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Performance Evaluation of a Modern Wood Stove Using Charcoal

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Abstract

Modern wood stoves can achieve high efficiency and relatively low levels of harmful emissions. However, controlling wood logs' combustion remains challenging, and the emission levels of unburnt compounds are generally higher than for e.g. wood pellet stoves. One solution is to upgrade the fuel quality, enabling a more stable combustion process. Thermal upgrading of wood through carbonization yields the highest achievable quality of solid fuel from wood. In this work, two types of charcoal were tested in a commercially available wood stove at various loads, with and without a retrofitted custom-design catalytic converter. The test procedure was adapted from the Norwegian test standard NS 3058 for higher repeatability and comparison with existing data. Emission levels were continuously measured using both a conventional- and a FTIR gas analyser. Particle emissions were measured both using a dilution tunnel with a total filter and an Electric Low Pressure Impactor (ELPI).
The test results show that for the selected stove, without any modifications, the emission performance for most of the measured compounds was in a similar range to wood logs. CO emissions were significantly higher, though with the addition of a catalytic converter, measured CO emissions could be cut by 74-83% on average. The test campaign demonstrates that combustion stability improvement and reduced heat output throughout a longer combustion time can be achieved by using charcoal in a wood stove, but highlights the need for both design and operational changes to reach commercial solutions.

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Keywords: Charcoal, Carbonization, Emissions, Wood stove, Catalytic converter, Operational stability

1. Introduction

Emissions of particulate matter (PM) and harmful gases from combustion are a great concern due to their negative effects on health and environment [1-4]. Emissions from residential wood combustion are known to present a large

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range in available emission factors due to the variety of combustion technologies, fuel quality, operating conditions and emissions analysis methods.

Modern wood stoves can achieve high efficiency and relatively low levels of harmful emissions. However, controlling wood logs' combustion remains challenging, and the emission levels of unburnt compounds are generally higher than for e.g. wood pellet stoves. Applying advanced control systems, automatically regulating the air amount and distribution is one method to decrease the emissions of unburnt compounds further. Another solution is to upgrade the fuel quality, enabling a more stable combustion process. Thermal upgrading of wood (e.g., torrefaction, carbonization) yields improved fuel qualities [5, 6].

In addition, one can also consider the implementation of a catalytic converter at the stove outlet, which has the potential to further reduce emissions of unburnt compounds (e.g., CO, organic compounds, PM) [7, 8]. The reduction is based on the oxidation of gaseous and PM pollutants promoted by catalytic transition metal surfaces.

The general approach of the present work was to use charcoal in an unmodified modern wood stove and to evaluate its performance in terms of emissions. Two types of charcoal were tested in a commercially available wood stove at various loads, with and without a retrofitted custom-design catalytic converter. The test procedure was adapted from the Norwegian test standard NS 3058 [9] for higher repeatability and comparison with existing data. Emission levels were continuously measured using both a conventional- and a Fourier transform infrared spectroscopy (FTIR) gas analyser. Particle emissions were measured both using a dilution tunnel with a total filter and an Electric Low Pressure Impactor (ELPI) yielding particle size distribution and number quantification.

2. Experiments

2.1. Fuel characteristics

Two types of charcoal are used in the experiments, with charcoal pieces of similar size: (1) a commercially available charcoal sold in 10 kg paper-bags as a barbecue charcoal, hereafter called CharA; (2) a charcoal provided by Elkem mainly used as a reductant in metallurgical industry, hereafter called CharB. The results of the proximate and ultimate analyses are given in Table 1.

2.2. Combustion technology

A conventional modern wood stove with a nominal effect of 4.75 kW is used for the experiments. According to manufacturer's specifications, its heat effect can be varied from 2 to 7 kW using wood logs and it can achieve up to ca. 80 % efficiency. Particulate emission of 4.76 $g.kg^{-1}$ dry wood was measured when testing it in accordance with Norwegian Test Standard NS3058-NS3059. Converted to 13 % O_2, emissions in the nominal operating range have been measured to 0.09 vol% CO, 111 $mg.Nm^{-3}$ NO_x and 238 $mg.Nm^{-3}$ C_nH_m. Flue gas temperatures at the appliance exit are within 200-250 ºC in the nominal operating range. It has one main air supply inlet underneath the stove, a top flue gas exit and a single air slide-regulator. The air slide-regulator has three main positions. (1) Fully open (high burn rate): primary air open (when lighting the stove), secondary air open (afterburning) and glass rinse open. (2) Half-way (medium burn rate): secondary air open (afterburning) and glass rinse open. (3) Closed (low burn rate): minimum secondary air inlet open (afterburning).

A custom-made platinum/palladium catalytic converter was used to actively reduce the CO emissions and test its influence on other emissions. It consisted of a honeycomb structure located in the stovepipe just above the wood stove. It was activated by electric DC current of 4 A and 75 V, yielding a total effect of 300 W. This enabled the catalytic converter to maintain a temperature above 200 ºC. It was only present when activated, and thus its presence may have had an effect on the draught and thus generated slight differences in the combustion conditions.

2.3. Emissions measurement instrumentation

A Servomex online gas analyser monitored the O_2 and CO_2 concentrations sampled from the stovepipe ca. 50 cm above the wood stove. A Gasmet FTIR was used for quantification of H_2O, CO_2, CO, NO, N_2O, NO_2, SO_2, NH_3, HCl, HF, CH_4, C_2H_6, C_2H_4, C_3H_8, C_6H_{14}, CHOH and HCN. The heated sampling system was connected to the stovepipe ca. 50 cm above the wood stove.

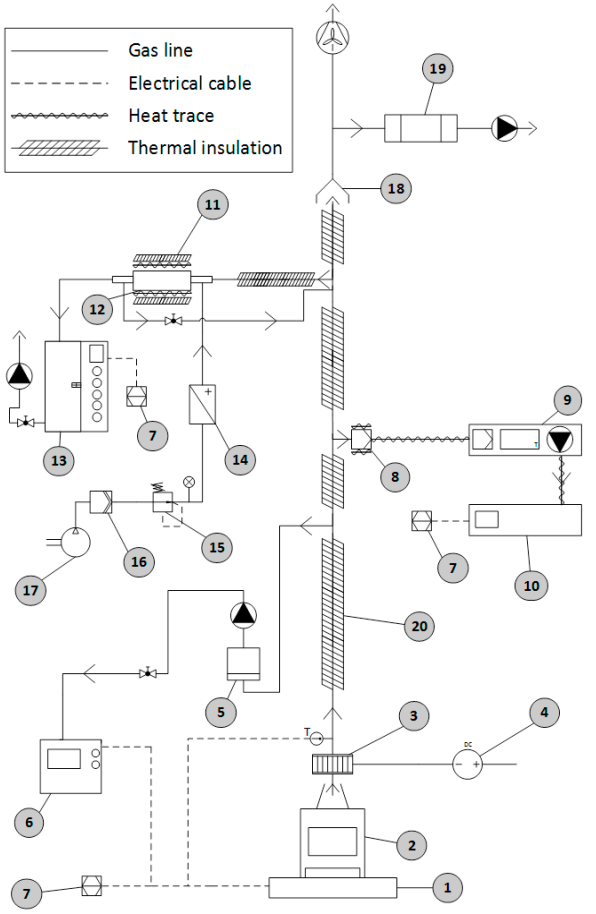

Figure 1: Schematic of the experimental setup. 1. Weight scale; 2. Modern wood stove; 3. Activated catalytic converter; 4. DC power supply; 5. Conventional filter; 6. Servomex online gas analyser; 7. Data collection; 8. Heated probe; 9. FTIR Sampling system; 10. FTIR gas analyser; 11. Heated jacket; 12. Sample gas diluter; 13. ELPI; 14. Air heater; 15. Pressure regulator; 16. Dust filter; 17. Pressurised air; 18. FFDT; 19. Total PM filter; 20. Stovepipe.

Table 1: Proximate and ultimate analysis of the tested charcoals. d.a.f.b.: dry ash-free basis; d.b.: dry basis; w%: weight percent. *: calculated by difference to 100.

Charcoal type	*CharA*	*CharB*
Volatile matter (w%, d.b.)	13.93 %	12.51 %
Fixed carbon (w%, d.b.)	79.43 %	85.40 %
Ash (w%, d.b.)	6.64 %	2.09 %
Moisture content (w%)	10.28 %	8.74 %
Effective heating value (MJ.kg^{-1})	27.2	27.2
C (carbon) (w%, d.a.f.b.)	85.69 %	84.50 %
H (hydrogen) (w%, d.a.f.b.)	1.96 %	2.02 %
N (nitrogen) (w%, d.a.f.b.)	0.54 %	0.48 %
*O (oxygen) (w%, d.a.f.b.)**	11.79 %	12.97 %
S (sulphur) (w%, d.a.f.b.)	<0.02 %	<0.03 %

PM were measured through two different methods: total PM through FFDT and particle size and number distribution through ELPI. The FFDT total PM measurement procedure is thoroughly described in NS 3058 [9], which is the test standard for enclosed wood heaters in Norway. The method relies especially on a dilution tunnel enabling to dilute and cool down the exhaust gas with ambient air to maximum 35 °C, at controlled and constant flow speed. The mass concentration of all PM, both solid particles and condensable gas, was captured by a glass fibre filter through an isokinetic sampler, over the whole test period. The FFDT total PM method enables to give a more realistic picture regarding the natural secondary PM formation mechanisms occurring after the chimney outlet, to account for the total PM released to the atmosphere [10, 11].

The concentration and size distribution of PM in the flue gas were measured by a Dekati ELPI. A partial stream of the flue gas was sampled through a stainless-steel probe located in the flue gas stack and diluted with air by a ratio of 1:8 prior to the ELPI inlet. The instrument is a real-time particle size analyser for monitoring aerosol particle size distribution and concentration. The ELPI measured the airborne particle size distribution in the range of 0.03 - 10 µm with 12 stages and a time resolution of 1 s. The nominal air flow was 10 Nl.min^{-1}, and the lowest stage pressure was 100 mbar. The ELPI operated at ambient temperature, while the gas sample was taken at a temperature varying between 80 and 110 °C. PM were separated and collected in the ELPI on sintered plates which were overlaid with an oil medium in order to prevent the collected particles from bouncing.

2.4. Experimental methods

The experimental test setup is shown in Figure 1. Exhaust gas from the wood stove flows through the activated catalytic converter (retrofitted only for a number of tests). Next, samples of the flue gas are taken through the stovepipe about 50 cm above the wood stove and independently directed towards the Servomex online gas analyser, the ELPI

and the FTIR system. On top of the stovepipe stands the inlet of the full-flow dilution tunnel (FFDT), where the flue gas is mixed with ambient air and flows through the FFDT at ca. 3.3 $m.s^{-1}$. This enables to create the conditions necessary for the isokinetic sampling of the total PM filter system, positioned on the FFDT sufficiently far from the inlet to consider the flue gas fully mixed with ambient air. The fuel consumption is controlled and logged through the weight loss recorded by a scale underneath the wood stove. A number of logged thermocouples and pressure transducers are located in the key parts of the experimental test setup to monitor the system.

A total of 14 experiments were performed to test the two types of charcoal, at three positions of the air inlet regulator rates (closed, half-way and open), with and without catalytic converter, including multiple tests at same conditions for assessing repeatability (cf. Tests #2-#4), as detailed in Table 2. The three positions of the air inlet regulator of the wood stove correspondingly affected the burn rate in the wood stove, which is known to have a significant influence on the total PM emitted through a combustion cycle [10, 12].

The experimental procedure was adapted from NS 3058 [9], starting with a pretest phase consisting of burning 2.0 kg of spruce logs with the air regulator fully open to bring the wood stove mass up to regular operating temperatures within 30-40 minutes. When only 250 g of hot charcoal remained from the pretest phase, the scale was zeroed and 1.0 kg of test charcoal was added and homogeneously arranged into the wood stove. The door remained opened for the first 2 minutes, and the air regulator remained fully opened for the first 5 minutes, to ensure that the charcoal was properly ignited. Then, the air regulator was adjusted to the tested position.

All measurements stopped when only 200 g of hot charcoal remained in the wood stove. Temperature measurements in the stack immediately before the test charcoal was inserted were on average 281 ºC ± 7.4 %, and 216 ºC ± 7.3 % on the top wall of the wood stove, indicating acceptable repeatability of the test start conditions.

3. Results and discussions

An overview of the general results is given in Table 2 and Table 3, with data arithmetically averaged over the whole test period. The key results, for CO and PM, are shown in Figure 2 and Figure 3. The test repeatability was evaluated throughout Tests #2-#4, all with CharA, air inlet regulator half-way and no catalytic converter. The average stack temperature during the test period was 162.2 ºC (435 K), within 1.4 % standard deviation. The average test period duration (combustion time of 800 g from an initial weight of 1000 g of charcoal) was 135 min, within 16.2 % standard deviation, while the output power was 2.4 kW within 15.0 % standard deviation. The concentration measurements for the main components of the exhaust flue gas gave on average (dry basis): CO_2: 2392 $g.kg^{-1}$ ± 0.66 % and CO: 179.7 $g.kg^{-1}$ ± 6.61 %.

Table 2: Experiment conditions and general results, delimited by series. d.b.: dry basis. [1]: Due to leakage in the total filter system.

Test #	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*	*#10*	*#11*	*#12*	*#13*	*#14*
Charcoal	CharA	CharA	CharA	CharA	CharA	CharA	CharA	CharA	CharB	CharB	CharB	CharB	CharB	CharB
Air regulator	Closed	Half-way	Half-way	Half-way	Open	Closed	Half-way	Open	Closed	Half-way	Open	Closed	Half-way	Open
Catalytic converter	No	No	No	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Average flue gas temperature (ºC)	141.4	166.6	153.7	150.8	125	243.8	244.7	228.8	136.2	165.3	174.4	214.9	216.4	220.1
Sampling time (min)	152	119	160	126	91	127	119	134	147	103	75	201	146	171
Burn rate ($kg.h^{-1}$ d.b.)	0.28	0.35	0.26	0.33	0.46	0.33	0.35	0.31	0.29	0.42	0.57	0.21	0.29	0.25
Power output (kW)	2.08	2.66	1.98	2.51	3.47	2.49	2.66	2.36	2.20	3.14	4.31	1.61	2.21	1.89
Total PM ($g.kg^{-1}$ d.b.)	7.40	2.86	6.17	2.10	2.71	4.58	3.86	2.70	3.53	3.55	4.93	4.30	3.09	NA[1]

Table 3: Main emissions measured in the flue gas averaged by series. W/o: without; w/: with; cat.: catalytic converter.

Emissions ($g.kg^{-1}$)	*#1-#5: CharA (w/o cat.)*	*#6-#8: CharA (w/ cat.)*	*#9-#11: CharB (w/o cat.)*	*#12-#14: CharB (w/ cat.)*
Total PM	4.6	3.7	4.0	3.7
CO	174.2	29.8	269.7	69.7
NO_x	2.35	2.75	1.31	0.99
NH_3	1.606	0.167	0.637	0.119
C_nH_m	11.0	9.17	9.81	5.17
SO_2	0.663	0.387	0.507	0.421

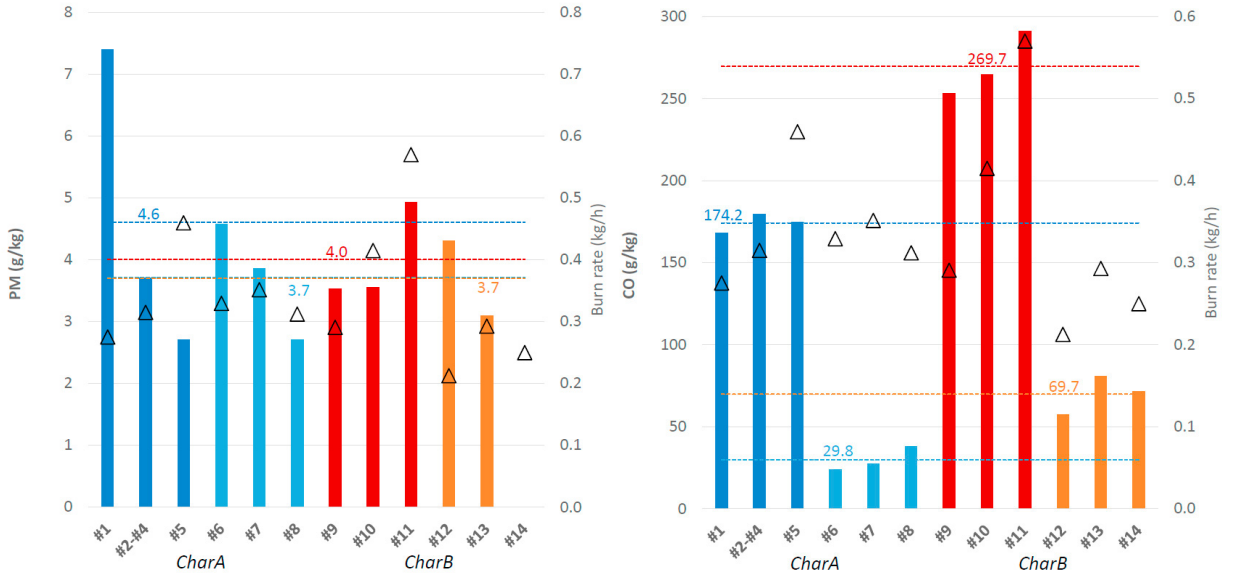

Figure 2: Total PM emissions measured (left, left y-axis) and CO emissions (right, left y-axis) in flue gas and corresponding burn rates (triangles, right y-axis) for all tests. Averaged total PM and CO emissions for each type of charcoal are displayed by the dash lines.

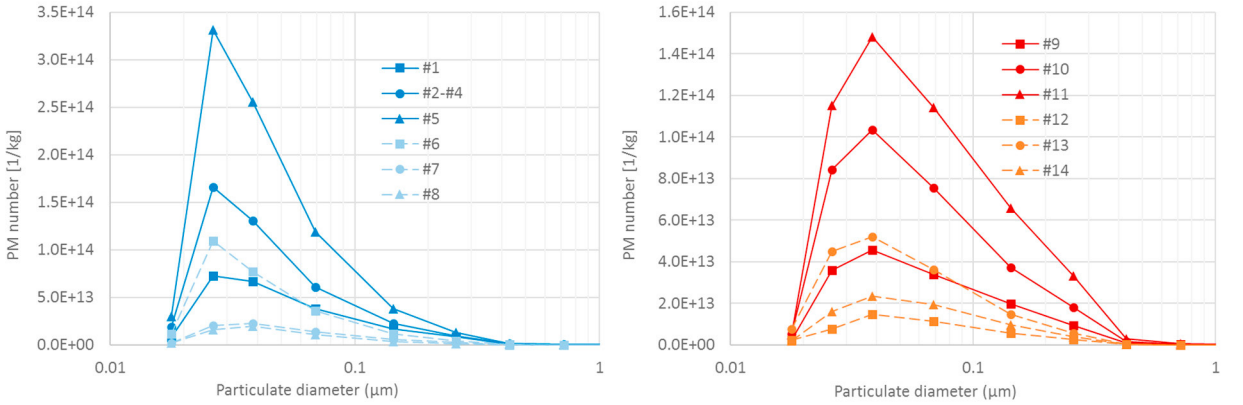

Figure 3: Particulate matter size distribution in particles number per kg of dry charcoal for CharA (left) and CharB (right). Results for tests without catalytic converter are displayed by solid lines, while those with catalytic converter are shown by dash lines.

The two types of charcoal achieved long burn times with low heat output. They both achieved relatively low total PM emissions (cf. Figure 2), in the range or lower than the manufacturer's reference with wood logs (4.76 g.kg^{-1} dry wood). The presence of the catalytic converter enabled a reduction of these emissions by 20 % and 7.5 % for CharA and CharB, respectively.

Char A and CharB led to relatively high CO emissions (cf. Figure 2), respectively 3 and 7 times higher than the manufacturer's reference with wood logs (0.09 vol%). These emissions justified the use of a catalytic converter, which effectively reduced CO emissions by 83 % and 74 % for CharA and CharB, down to levels close to the manufacturer's reference. CharB's 7.5 % higher fixed carbon content led to CO emissions that were 55 % higher on average, compared to CharA.

Large differences in measured emissions were observed between the two charcoal types, especially for nitrogen-containing species, though their nitrogen content is comparable. CharB, containing only 11 % less nitrogen by weight on dry basis compared to CharA, achieved 44 % lower NO_x emissions and 60 % lower NH_3 emissions on average (cf. Table 3).

As shown in Figure 3, the PM size distribution peaks in the nanoparticles range for both charcoals and is more evenly distributed for CharB and peaking to much higher levels for CharA, probably due to the higher contents of volatile matter and ash in CharA than in CharB.

Besides cutting CO emissions effectively, the catalytic converter reduced other emissions such as PM, C_nH_m, NO_2 and NH_3. The catalytic converter gave 5 to 10 times decrease in NH_3 emissions and a decrease in NO_2 emissions, while NO emissions increased. The number of PM was reduced by about 70 % for both charcoal types.

Another notable effect on the combustion process was its influence on the burn rate, which did not seem dependent on the air regulator as expected. The calculated burn rates were rather closer to the lowest burn rates achieved without a catalytic converter. The added pressure drop at the exhaust by restricting the flow in the channel with the catalytic converter may have affected the combustion processes and this effect should be investigated further.

4. Conclusions

Two types of charcoal were tested in a commercially available wood stove at various loads, with and without a retrofitted custom-design catalytic converter to investigate the feasibility of burning charcoal in an unmodified modern wood stove. Charcoal achieved long burn time with low heat effect compared to regular wood logs. Both charcoal types yielded relatively low PM emissions, high CO emissions and large differences for the other measured species, despite having relatively similar compositions. The addition of a catalytic converter effectively reduced the emission of CO, and also reduced emissions of PM, hydrocarbons, NO_2 and NH_3, while increasing NO emissions.

The combustion of charcoal in a wood stove has a potential for commercial applications, though it requires design and operational adaption, as well as possibly a catalytic converter to guarantee low CO emissions.

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Biography
Alexis Sevault is a Research Scientist in the department of Thermal Energy at SINTEF Energy Research (Norway). He obtained his PhD degree in 2012 on laser diagnostics for combustion at NTNU (Norway). He now works in the fields of small-scale solid biomass combustion and thermal energy storage.