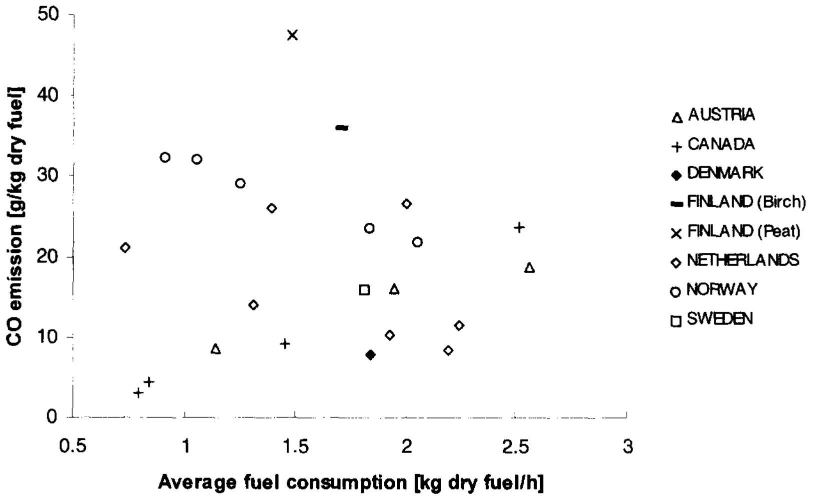

Fig. 2. CO emission levels reported from the round robin test.

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

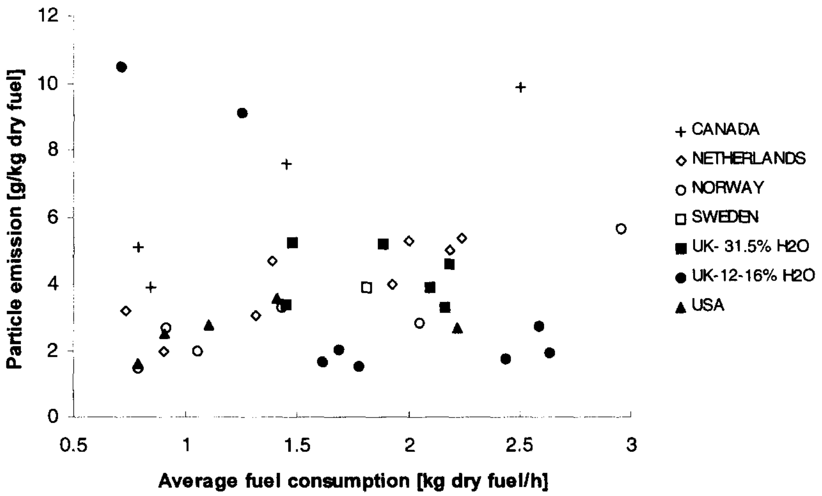

Fig. 3. Particle emission levels reported from the round robin test.

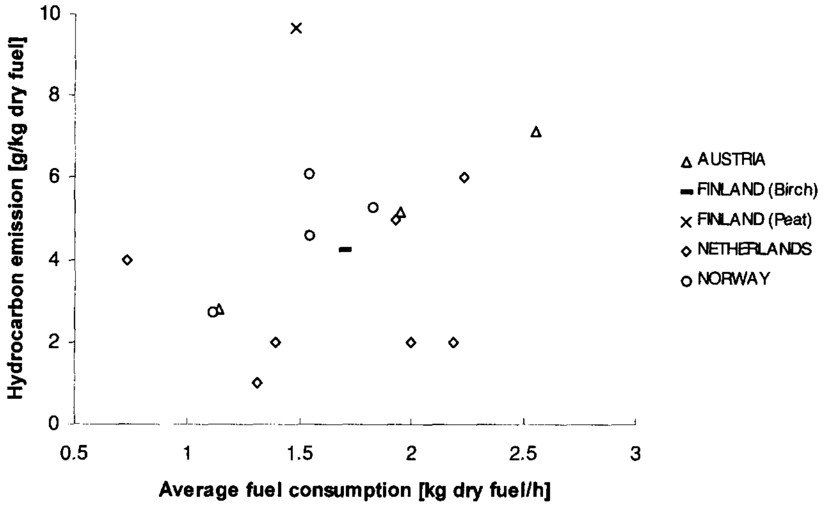

Fig. 4. Hydrocarbon emission levels reported from the round robin test.

countries use a hydrocarbon analyser that measures the total transient volumetric hydrocarbon emission level. All countries have performed their hydrocarbon measurements in the chimney. Finland used the FTIR technique and measured CH_4, C_2H_6, C_2H_2 and C_2H_4. The reported hydrocarbon emission level from Finland is the sum of these.

Only Austria (the Styria area) has an emission limit for hydrocarbons, The limit is 80 mg/MJ, which corresponds to 1.4 g/kg dry fuel. This limit will be the Austrian national limit from the beginning of 1997. In Fig. 4 it can be seen that the reported emission value from Austria is above the emission limit. Except for the reported emission level from Finland, using peat as fuel, all measured hydrocarbon emission levels are below 7.5 g/kg dry fuel. In Fig. 4 it can further be seen that the hydrocarbon emission levels increase with increasing average fuel consumption.

2.4. NO_x emissions

NO_x emission levels are reported from Austria, Finland, the Netherlands and Norway, and can be seen in Fig. 5. Only Austria reports using a written standard (VDI 3481). The other countries use common test procedures normally used for that type of measurement in laboratory studies. Only Austria (the Styria area) has an emission limit for NO_x. The limit is 150 mg/MJ, which corresponds to 2.6 g/kg dry fuel. This limit will be the national limit for Austria from the beginning of 1997. The reported NO_x emission levels from Austria are below 2 g/kg dry fuel. This is below the emission limit. Except

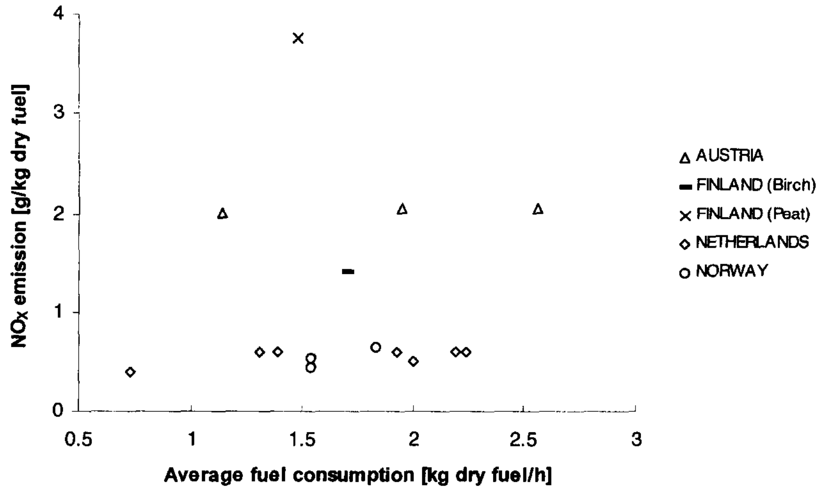

Fig. 5. NO_x emission levels reported from the round robin test.

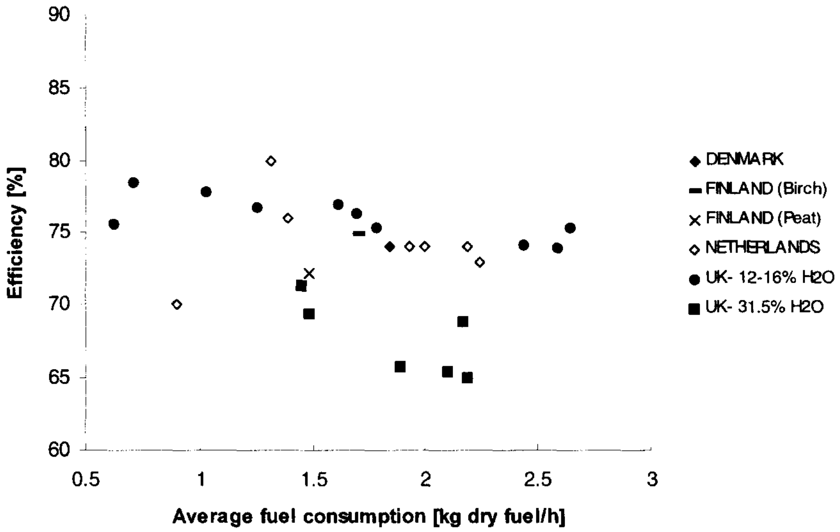

Fig. 6. Efficiency based on effective heating value, reported from the round robin test.

for the reported emission level from Finland, using peat as fuel, all reported NO_x emission levels are below 2.5 g/kg dry fuel. The high NO_x emission level using peat as fuel is due to the much higher nitrogen content in peat compared with wood.

2.5. *Thermal efficiencies*

Thermal efficiencies are reported from Denmark, Finland, the Netherlands and U.K. The obtained thermal efficiencies are based on indirect methods. Only Denmark (DS 8887-2) and the U.K. (BS 3250, Part 1, 1993) have national standards and test procedures for the reported thermal efficiencies. Finland and the Netherlands use common test procedures normally used for that type of measurement in laboratory work. The thermal efficiencies are plotted in Fig. 6 based on effective heating value. Denmark has put restrictions to the efficiency calculated on effective heating value. This efficiency has to be above 70%. The reported thermal efficiency from Denmark is above this limit.

2.6. *Leakage tests*

The tested stoves from Austria, Canada, Finland, Norway, the Netherlands, Sweden and U.K. were returned to SINTEF (Norway) for investigation of damages and leakage. No damages were observed. However, there were considerable differences in leakage. The leakage

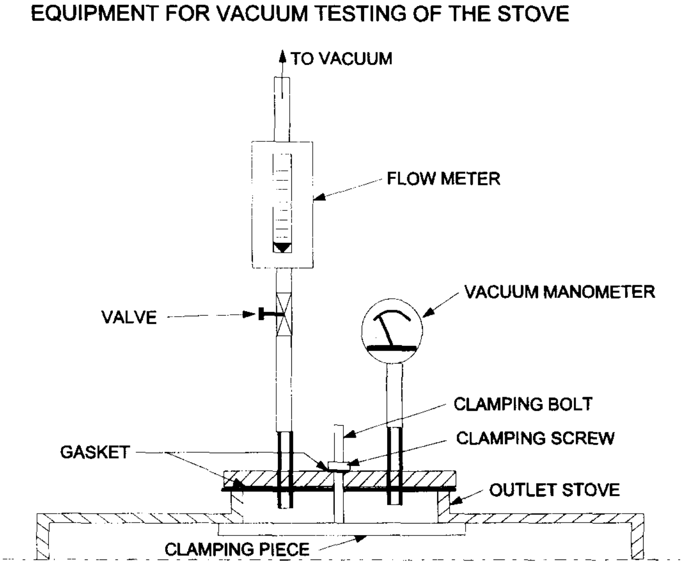

Fig. 7. Equipment for vacuum testing of the stove.

Table 6. Leakage testing

	Leakage of the stove in m^3/h at 20 Pa vacuum	Leakage of the by-pass damper in m^3/h at 20 Pa vacuum and closed stove door	Leakage of the by-pass damper in m^3/h at 20 Pa vacuum and open stove door
Norway	12.2	4.1	4.4
Netherlands	13.0	8.4	8.9
Sweden	8.5	2.1	2.3
Finland	11.4	2.4	2.5
Austria	11.8	4.5	5.0
Canada	12.8	3.9	4.0
U.K.	11.9	1.2	1.2

tests were performed at 20 Pa vacuum. The test facility is described in Fig. 7. Three tests were run with the primary air valve closed. The valve was opened and closed between each test. The average value from these three tests, in m^3/h at 20 Pa, is reported in Table 6. The leakage through the by-pass damper, in m^3/h at 20 Pa, was checked by blocking the channel where the catalytic afterburner was placed. This test was performed both with the stove door open and closed, and a somewhat higher leakage was measured with the stove door open. These results are also given in Table 6.

The leakage tests revealed a considerable difference in leakage. Leakage in the by-pass damper influences the emission level, since the flue gas does not go through the catalytic afterburner. However, the tests were done at 20 Pa vacuum. This is much higher than the pressure drop over the by-pass damper when running the actual emission tests. Comparing the emission levels from all tests, it cannot be concluded that the differences between the different countries only occur due to the differences in leakage. This can be illustrated by comparing the emission levels from Canada and the Netherlands. They have used nearly the same test methods. The by-pass leakage from the stove tested in the Netherlands is more than twice as high as is the case for the stove tested in Canada, while the reported particle emissions from the stove tested in Canada is much higher compared with those reported from the Netherlands. This eliminates any speculation that a large by-pass leakage should be the reason of the large particle emission levels reported from Canada.

3. ROUND ROBIN CALCULATIONS

To reveal the influence of different calculation procedures on reported emission levels, a study was carried out to investigate the influence of: (1) the use of different spreadsheet models to convert averaged volumetric levels emission values into average emission levels in g/kg dry fuel; and (2) the use of arithmetic averaged measured emission values versus weighted averaged emission values. Since the JØTUL stove is not equipped with a fan, the flue-gas flow will vary continuously, as will the emission levels. This may lead to a significant difference in the emission levels, since peak emissions of CO and hydrocarbons usually occur in specific periods of the combustion cycle, in contrast to the NO_x emissions.

3.1. *Comparison of different spreadsheet models*

Spreadsheet models used for the conversion of averaged volumetric emission levels into average emission levels in g/kg day fuel, were collected from Austria, Finland, Norway and Sweden. Using input values collected from 17 experiments performed with the JØTUL stove at SINTEF in Norway, covering a wide range of heat outputs and emission levels, a comparison was done to investigate the influence of different spreadsheet models on the reported emission levels.

All spreadsheet models are derived from an elementary combustion equation. Dependent of the specific demands of the standards for each country, a number of different outputs are calculated. All four countries reported CO emissions in g/kg dry fuel, and the CO emission level was, therefore, used in the comparison. Since the Norwegian spreadsheet model was found to be the most comprehensive, taking into account effects that were not considered in the other spreadsheet models, it was chosen as the reference spreadsheet model. Percentage deviations in the reported CO emission level compared with the reference spreadsheet model are given in Fig. 8. The other three countries are referred to as 1, 2 and 3 in no specific order. First, the spreadsheet models were used as received, and the deviation in the CO emission level compared with the reference spreadsheet

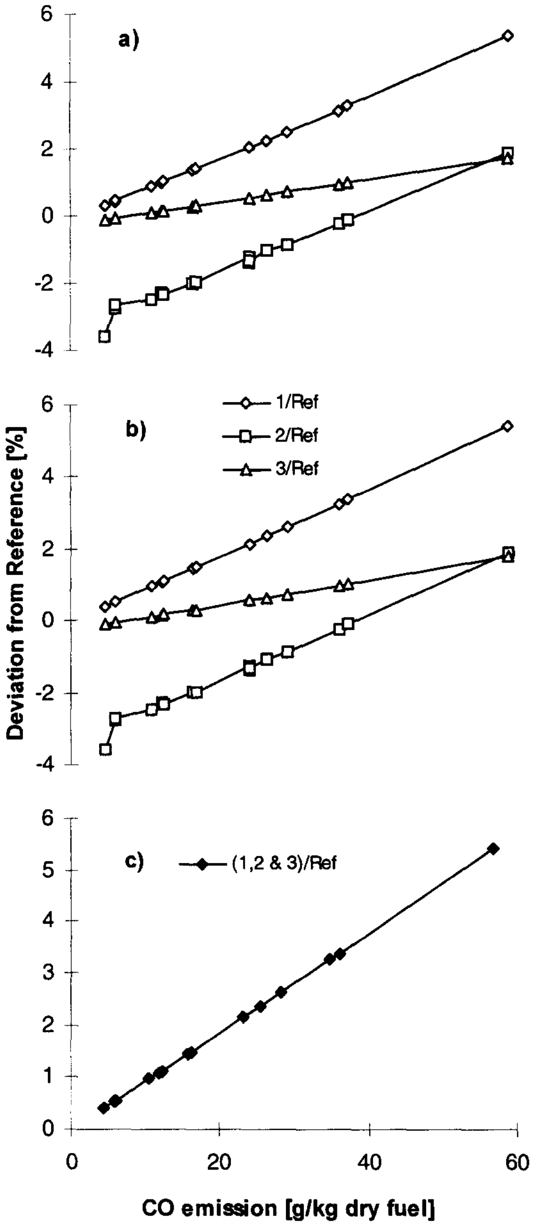

Fig. 8. Comparison of spreadsheet models from Austria, Finland, Norway and Sweden.

model can be seen in Fig. 8(a). As can be seen, the maximum deviation does not exceed 6%. Secondly, spreadsheet model constants, such as molar volumes, air composition and molecular weights were set equal. The effect of these differences did not have any significant influence on the results, as can be seen in Fig. 8(b). Hence, significant deviations with respect to the CO emission level will also be valid for hydrocarbons and NO_x. Thirdly, the effect of different methods to calculate the excess air ratio and the dry flue-gas flow was investigated. None of the three countries took into account the CO emission level when calculating the excess air ratio and the dry flue-gas flow. Except for this, country 1 did the calculations correctly. By upgrading the calculation procedures for the excess air ratio for country 2 and the excess air ratio and the dry flue-gas flow for country 3, identical CO emission levels were obtained. This can be seen in Fig. 8(c). However, a significant deviation compared with the reference spreadsheet model still remained. This deviation increased linearly with increasing CO emission level and was due to the effect of not including the CO emission level when calculating the excess air ratio and the flue-gas flow. Hence, by assuming complete combustion when relatively high CO emission levels exist, a significant error is introduced. If high hydrocarbon emission levels also exist, this should also be taken into account in the spreadsheet models when calculating the excess air ratio and the dry flue-gas flow. However, none of the four countries took this into account in their spreadsheet models.

3.2. *Comparison of averaging methods*

The reference spreadsheet model used in section 3.1 is part of a program package, WOODSIM, developed for batch-wood stove combustion at SINTEF in Norway. The emission levels used as input in the reference spreadsheet model are weighted average volumetric emission levels, taking into account the transient behaviour of the batch combustion process. During such a process, the fuel composition and the flue-gas flow changes continuously, together with emission levels. By measuring the transient wood consumption, and using the transient CO_2 and CO emission levels as input, a spreadsheet model can be developed based on the same set of equations used in the reference spreadsheet model. In addition, the transient empirical models for drying and the fuel composition are needed.

Peak emissions of CO and hydrocarbons usually occur in specific periods of the combustion cycle. Usually, there will be peak emissions of CO at the beginning of the volatile combustion phase and at the end of the char combustion phase. The dry flue-gas flow must be used when converting the transient volumetric emission levels to weighted average volumetric emission levels if the CO emission levels are measured on dry basis. The wet flue-gas flow must be used if the transient volumetric emission levels are measured on wet basis. Only

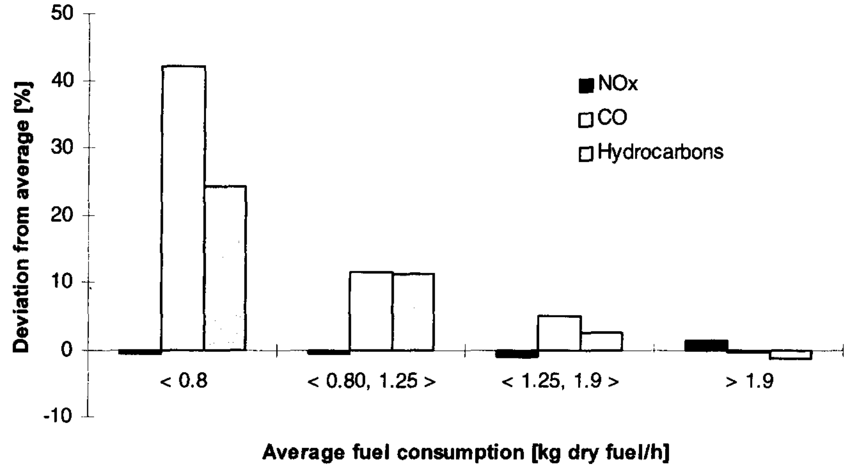

Fig. 9. Weighted versus arithmetic averaged input values.

arithmetic averaging of the transient volumetric emission levels can be used to calculate the average volumetric emission level, if the transient flue-gas flow has not been measured or calculated.

To investigate the effect of these two methods of averaging on the calculated average emission levels in g/kg dry fuel, both arithmetic and weighted averaging of the transient volumetric emission levels were performed, using the same 17 experiments as in section 3.1. The average volumetric emission values were then used as input in the reference spreadsheet model. The 17 experiments were divided into four groups of average fuel consumption and the average percentage deviation for each group, using the arithmetic averaging approach compared with the weighted averaging approach, is given in Fig. 9 for CO, hydrocarbons and NO_x. As can be seen, the deviation is significant for both CO and hydrocarbons, and the deviation increases with decreasing average fuel consumption. The deviation is small for NO_x, which is consistent with the relatively steady transient volumetric emission level of NO_x in batch-wood stove combustion.

The increasing deviation with decreasing average fuel consumption can be explained by looking at the average percentage deviation between the transient and average dry flue-flow for the 17 experiments, divided into the same four groups of average fuel consumption as a function of percentage dry fuel consumed. This is shown in Fig. 10. As can be seen, the deviation increases with decreasing average fuel consumption, and the largest deviations can be found in periods of the combustion

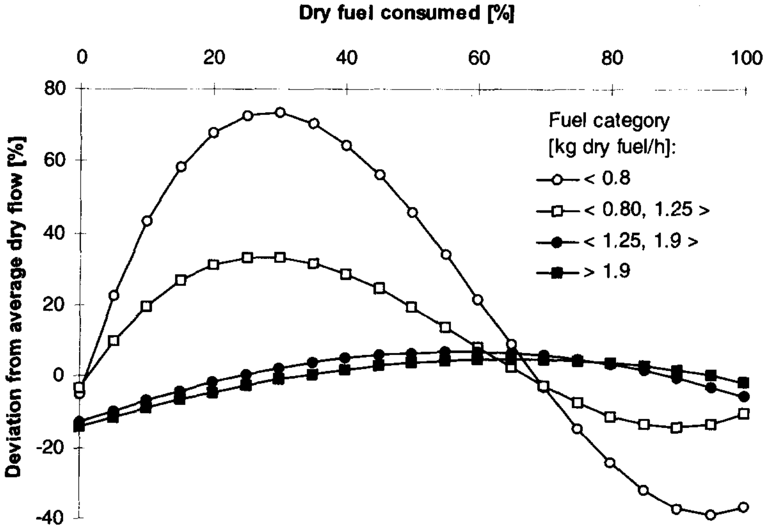

Fig. 10. Deviation between instantaneous and average dry flow.

cycle where peak emissions of CO and hydrocarbons usually exist at low average fuel consumptions. This explains the results shown in Fig. 9.

4. TRANSIENT PARTICLE AND HYDROCARBON MEASUREMENTS

In addition to the round robin test, detailed transient particle and hydrocarbon emission measurements were performed at SINTEF/NTNU. These measurements reveal a close relationship between particle and hydrocarbon emissions. Particles in the flue gas may consist of condensed heavy hydrocarbons, soot particles and fly ash. Figure 11 shows the transient particle and hydrocarbon emission level in g/kg dry fuel as a function of percentage dry fuel consumed for two experiments with a traditional wood stove, which is not equipped with a catalytic afterburner. As can be seen, the particle emission level follows the hydrocarbon emission level quite closely.

Using 10 experiments where hydrocarbon emission levels were measured, out of the 17 used in the spreadsheet model comparison in section 3, a study was performed to investigate the ratio between the average particle and hydrocarbon emission level. This ratio is shown in Fig. 12(a) as a function of average fuel consumption in kg dry fuel/h, together with a linear trend line. The particle/hydrocarbon ratio is close to 0.3 for all experiments, and the trend line shows no significant dependence of the average fuel consumption. The average particle emission level in g/kg dry fuel is shown as a function of average fuel consumption in Fig. 12(b), and equally for the average hydrocarbon emission level in Fig. 12(c). There is a scatter in the position of the points, but still, the linear trend line shows an increasing average particle and hydrocarbon emission level with increasing average fuel consumption.

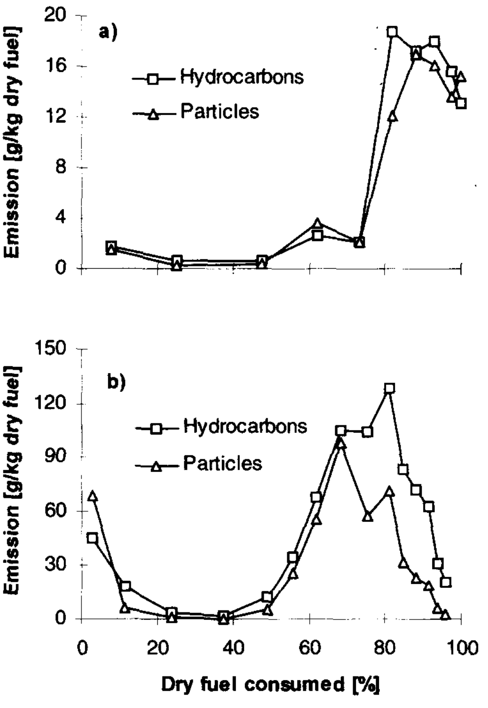

Fig. 11. Transient particle and hydrocarbon emissions for a non-catalytic stove.

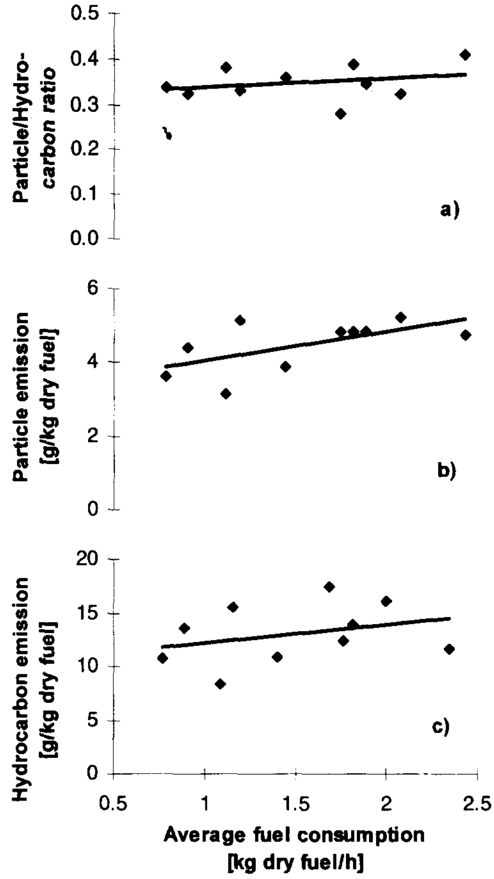

Fig. 12. Average particle and hydrocarbon emissions and the particle/hydrocarbon ratio.

From the results presented, the following conclusions can be derived: (1) The ratio between the average particle and hydrocarbon emission level is independent of the average fuel consumption and therefore, of the flue-gas flow, and indicates that fly ash is of minor importance; (2) both the transient and average hydrocarbon emission levels are either close to or higher than the particle emission level and indicates that only heavy hydrocarbons condense and form particles; (3) both the average particle and hydrocarbon emission level increases with average fuel consumption and, therefore, also with average combustion chamber temperature, and indicates that the residence time in the catalytic afterburner is too low at higher average fuel consumptions; (4) the difference in the ratio between the average particle and hydrocarbon emission level indicates that heavy hydrocarbons account for the main part of the total hydrocarbon emission level in the traditional wood stove, and lighter hydrocarbons in the wood stove equipped with a catalytic afterburner; and (5) particle and hydrocarbon emissions are not limited to the volatile combustion phase, the major part of the particle emission may be emitted in the char combustion phase, even for traditional stoves.

5. DISCUSSION

This work has shown that considerable differences exist in the reported average emission levels in g/kg dry fuel in the round robin test. This is due to several reasons. However, by analysing the results, the importance of the different factors can be found. The analysis is based on the reported emission levels of CO, particles and hydrocarbons from all countries except Canada and U.K. The results from Canada and U.K. were left out since some of the reported emission levels from these two countries were found to be inconsistent with the results from the other countries, as discussed previously.

The remaining reported emission levels for CO, particles and hydrocarbons were plotted as a function of average fuel consumption in kg dry fuel/h, as shown in Fig. 13. In addition, exponential trend lines and curves representing ±30% deviation from the trend lines were plotted.

As can be seen, there is still a considerable scatter in the emission levels for CO, only 4 of 18 reported emission levels lie within the 30% deviation curves. The trend line shows an increasing emission level with decreasing average fuel consumption. This is opposite to the trend shown for particles and hydrocarbons. The scatter in the emission levels for particles is much lower than for CO, with 15 of 19 reported emission levels lie within the 30% deviation curves. For hydrocarbons, the scatter in the emission levels is similar to the CO behaviour, with only 3 of 14 reported emission levels being within the 30% deviation curves.

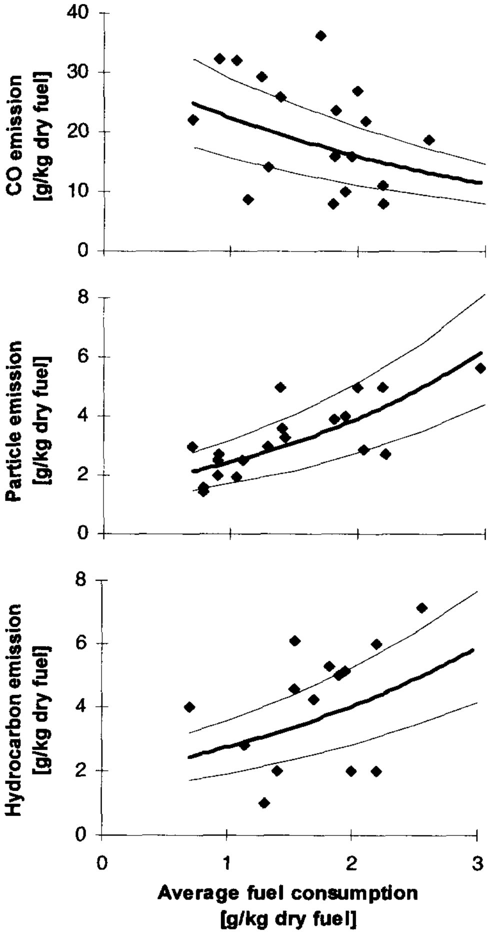

Fig. 13. Average CO, particle and hydrocarbon emission levels from the round robin test, including exponential trend lines (thick lines) and curves representing ±30% deviation from the trend lines.

Performing the same analysis, but only using the reported emission levels from the Netherlands, Norway and U.S.A., which have comparable standards, should reveal if differences in the standards are of great importance. Now, 6 of 12 emission levels for CO, 14 of 18 emission levels for particles and 0 of 10 emission levels for hydrocarbons lie within the 30% deviation curves. Hence, the curve fit result improves for CO, decreases slightly for the particles and gets much worse for the hydrocarbons.

This leads to the following conclusions: (1) the differences in the standards do not seem to be causing the considerable differences in the reported average emission levels in g/kg dry fuel the round robin test; (2) particle emission measurements are the most optimal method for evaluating the environmental acceptability of the tested stove; and (3) CO emission measurements do not give a good indication of the total emission level of harmful air pollution compounds for the tested stove since the particle and hydrocarbon emission levels may be high when the CO emission level is low.

Differences in calculation procedures may be of significant importance, as shown in this work. Flow measurements or calculations are necessary to convert transient volumetric emission levels into average emission levels in g/kg dry fuel. To be able to do this conversion correctly, the transient dry flue-gas flow must be used if the volumetric emission levels are measured or calculated on dry basis. Differences in calculation procedures and flow measurements may explain the increased scatter in the reported emission levels for CO and hydrocarbons compared with the particles, since the particle emission measurements are not dependent of complex calculations or flow measurements.

Leakage may be an important factor, as shown in this work, but no direct correlation was found between high emission levels and large leakage. A proper ignition of the catalytic afterburner is important, and the efficiency of the catalytic afterburner may vary due to differences in surface conditions and test conditions. Finally, laboratory conditions, such as human error introduced when determining the weight of the particle filters before and after the test, may introduce significant uncertainties. Together, these factors could be the explanation of the deviation in the particle emission results.

The use of different gas analysis techniques may introduce different levels of uncertainty in the measured emission levels, but this factor is believed to be of minor importance since most gas analysers operate with an uncertainty of 2% or better of the peak value in the measurement range chosen. However, care should be taken to use the lowest measurement range possible to avoid large uncertainties.

6. CONCLUSIONS

Austria (the Styria area), Canada, Denmark, Norway, Sweden, U.K. (smoke-controlled areas) and U.S.A. have reported national emission limits, while Finland and the Netherlands have not. The stove passed the national test standard in Denmark, Norway, U.K. (for medium and high heat output) and U.S.A. For U.K. this means an average fuel consumption above 1.5 kg dry fuel/h. The hydrocarbon emission level reported from Austria was above the emission limit. However, the CO and NO_x emission levels were below the emission limit. The Canadian tests did not give an acceptable result, which is unexpected since the Canadian test standard is similar to the test standard used in U.S.A., where the stove passed with good margin. The tar emissions measured in Sweden were above the emission limit. All together, this leads to the following conclusion: the environmental acceptance of a specific wood stove, based on emission testing in different countries, gives a random outcome.

The reported CO emission levels are below 50 g/kg dry fuel for all countries. The reported particle emission levels are below 6 g/kg dry fuel, with the exception of a few reported values from Canada and U.K. The reported hydrocarbon emission levels are below 7.5 g/kg dry fuel, except for one reported level from Finland, using peat as fuel. Finally, the reported NO_x emission levels are below 2.5 g/kg dry fuel, except from one reported value from Finland, using peat as fuel.

The standards, test procedures and calculation procedures are of fundamental importance in the work to test low emission stoves. Differences may result in different evaluation and conclusions regarding the emission level. As shown in this work, particle emission measurements are the best method to evaluate the environmental acceptability of the tested stove, since uncertainties connected to calculation procedures and flow measurements are eliminated. Standards which evaluate a stove based only on CO emission measurements may give a green light for a stove which has considerable amounts of particle and hydrocarbon emissions, and these compounds are without doubt more harmful than CO.

Standards which only take into consideration emission levels at one average fuel consumption give a poor basis for evaluation of the stoves heat output range (average fuel consumption range), since many wood stoves originally designed to operate in a medium or high heat output range are used in a low heat output range instead. The total emission level usually increases exponentially with decreasing average fuel consumption for wood stoves not equipped with catalytic afterburners. However, the stove tested in this work was equipped with a catalytic afterburner, and showed an increasing particle and hydrocarbon emission level with increasing average fuel consumption. This is believed to be caused by a decreasing residence time in the catalytic afterburner when the average fuel consumption increases.

Transient particle emission measurements have revealed a close relationship between particle and hydrocarbon emissions. However, this relationship is not the same for all stove designs. Emissions of particles, hydrocarbons and also CO are not limited to the volatile combustion phase. Significant emission levels of these compounds are found also in the char combustion phase. Up to now, all effort has been directed towards emission reduction in the volatile combustion phase, resulting in very low emission levels of unburned compounds. In the future, the challenge will be to develop wood stoves with low emission levels of unburned compounds also in the char combustion phase.

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