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Reducing Emissions from Current Clean-Burn Wood Stove Technology by Automating the Combustion Air Supply and Improving the End-User Interaction – Two Important Primary Measures

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The current work concerns two of the most important primary measures to reduce emissions from small scale appliances for space heating; improvement and optimization of current technology and user behavior, where the latter is related to the effects of the ignition procedure, fuel quality and type, and amount of wood when loading and re-loading. Air-control both concerns user behavior and technology improvement. A recently developed in-house automatic air-control system was compared to manual operation. The ignition procedure is important and affects the quality of the combustion, not only for the ignition period itself but also for the subsequent burning periods. Two self-defined categories of primary measures were studied, primary measure A and B, as PMA (automated air flow) and PMB (manual operation varying the ignition procedure, wood specie, amount of fuel, log size and moisture content), respectively. Woodstove testing in our laboratory showed that for emissions related to primary measures, PMA, automating the combustion air reduced the particulate matter (PM) with **66%** applying the Norwegian test method**.** Using the European test method, automation increased the efficiency with **8%** and decreased PM, CO, and Organic gaseous compounds (OGC), with **12%**, **34%** and **55%**, respectively. Comparing nominal and high fuel loads with birch, at low burn rates, automation reduced PM and CO with **4%** and **61%**, respectively, for a fuel load of 1.2 kg. For a 1.8 kg fuel load, automation resulted in even higher reductions in PM, CO and OGC of **68%**, **52%** and **82%**, respectively. Automation also substantially decreased CO (**70%**) emissions when burning briquette presses. The effect of end-user operation as for the ignition from cold stove, and use of fuel with varying properties, as in PMB, showed significant variation in emissions over the ignition period. Good ignition, when firing according to the Norwegian standard, can be achieved repeatedly by assuring that the fuel catches fire before closing the door and/or reduce the primary/secondary air flows. Bad ignition due to over-/under firing and dense stacking, can produce at least twice as much PM and CO and 3-4 times the OGC, compared to correct ignition. No significant differences in emissions were found when comparing birch, spruce, and pine, for wood with equal moisture content. However, burning pine, showed higher emissions of total carbon particles, as elemental and organic carbon, on the same level as with poor ignition.

1. Introduction

Primary measures to reduce emissions from wood stoves include proper installation and maintenance of the stove, using dry, well-seasoned wood, and the use of certified stoves. Proper installation makes sure the stove is placed on a non-combustible surface and that there is adequate ventilation for proper combustion. Regular maintenance, such as cleaning the chimney and stovepipe, will also help reduce emissions. Using dry, well-seasoned wood will help reduce emissions because it burns more efficiently and produces less smoke. This can be done by storing the wood in a dry, covered area for at least six months before using it in the stove. Last, using certified stoves will also help reduce emissions. These stoves have been tested and certified to meet emissions standards set by the European union. By choosing certified stoves, consumers can be assured they are using a stove proven to reduce emissions. Overall, proper installation, maintenance, use of dry, well-

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seasoned wood and using a certified stove are primary measures to reduce emissions from wood stoves. Using wood logs as solid fuel in Norway has been decreasing since 2010 but has recently reawaken due to the steady increase in electricity prices since 2019 and now, because of the sudden jump related to the current European energy crisis. The Norwegian electricity grid has been gradually interconnected with Europe, meaning the price in Norway is increasingly following the cost of electricity in Europe. This especially concerns the southern part of Norway and less the middle and northern part, due to the lack of transport capacity of electricity from north to south. Between 2019 and today, using wood for residential heating increased with around 1.1 TWh, to 6.16 TWh. And the potential for wood-burning is formidable - according to the last user survey in 2016, the total stoves installed in Norway are around 2.6 million and assuming an average power of 6 kW per stove, a conservative estimate, this amounts to a total installed power of 15.6 GW. For comparison, the total installed hydropower capacity in Norway in 2022 is around 33.4 GW. What is concerning with this increase in wood consumption is the increase in related emissions, especially of particles (TSP), but also VOC/OGC, PAH, CO, BC and NOx. The emission of particles, mostly as PM2.5, from wood-burning in Norway in 2020 was around 15.000 tons as compared to 2.300 tons (as PM10) from road traffic, according to Statistics Norway. BC from wood-burning is assumed to contribute to around 30 % of all such emissions, VOC to about 12 %, PAH to about 1.5 %, CO to 23 % and NO_x to 1 %. The 21.3 % increase in wood consumption from 2019 to 2021 in Norway, then means an equivalent increase in emissions. For wood-burning appliances, immediate action should be taken not only regarding exchange of old stoves for modern ones, but also with primary measures regarding the advance in stove technology and the optimization of such. The current principle of using (poorly) pre-heated air and secondary combustion is approaching its limits regarding emissions. It can still be optimized to some extent but has no further potential to drastically reduce emissions, though these can further be reduced using secondary measures such as catalysts and various flue gas cleaning techniques. As for primary measures, stove design, several official recommendations exist (Du, 2020; Illerup et al., 2015; Janssens et al., 2020; Mack et al., 2017; Schön et al., 2012; Schwarzer et al., 2022). More "code of good practices" for wood-burning have been proposed since the last two decades, in most countries over the world both by manufacturers, organizations and government bodies e.g. ("Burnright," 2018; "How to Use a Wood Stove," 2023; UNECE, 2021; US EPA, 2013).

2. Methods and materials

Either of the two test standards (consists of a method and a procedure), the European one or the national test standard, were applied during the experiments, being the recently updated European standard (EN22) ("NS-EN16510-1:2022," 2022) one and the discontinued Norwegian standard (NS94) ("NS 3058-1/2:1994 and NS3059:1994," 1994), respectively. Two self-defined categories of primary measures were studied, primary measure A and B, as PMA and PMB, respectively. PMA involved testing a representative clean-burning cast-iron woodstove operated in either manual (see Figure 1 a1), a2)) or automatic (see Figure 1 b1), b2)) air-control mode, both according to either NS94, EN22 or a mix of both methods. PMB consisted of testing a representative clean-burning cast-iron woodstove operated in manual (see Figure 1 a1), a2)) mode according to real-life use with natural draft, by varying the ignition procedure, wood specie, amount of fuel, log size and moisture content. In addition to PM as NS94, other emissions (CO, OGC) were measured according to EN22.

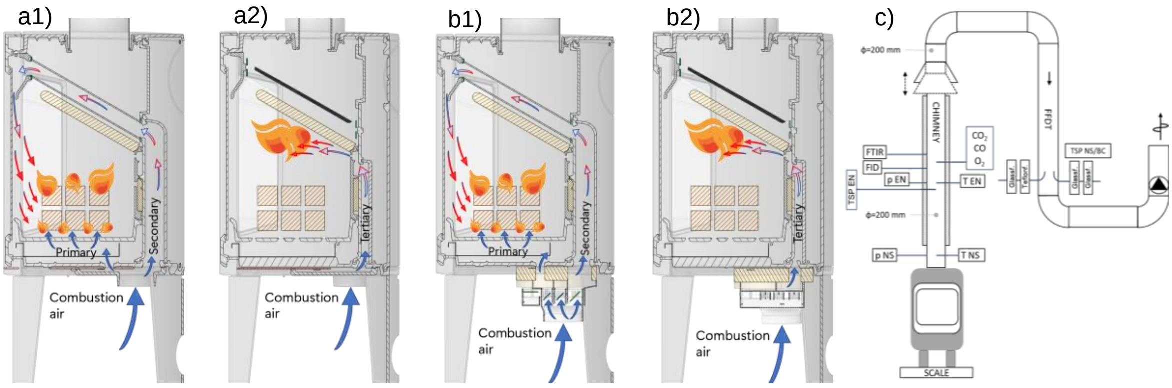

Figure 1: Typical cast-iron clean-burning woodstove used in Scandinavia, manual and automated version a1) Manual valves, primary and secondary air channels a2) Tertiary air channels b1) Automatic valves, primary and secondary air channels b2) tertiary air channels c) Woodstove test stand for separate/combined NS94/EN22 methods.

PMA: improving performance by automating the combustion airflow.
The stove, originally equipped with manual (one handle to run primary, secondary, and tertiary airflow) was adapted to an in-house automated airflow control system. This setup was used for testing acc. to NS94 and/or EN22, using both NS94 test fuel and EN22 birch logs with bark.
PMB: improving performance by varying ignition procedure, wood specie, amount of fuel, log size and moisture content.
Three wood species (birch, spruce, and pine) were tested in a representative cast-iron stove (see Figure 1 a1), a2)), using an in-house design to adjust the combustion airflows according to the outlet flue gas temperature. The test procedure when comparing emission, was to use natural draft in a 4.5 m high chimney (NS94), manual air-control and wood logs with bark. The ignition procedure was varied by studying the effect of time before closing the front door completely, wood specie, log size and number of logs, humidity, and amount of test fuel. The following variation was tested: pine 1.8 kg with 25% moisture, pine 1.2/1.8 kg with 15% moisture, spruce 1.2/1.8 kg with 16% moisture and birch 1.2 kg with 16% moisture.

2.1 Experimental setup

The experimental setup consisted of a combined test rig for both the NS94 and the EN22 methods, as illustrated in Figure 1 c). In addition to the applied NS94 method/procedure, the EN22 procedure was changed from using logs without bark to logs with bark, and logs with bark and natural draft, as compared to 12 Pa forced draft. Particles (as total suspended particles, TSP) were sampled gravimetrically either using the hot filter method EN-PME (Fraboulet, 2016) as described in EN22 and/or in the full flow dilution tunnel acc. to NS94. An ABB online gas analyzer tracked the O_2, CO and CO_2 concentrations withdrawn as a part flow from the chimney. OGC was sampled from the hot undiluted flue gas, with a flame ionization detector. The TSP measurements included a double filter sampling system in the dilution tunnel with glass fiber filters for elemental (EC) and organic (OC) carbon analysis. The filter-intake nozzle size was selected from a proposed standard for measuring BC (Andersen and Jespersen, 2016), resulting in a lower volume flow through the filter than normally used with the NS94 standard. The lower volume flow reduced the PM loading of the filter ensuring lower uncertainties when analyzing the filter at the Sunset Laboratories Inc. ("Sunset Laboratory BV," n.d.) with an OC/EC aerosol analyzer. A Teflon (PTFE) front filter was used in the second sampling line, allowing the separation of condensed OC from particulate OC. The FTIR used for the gas measurements is an atmosFIR, with a resolution of 1cm-1 and an in-built sampling system kept at 180 °C. The gas cell has a volume of 300 mL, an optical pathlength of 4.2 m. The average value of 6 scans is used to report the concentration logged once per minute. The unit also has a controlled an accurate dilution system. The prediction model used, is developed for hot flue gases from wood burning, has 26 VOC compounds and can also predict CO, CO_2, NO_x, SO_2, NH_3, HCl, HCN, HF and H_2O.

2.2 Results and discussions

PMA - manual vs. automated combustion air-control
Emission reductions related to PMA, was such that automating the combustion air, and performing experiments acc. to NS94, a reduction in PM emissions, of 66% was measured (see Figure 2). It is possible to achieve similar low emissions when firing the stove manually, but this requires a rather skilled user. It was possible to achieve repeatedly lower emission with the automatic air-flow control. Applying EN22, automation increased the efficiency with 8% and decreased PM (mg/Nm^3), CO and OGC, with 12%, 34% and 55%, respectively (see Figure 3). One should keep in mind that the test performed acc. to EN22 is at highly optimized conditions generally resulting in systematic low emissions. With more testing, the automated control system could probably have improved the combustion even further.

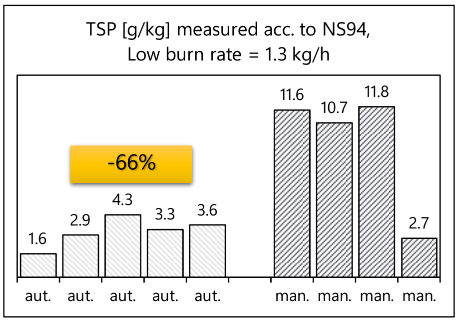

Figure 2: Tested according to NS94.

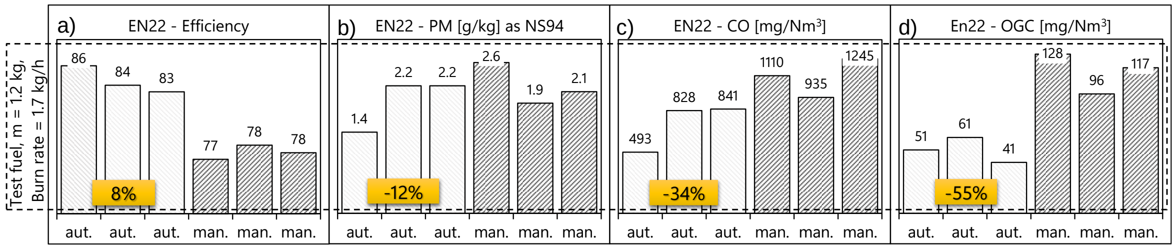

Figure 3: Tested according to EN22. Comparing automated and manually operated wood stove a) Efficiency b) PM [g/kg] measured and calculated as NS94 c) CO [mg/Nm3] d) OGC [mg/Nm3]

Figure 4 shows that comparing nominal and high fuel loads with birch, at low burn rates, automation reduced PM and CO with, 4% and 61%, respectively, for a fuel load of 1.2 kg. For a 1.8 kg fuel load, automation resulted in even higher reductions in PM, CO and OGC of 68%, 52% and 82%, respectively. The efficiency was only marginally affected by fuel load.

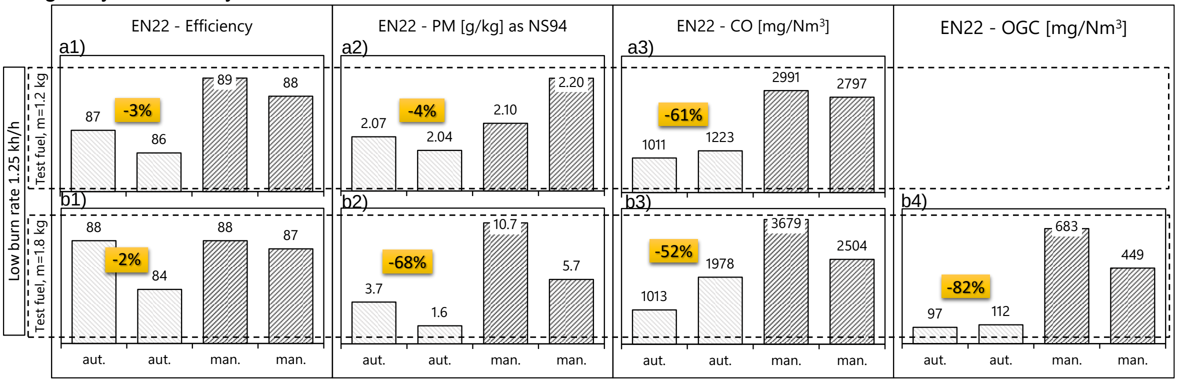

Figure 4: Tested according to EN22. 1.2 kg test fuel. Comparing automated and manually operated wood stove a1) Efficiency a2) PM [g/kg] measured and calculated as NS94 a3) CO [mg/Nm³].

Using briquette presses as fuel in the same setup, only slightly increased the efficiency with 3% but resulted in a significant 70% reduction of CO (See Figure 5). PM was unfortunately not measured in these tests.

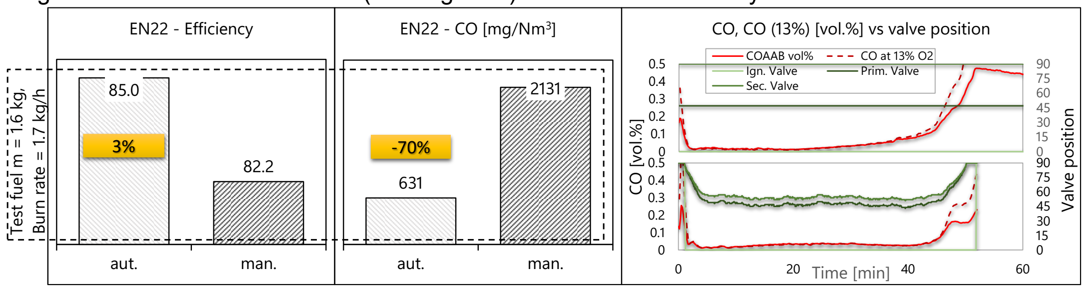

Figure 5: Tested according to EN22, with briquette presses as fuel.

PMB – improving performance by varying ignition procedure, wood specie, amount of fuel, log size and moisture content.

The effect of end-user operation as for the ignition from cold stove, and use of fuel with varying properties, as in PMB, showed significant variation in emissions over the ignition period. Good ignition (Ign. 1,6 in Figure 6), here at natural draft conditions, can be achieved repeatedly by assuring that the fuel catches fire before closing the door and/or reduce the primary/secondary air flows. High emissions will occur if the stove is over-fired (Ign. 2,4 in Figure 6), resulting in too high fuel volatilization and a lack of O_2, or under-fired, as with too little air, not enough primary/secondary air or closing the door too early, when establishing flames. Moist wood and dense log stacking (Ign. 5 in Figure 6) also require more air over a longer period, to establish a correct flame picture. “Correct” ignition test showed emissions of CO and OGC, on the same levels as for a hot stove at nominal load. Just poor ignition (Ign. 3 in Figure 6) or poor ignition due to over-/under-firing and dense stacking, produced twice as much PM and CO and 3-4 times the OGC, compared to correct ignition. Correct ignition produces higher efficiencies, even higher than at nominal load, because less heat leaves the chimney due to the cold stove absorbing more heat. The best ignition is when both low emissions and high efficiency is achieved.

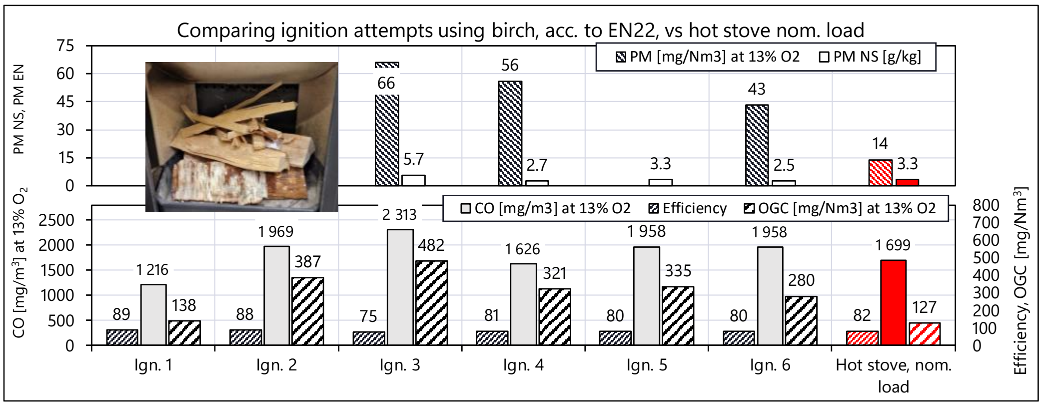

Figure 6: Comparing ignition attempts using birch (16% moisture with bark), acc. to EN22, vs hot stove.

Tests showed that a few larger logs are much worse than several smaller ones (see Figure 7), significantly increasing all emissions. Increased moisture, from 16% to 26%, again substantially increases the emissions, especially for CO and OGC. Then again comparing the three species tested, no real difference in either PM, CO, or OGC was measured, for similar fuel loads.

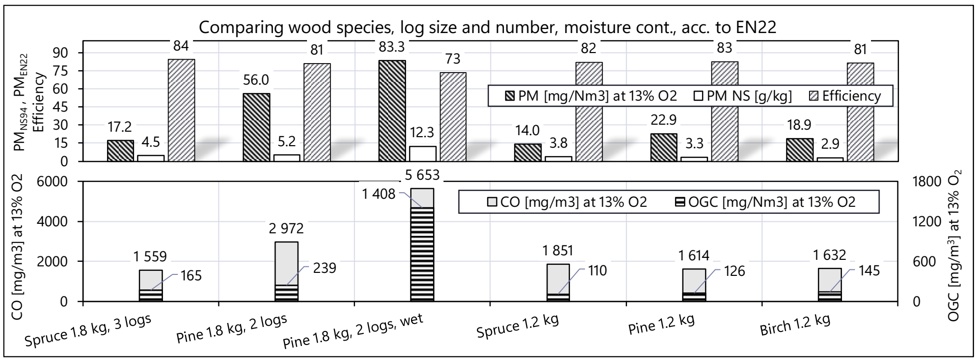

Figure 7: Comparing emissions from burning moist/dry pine, varying fuel load 1.2/1.8 kg, species and num. and size of logs.

Filter analysis, providing BC/OC particle composition for the species in question, showed little variation in OC between the species (see Figure 8). However, poor ignition increases EC/OC/PMT by a two-fold. Pine though, produces 2 times as much EC at comparable fuel load and 3.5 times more EC for 1.8 kg versus 1.2 kg of fuel load. Observing related filters visualizes this difference for pine, as in the left picture in Figure 8 (1st in lower column: poor ignition, 2nd in upper column: pine 1.2 kg, 2nd in lower column: pine 1.8 kg).

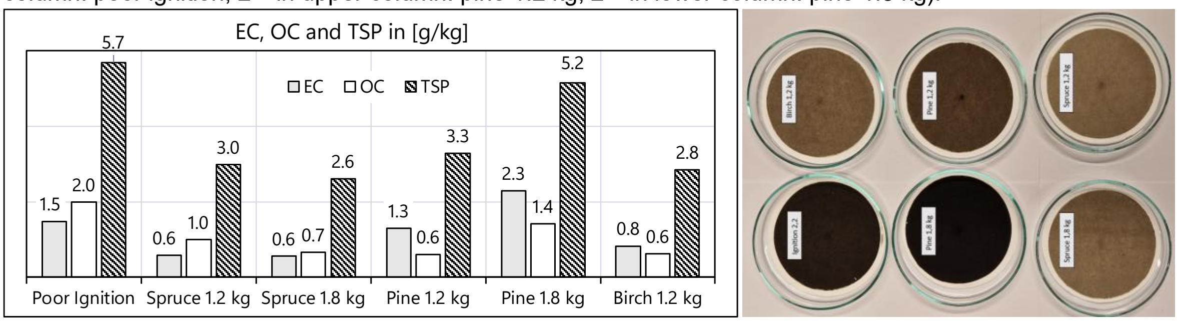

Figure 8: Comparing EC, OC, and TSP and illustrating these, by visualizing the associated filters.

This similarity between birch, spruce and pine was also backed by FTIR measurements. These measurements provided the concentrations, in [mg/Nm^3], of the VOC compounds in the hot flue gas. All tested wood species showed a remarkable resemblance when comparing VOC emission at nominal load, as illustrated in Figure 9, where the VOC flue gas concentrations have been normalized and compared for the different species. This similarity in VOC composition is backed by the similarities in in the OC measurements.

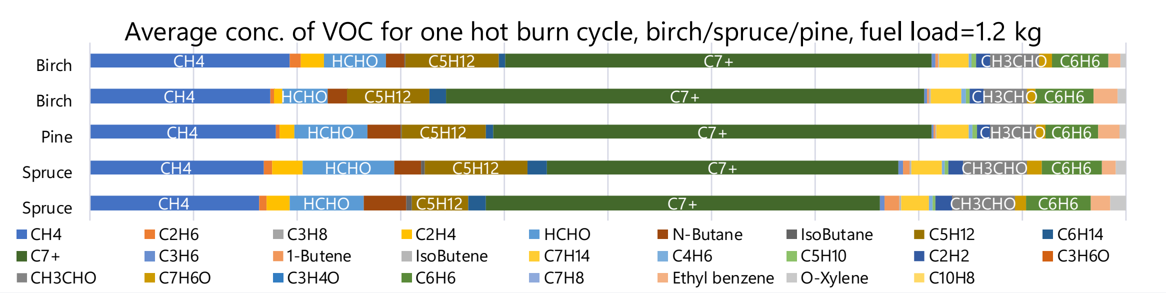

Figure 9: FTIR measurements provided concentrations of the VOC compounds in [mg/Nm3].

The manually batch fired process of heating with wood logs in small scale appliances for space heating, is highly affected by the user and the correct use is crucial to achieve low emissions. The correct use with the intended fuel (amount, size and moisture) produces lower emissions in the gas phase. Stove manufactures should therefore always provide an easy, understandable user guide with self-explaining pictures, showing the loading of the appliances with fuel and air valve settings when starting from cold stove and the following reloading. It is equally important to achieve sufficient ignition, meaning that flames must be established on most of the visible surface of the wood. One should also avoid over-firing, both when igniting a cold stove and when reloading a hot one.

3. Conclusions

Automated air-control results in a significant reduction in all emissions. Good ignition is possible but difficult to repeat. Avoid using large logs, use medium sized logs. Do not overload the stove. Do not use wood with higher moisture content than 20%, and finally, both hard- and softwood seem to have negligible differences in emissions of both gaseous compounds and particles.

Acknowledgments

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