INFLUENCE OF USER BEHAVIOUR ON EMISSIONS FROM FIREWOOD STOVES

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ABSTRACT: Firewood stoves may cause high particulate matter (PM) and gaseous emissions, and user behaviour is an important influence, although to date only rarely quantified. Therefore, a manually operated modern firewood stove (7 kW) was selected and tested on a combustion test stand in a comprehensive experimental plan where in total 5 stove ignition variants (cold starts at natural draught) and 9 stove operational variants were investigated, each in 3 replications. Ignition variants differed in the position of starter blocks igniters as well in the orientation and position of wood logs and kindling used, including the “top down” and “bottom up” ignition modes, which both were additionally tested in a setup with controlled chimney draught at -12 Pa. Operational variants comprised a refilling according to the stove user manual (a), different primary air settings (b), overload of fuel (c), different moisture contents between 7 and 30 w-% (d), too long logs (e), delayed recharging (f) a "quasi-continuous" charging of individual logs (g). The ignition from the bottom caused lower CO-, OGC, and PM-emissions compared to the ignition from the top, but highest concentrations were observed when using crumped newspaper as igniter from the bottom in an "inaccurate" fuel arrangement. In subsequent batches the firewood stove performed very well when operated according to the user manual (CO: 1,687 mg/m^3; OGC: 212 mg/m^3; PM: 22 mg/m^3, related to 13 % O_2-conc.). Highest emissions were released when the primary air flap remained open after the ignition batch (CO: 9,379 mg/m^3; OGC: 1,283 mg/m^3; PM: 142 mg/m^3). Such maloperation would be avoided if the stove was equipped with a relatively simple automatic combustion air control. High emissions also occurred when the stove was recharged after the flames were already extinguished or when the fuel was too wet. By throttling the combustion air flow, the CO emissions were increased by the factor 1.7 compared to the proper stove operation. Similarly, an overfilling of the combustion chamber also led to increased gaseous emissions. The use of too long wood logs, too dry wood or the continuous refilling with single logs led to similar or slightly lower gaseous and particulate matter emissions compared an orderly stove operation as defined as reference case.
Keywords: wood stove, user impact, fuel moisture, combustion control systems

1 INTRODUCTION & PROBLEM DEFINITION

Wood fuels are widely used in Europe and they can cause high pollutant emissions, e.g. particulate matter (PM). In Germany, for example, the total amount of fine particle emissions from wood combustion in small scale appliances (i.e. room heaters, slow heat releasing appliances, closed fireplaces cooking and pellet stoves, etc. but also automatic and manual stoked boilers) is around 19,800 t/a (PM_{10} in 2016) [1], this is an equivalent of 9.7 % of all annual PM_{10} emissions in the country. An obligatory replacement schedule was set into power where older stoves are now stepwise removed for newer technology. However, this newer technology does not automatically guarantee lower emissions. One reason for this is that the current type testing method does not effectively enforce the choice of appliances which would be capable to provide low emissions during a real life operation. This is because the current test method excludes critical operational phases such as the cold start, the moment of recharging and low load operation. New method developments (e.g. beReal method [2] or the German environmental certificate "Blue Angel") for stoves are on the way, but initially their application is only targeted on the introduction of voluntary quality labels rather than becoming mandatory.

Another maybe even more important reason why newer stoves do not automatically improve the emission level is that the user behavior is highly influential for pollutant emissions of manually operated firewood stoves, too. But to date it is still largely unknown to what degree the user himself is responsible and which magnitude of emission increase can at all be triggered by wrong stove operation. Furthermore, in many cases the optimum stove operation itself is often unknown, too, or is insufficiently and sometimes even falsely documented in the user manuals which are mostly not specifically developed for each stove model.

To meet strict air quality requirements, operational impact on the combustion process and pollutant emissions needs to be minimized. Such influences are manifold, they can either be caused by

- the fuel choice (e.g. wood species, log size, moisture content),
- recharging habits (e.g. late recharging, overloading, fuel orientation),
- the mode and carefulness of stove ignition (e.g. choice of igniter material, positioning of logs and fine starter wood) and by
- manual adjustment of air flaps (e.g. primary and secondary air settings).

To a certain degree the sensitivity towards all these operational influences is believed to be stove specific. However, during regular stove testing for market introduction all such influences can never be comprehensively assessed. Therefore, only dedicated research can show and quantify the user impact on flue gas emissions for a given stove.

2 AIM

It was the aim to demonstrate to which degree modern firewood room heaters (so-called "chimney stoves") could become hazardous to the environment when being wrongly operated or when existing user instructions are inappropriate. This was done by identifying major operating variants or typical user errors which occur in practise. These operational cases were systematically addressed in a dedicated experimental plan for a modern low emission log wood stove operated in a realistic environment. A suitable number of three replications were chosen to allow an identification of significant differences and quantitative effects concerning pollutant emissions (CO, OGC, PM, NO_X). From the obtained results, it was also the aim to draw useful recommendations for correct stove operation and for further technical development. As only one stove was chosen for the experiments, the research was rather designed as a case study to provide some indication, while the magnitude of all observed emission changes shall not readily be transferred to all other log wood stoves.

3 MATERIAL & METHODS

3.1 Stove used

A modern manually operated firewood stove was selected. This stove („Sino L“ by Spartherm Feuerungs-technik GmbH, see Figure 1) has a nominal heating power of 7 kW (power range 4,9 – 9,1 kW) and an outer casing made of cast iron. It has a central combustion air inlet socket and a vertical flue gas outlet of 150 mm diameter, positioned at the stove top. Primary air is inserted via the grate and partly via the window purge air, while additional secondary flows through 8 air nozzles positioned in the rear wall of the refractory lining at about a height of 32 cm above grate level. The adjustment of primary and secondary air is performed via a combined single hand lever. Ash falls through a grate into an ash drawer which can be removed when the charging door is opened, the door sealing thus avoids any false air insertion via the ash box. Total mass of the empty stove is 200 kg and the manufacturer suggests a wood mass insertion of 2.2 kg/h for charging.

Figure 1: Stove "Sino L" upon delivery

3.2 Test stand

All measurements were performed on combustion test stands at TFZ using the setup as described in Figure 2. The dimensions of the scheme follow the current in-structions given in the European standard for type testing (DIN EN 13240 [3]).

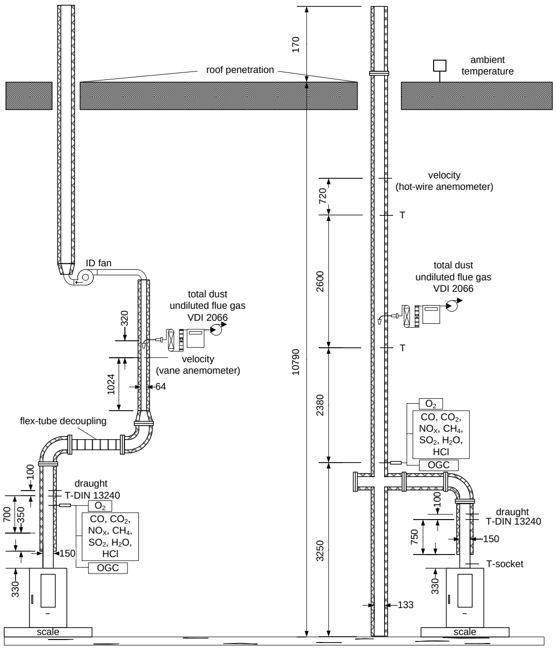

Figure 2: Scheme of the two test benches used and location of sampling points for controlled draught (left side) or natural draught (right side). All dimensions given in mm.

The combustion appliances were placed on a scale in order to record the mass loss continuously during combustion. The Flue gas temperature was measured with a thermocouple according to DIN EN 13240 [5] (instead of a suction pyrometer) it was combined with the gas sampling. Particle sampling was performed following VDI-Guideline 2066 [4]. In deviation, the sampling temperature at the sampling probe was raised from 160 °C to 180 °C. The filter pre- and post-treatment happened at 180 °C.

Emissions of OGC (organic gaseous carbon) were determined using a flame ionisation detector (FID) (Mess- & Analysentechnik GmbH ThermoFID). Other gaseous components O_2, CO_2, and CO were measured by single component analysers (non-dispersive IR-Spektroscopy) (by ABB Automation GmbH ABB AO2020), NO_x via Chemiluminescence-detector (CLD) (ECO PHYSICS GmbH CLD 822 Mhr Analysator) and for determination of water vapour in the flue gas a Fourier-Transformed-Infrared spectrometer (FTIR) was applied (Ansyco GmbH FTIR DX4000N).

For the experiments with controlled chimney draught (-12 Pa) the flow velocity was determined using a vane wheel anemometer (Höntzsch GmbH Flügelrad Strömungssensor ZS25/25-ZG4) positioned in a narrowed stretch of the measurement section of only 64 mm diameter (see Figure 2, left hand side). For determining flue gas velocity and flue gas mass flow in the natural draught chimney, a high temperature tolerant hot wire anemometer (by Schmidt Technology GmbH SS 20.650) was applied in order to allow accurate determination of low velocities while here no narrow stretch in the measurement section was permissible.

For tests on air tightness of the stove, leakage tests were performed using a DP 600 (Wöhler GmbH). These tests were done at the beginning of the whole measurement campaign (on the new unused stove), after all trials at the natural draught and as well after the trials under controlled draught conditions.

3.3 Fuel used

Air dried hardwood (beech) with a moisture content of 14 % was uniformly used in most trials. Only for those trials with "too wet" fuel, recently cut beech wood with moisture content of 30 % was applied. A portion of this wet fuel was subsequently also dried in a drying cabinet at 105 °C until a moisture content of 7 % was achieved; this fuel was then stored over 7 days before being used for the trials with "too dry" fuel. For the igniting batch some additional fine starter fuel was also required, fine split spruce wood sticks as available in retail stores or petrol stations in Germany were used. The starter blocks for easy ignition were conventional barbeque or stove igniters which were manufactured from natural wax-soaked wood fibres. In of the ignition variants also paper was used instead.

3.4 Experimental plan

3.4.1 Igniting modes

In total 5 stove igniting modes were tested. They differed in the position of the chosen igniters as well in the orientation and the choice of wood sizes used; this included the "top down" and "bottom up" ignition modes. Table I and Figure 3 describe the tested variants for ignition. Each variant was performed 3 times, each in the cold start on a new testing day. Mean values were calculated from all three replications.

Table I: Ignition modes tested and fuel mass used

No	Ignition mode as shown in Figure 3	Fuel used
A1	top-down ignition with kindling and starter block	4 logs of 500 g + 4 pieces. of kindling
A2	bottom-up ignition without kindling but with starter block	2 logs of 500 g + 1 log of 700 g
A3	bottom-up ignition with kindling and starter block	4 logs of 500 g + 4 pieces of kindling
A4	ignition from centre with kindling and starter block	2 logs of 700 g + 1 log of 500 g + 4 pieces of kindling
A5	"inaccurate" batch setting: bottom-up ignition without starter block but using newspaper, kindling and logs mixed in "wild" log orientation (Figure 3)	2 logs of 700 + 1 log of 500 g + 4 pieces of kindling

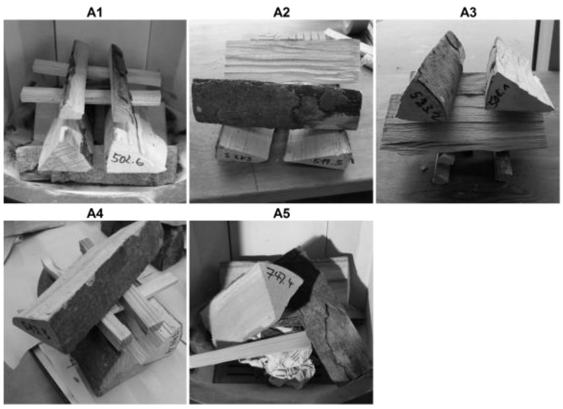

Figure 3: Tested stove ignition modes as described in Table I

3.4.2 Other operational modes

In direct sequence to each igniting test as described in Chapter 3.4.1 an intermediate batch using three logs of totally 2.2 kg dry beech wood was performed. These batches were not evaluated, the objective was simply to delete any pre-conditioning which might have been caused by the igniting batches before. After the intermediate batch one of 9 different variants for recharging or stove operation were tested. All these variants are described in Table II.

Table II: Tested operational modes and fuel variants

No	Variant name	Description	Fuel mass charged
V1	"orderly operation"	standard operation according to user manual, recharging at flame extinction	2.2 kg ± 0.04 kg
V2	"open primary air"	maloperation after ignition: air dampers remain in start position	2.2 kg ± 0.04 kg
V3	"reduced air supply"	fuel save mode (oxygen depletion), deliberate power throttling at nominal fuel load	2.2 kg ± 0.04 kg
V4	"overloading at medium air supply"	"reserve heating" by overloading, 1.7-fold fuel mass (charging of 5 logs)	3.7 kg ± 0.04 kg
V5	"overlong logs at medium air supply"	too long logs of ca. 40 – 50 cm, they lean at the refractory lining with only little contact to the ember	2.2 kg ± 0.04 kg
V6	"too wet fuel at medium air supply"	wood moisture too high, at about M=30 %	2.2 kg ± 0.04 kg
V7	"too dry fuel at medium air supply"	wood moisture too low, at about M=7 %	2.2 kg ± 0.04 kg
V8	"too late recharging, about 85 min after flame extinction"	very late recharging when the ember provides just enough heat for ignition	2.2 kg ± 0.04 kg
V9	"continuous recharging of single logs"	„quasi-continuous" fuel feeding by frequent charging of small portions (i.e. single logs) triggered by scale reading, applying 50 % of usual recharging mass, flame never extinguishes	logs of 0.7 kg each ± 0.04 kg

Between all variants described in Table II intermediate batches were always inserted, thus it can be assumed that the ember was comparable when the test started. The criterion for recharging was the moment when there were no more visible flames. Each variant was repeated three times and mean values were calculated from these three replications.

3.5 Gas sampling and evaluation periods

Total PM-emission measurement (dust sampling) was always started immediately after the door was closed after recharging, this happened without any delay after dropping the logs. This applies for ignition trials (A1 to A5) and for operational trials (V1 to V9). Measurement always ended at flame extinction when the moment of recharging was reached. However, all gaseous concentrations were continuously recorded, but the evaluation and mean value calculation was related to the same period of time as for PM sampling. All reported measurement values are related to standard test conditions of 0 °C, 1,013 hPa and 13 % oxygen concentration.

3.6 Statistical assessment

All statistical analyses of measured values were assessed using OriginPro 2015. Tests for normal distribution used the Shapiro-Wilk-Test. For analysis of variance (at normal distribution of individual values) a simple ANOVA was applied. Pairwise comparison of mean values applied the least significant difference-(LSD)-method of Fisher. For direct comparison of two mean values a t-test was performed. Significant differences were detected when error probability was lower than 5 % ($p \leq 0.05$).

4 RESULTS & DISCUSSION

4.1 Air tightness of stove

In the course of all test campaign the stove proved to have remained in unchanged in terms of leakage. High air tightness had remained stable throughout the experiments. This is shown in Figure 4.

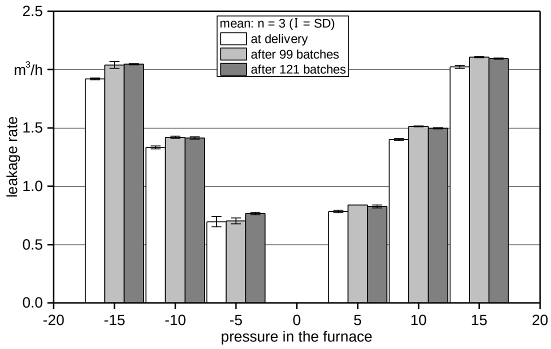

Figure 4: Mean leakage rates of the tested stove upon delivery (new) and after trials at natural draught (99 batches) and controlled draught (121 batches). SD – standard deviation)

4.2 Impact of ignition mode

The five tested ignition modes (as described in Table I) were reason for quite inconsistent combustion behavior. When comparing the CO-emissions (Figure 5) it becomes obvious, that a proper ignition from the bottom (A3) caused lower emissions of 2,761 mg/m³ compared to an ignition from the top in variant A1 (4,111 mg/m³); this difference was statistically significant at the 5 % error level. But the highest CO-emissions in the ignition studies were caused in the mode when operating inaccurately using crumpled newspaper as igniter from the bottom. An igniting from the center (variant A4) caused high CO-emissions of 4,282 mg/m³ in average, too. However, the variation between the three replications was also quite high. Furthermore, in respect of CO-emissions this variant had also yielded the best single measurement among all 15 igniting tests performed, this is shown by the error bars for the three replications displayed in Figure 5. Igniting from the bottom (A2) without kindling increased the CO-emissions about 1.7-fold compared to igniting from below with kindling (A3) (significance $p \leq 0.05$). This may be attributed to the slower temperature rise in the combustion chamber. The worst performance was given for "inaccurate" igniting from below with newspaper (A5), but due to high variance between replications a significant difference can only be stated in a pairwise comparison to an igniting from below with kindling (A3). The reason for this high emission may be found in the short burning time of the ignition material (crumpled newspaper) which delays a rapid inflammation of the logs. Furthermore, the newspaper material - having a high ash content of about 17 to 21 % [5] - creates a bed of ash on the grate which prevents combustion air from easily accessing the logs above.

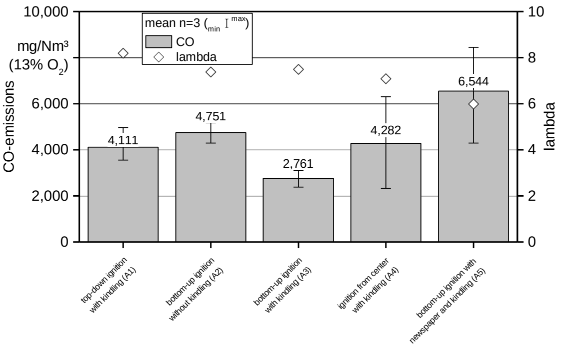

Figure 5: CO-emissions for 5 different ignition modes using the Spartherm Sino L stove at natural draught conditions

A similar and even more pronounced emission pattern was observed for organic gaseous carbon (OGC)-emissions, as shown in Figure 6. The OGC-concentrations were in average 60 % lower when applying the proper "bottom up ignition" method (A3) instead of an top down ignition (A1); however, this effect was not significant at the 5 % error level. Here too, the best individual batch measurement from all 15 ignition tests made was achieved in one of the replications for variant A4 (igniting from the centre). Worst performance considering mean values was again observed when the "inaccurate" ignition variant with newspaper (A5) was chosen. This difference however, was only significant ($p \leq 0.05$) when comparing to A3. The jump in emissions from A3 to A2, where the only difference was that in A2 no kindling (i.e. 4 fine split sticks from spruce wood) was used, is remarkably high, the observed OGC-emission is 4.4-fold higher. This underlines the necessity to carefully select the starter fuel and that fine wood pieces are always needed for flame stabilization.

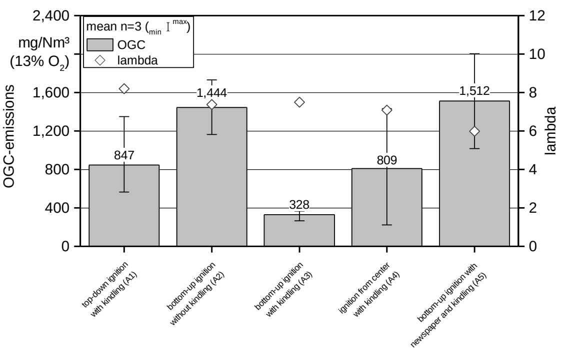

Figure 6: OGC-emissions for 5 different ignition modes using the Spartherm Sino L stove at natural draught conditions

For NO_x-emissions the igniting procedure proved to be irrelevant (Figure 7). The mean values for NO_x in all 5 variants were in a narrow range between 121 and 129 mg/m^3, with no significant differences.

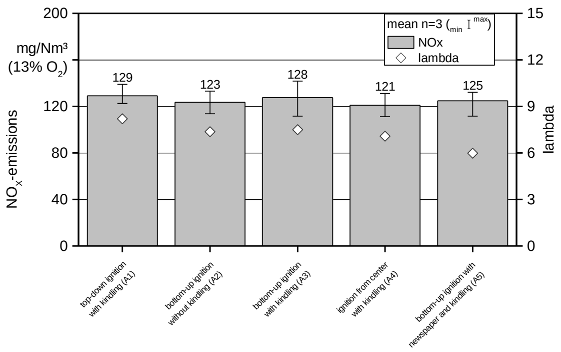

Figure 7: NO_x-emissions for 5 different ignition modes using the Spartherm Sino L stove at natural draught conditions

For total PM-emissions however, the emission level was again largely depending on the ignition mode (Figure 8). Here too, the variant A3 (ignition from bottom with kindling and starter block) performed best at 66 mg/m³. However, the observed differences between this mode and and the ignition from the top (A1), where PM-emission was at 73 mg/m^3, were insignificant at the 5 % error level. Only an igniting from below without kindling (A2) was significantly higher at 107 mg/m^3, compared to A1, A3 and A4. Highest PM-release was again measured for the "inaccurate" variant A2 where only newspaper was used in this "inaccurate" fuel arrangement; the measured differences to all other variants were here always significant at the 5 % error level. These findings underline that a careful fuel setup is required for the start-up batch, the use of newspaper shall be avoided but proper starter blocks shall be used instead.

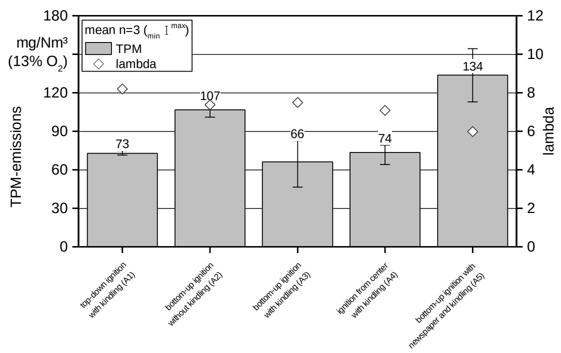

Figure 8: PM-emissions for 5 different ignition modes using the Spartherm Sino L stove at natural draught conditions

The velocity of stove heat-up during cold start (igniting batch) is known to be dependent on draught conditions. Therefore questions arose during the experiments whether the findings made above in trials with natural draught could be repeated under controlled draught conditions of a type testing setup, where chimney pressure is always kept constant at -12 Pa. For two of the variants tested above, A3 (ignition from bottom with kindling and starter block) and A1 (ignition from the top) the cold start tests (3 replications) were again performed under the same fuel and stove settings as before, but at controlled draught.

CO-emissions (Figure 9) for both variants were then generally lower than for natural draught conditions (-35 % and -32 % for top-down and bottom-up mode, respectively). This may be attributed to the fact that at the very moment of lightening the chimney draught is higher than under natural draught conditions.

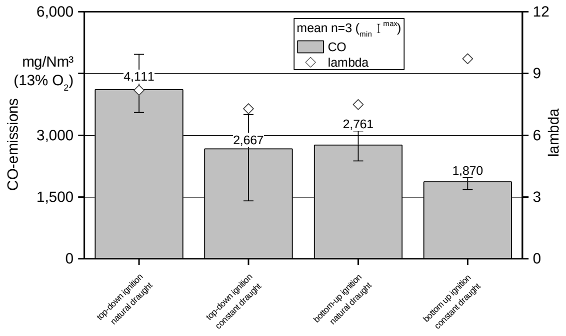

Figure 9: CO-emissions for 2 different ignition modes using the Spartherm Sino L stove at controlled draught conditions of -12 Pa

When comparing only the two ignition modes at controlled draught, a similar pattern was found. The ignition from the bottom performed better, compared to ignition from the top, CO-emissions rose from 1,870 mg/m^3 to 2,667 mg/m^3 (Figure 9).

Similar observation was also made for OGC-emissions (Figure 10), which were generally lower at controlled draught (-58 % and -54 %). And again, the differences between the variants were similar, OGC rose from 151 mg/m^3 to 352 mg/m^3 when igniting was done from the top.

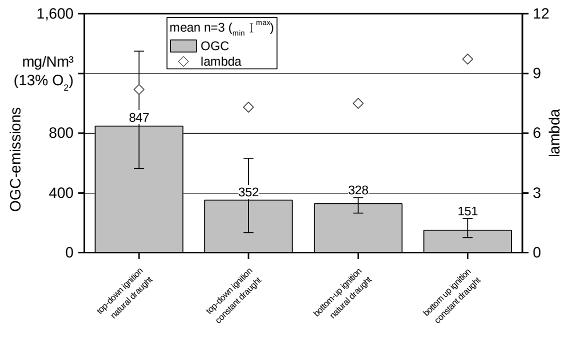

Figure 10: OGC-emissions for 2 different ignition modes using the Spartherm Sino L stove at controlled draught conditions of -12 Pa

As for total PM-emissions (dust), here the general differences were low; constant draught improved the PM emission only by around 5 and 8 %. Also when comparing only the two igniting variants, the benefits for the bottom-up variant was only relatively small for PM-emission (Figure 11), 61 versus 69 mg/m^3). It should be mentioned that all differences for CO, OGC and PM-emissions for the two igniting variants were not significant at the 5 % error level.

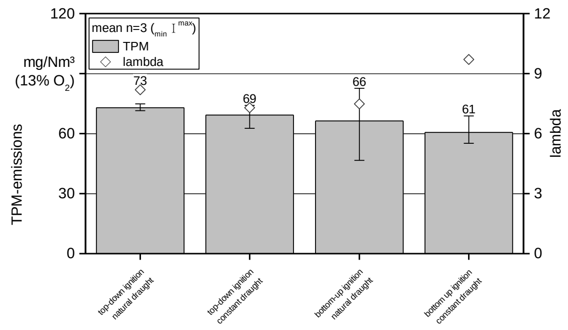

Figure 11: Total PM-emissions for 2 different ignition modes using the Spartherm Sino L stove at controlled draught conditions of -12 Pa

In summary, the presented findings concerning the best ignition modes are in contrast to previous studies [8] and to earlier (unpublished) findings made by TFZ. Those results had given the basis for a generalized suggestion that an ignition from the top is in most cases beneficial for reducing pollutant emissions. However, these suggestions had already been questioned by REICHERT ET AL. [9], who had tested two firewood room heaters, applying both, an ignition from the top and from the bottom ("top-down" and "bottom-up" ignition). The comparison of both techniques showed no general advantage of the top-down ignition method and the high reductive effect of top-down ignition on PM-emissions as reported by literature was not observed. As a consequence, the specific ignition procedure should be developed independently for a stove.

4.3 Impact of recharging and operational mode

In Figure 12 the measured CO-emissions from all assessed operational modes are shown.

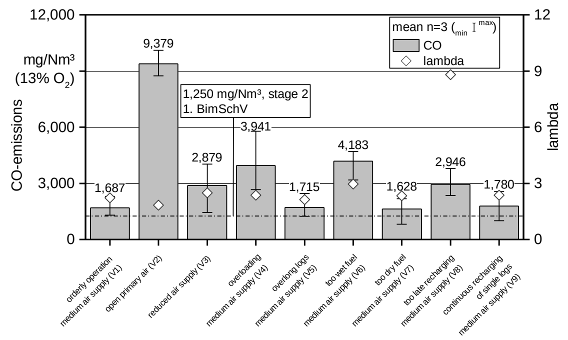

Figure 12: CO-emission of all recharging and operational modes using the Spartherm Sino L stove

The standard case for stove use is the "orderly operation" of variant V1 where mean CO-emissions are at 1,687 mg/m^3, during these measurements the mean chimney pressure at the flue gas outlet socket was at -17 Pa and the batch duration was 48 minutes (Figure 13) which meets the minimum requirement of 45 minutes as defined in the European Standard DIN EN 13240 [3].

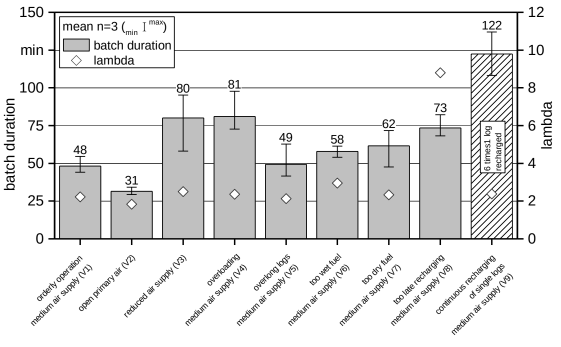

Figure 13: Mean batch duration in all trials with variable recharging and operational modes using the Spartherm Sino L stove

Several other operational variants such as the use of overlong logs (V5: 1,715 mg/m^3), too dry fuel (V7: 1,628 mg/m^3) and a continuous recharging of single logs (V9: 1,780 mg/m^3) performed on a similar CO-emission level (Figure 12).

However, if primary air was left open after the start-up batch (V2), CO-emissions significantly rose to 9,379 mg/m^3, this is a 5.6-fold increase compared to the orderly operation of V1. Due to the fact that in this operation both open air flaps provided an excess air supply, the conversion rate of the fuel was boosted. As a result, the residence time of all formed pyrolysis gases in the combustion chamber was presumably very short, this means a violation of the "3-T-rule" for clean combustion (time-temperature-turbulence). The disadvantage of short residence can obviously not be compensated by higher mean flue gas temperature which in the described case with both air flaps in fully open position was significantly higher (+95 K, see Figure 14). At the same time the batch duration is significantly reduced from 48 to only 32 minutes (Figure 13). The excessively high flue gas flow is also reflected by a slightly lower chimney draught which was at only -15 Pa. At the same time also the air excess ratio (lambda) was lower for the air setting of V2, this is also shown in Figure 12. It becomes apparent, that despite of the fact that the open primary air flap creates an intensive "forge-like" fire, the overall oxygen depletion can still not be avoided. All the more, it may be assumed that local oxygen depletion phenomena in the secondary combustion area are then even more pronounced, and thus the excess fuel power cannot anymore be met by an effective gas burnout.

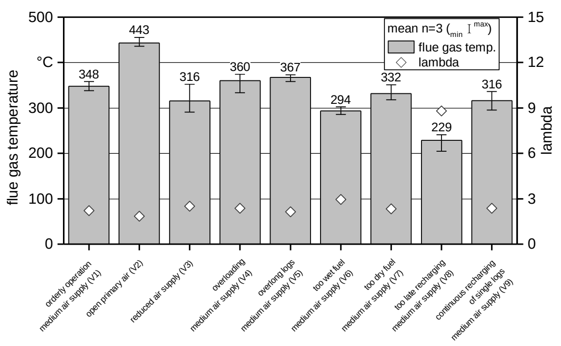

Figure 14: Mean flue gas temperature at flue gas socket in all trials with variable recharging and operational modes using the Spartherm Sino L stove

An overfilled combustion chamber ("reserve heating case", V4) caused an average 2.3-fold increase of CO-emissions to 3,941 mg/m^3 compared to the orderly variant V1. This overfilling mode was thus creating a similar emission level as it was measured for "too wet fuel" (V6: 4,183 mg/m^3).

In terms of CO-emission, "too late recharging" (V8) gave a similar performance as for reloading at "reduced air supply" (V3). The latter case describes the behaviour when the user throttles the total air flow to reduce heat power output (e.g. when the stove power is over dimensioned for the given heated space). Then the measured mean flue gas temperature was only at 316 °C (Figure 14) and the mean batch duration was 80 minutes (Figure 13), although fuel mass had remained unchanged (differences to V1 were not significant at the 5 % error level). This batch duration was thus the same as for the overloading batch (V4 in Figure 13) where fuel mass was 1.7-fold higher (at medium air supply settings). However, for V4 the mean flue gas temperature was at 360 °C which is around 50 K higher than for V3 (Figure 14). Another plausible difference observed was the trend towards a higher chimney draught (-19 Pa), which indicates that throttling the air supply in V4 increases the pressure drop over the stove.

For both, "too wet fuel" (V6) and "too late recharging" (V8), low combustion temperatures are believed to have caused higher CO-emissions compared to the "orderly" operation. This is indicated by the measured flue gas temperatures in Figure 14, they mark the two variants with the lowest levels in all stove operation trials of this study.

The use of "too dry fuel" (V7) did not create any emission peaks as it had been reported in previous studies at TFZ [7], neither were the mean flue gas temperatures elevated, compared to the standard case V1 (Figure 14). Due to the higher calorific value of the wood charged, which was always 2.2 kg at moisture content as received, the batch duration was longer than for the the reference case V1 (+14 min, see Figure 13).

An interesting but practically not easy to realize operational mode was the "quasi-continuous recharging" (V9). Here the visible yellow flames never extinguished. In these trials a single log was always dropped into the stove as soon as the mass of the previous single log loading had been fully consumed, these trials were operated according to the reading from the combustion scale. Mean CO-emissions were at around the same level as for the standard reference case V1 (Figure 12), but mean flue gas temperature was lower at 316 °C (Figure 14), which could indicate some benefits concerning efficiency although the differences were not significant at the 5 % error level. However, the true benefits of this variant rather become apparent when regarding PM-emissions (see Figure 17).

For orientation, the CO-emissions in Figure 12 and also the OGC- and PM emissions in Figure 17 are compared to a dotted line indicating the current German emission limit according to 1.BImSchV [6] of 1,250 mg/m^3 (for CO) and 40 mg/m^3 (for total PM), as measured during type tests which shall follow the European Standard DIN EN 13240. For OGC the dotted line in Figure 15 reflects the upcoming emission limit of 120 mg/m³ in the European Ecodesign directive.

However, strictly speaking, such comparison with measurements made here is not permissible. The testing procedure of a type test does not reflect real life operation which however had been in the focus of this study. Incompatibility is given because in a type testing

- PM sampling may be started with delay after recharging,
- it is permissible that data evaluation of gaseous concentrations may cut-off the chosen delay after recharging
- Sampling for PM emission is stopped after 30 minutes,
- the recharging door must not be closed immediately after refilling new logs,
- all tests are made under controlled draught conditions of -12 Pa instead of using natural draught.

Nevertheless, this "illegal" comparison shows, that the tested stove can even in a practice related test procedure partly fulfil the CO-requirements as defined for results from a type testing procedure (see minimum values in Figure 12).

The complete results on OGC-emissions are shown in Figure 15. Unfavorable combustion conditions as indicated by low mean flue gas temperatures seem to provide significant impact on emission level. This is particularly true for trials with "too wet fuel" (V6: 1,283 mg/m^3) and for "late recharging" (V8: 1,102 mg/m^3). Furthermore, a presumably too rapid fuel conversion as triggered by "forgetting" to close the primary air flap (V2: 1,283 mg/m^3) raises OGC-level even more dramatically. More causes for elevated OGC-emission are given by fuel overloading, which inevitably leads to excessive production of pyrolysis gases (V4: 548 mg/m^3).

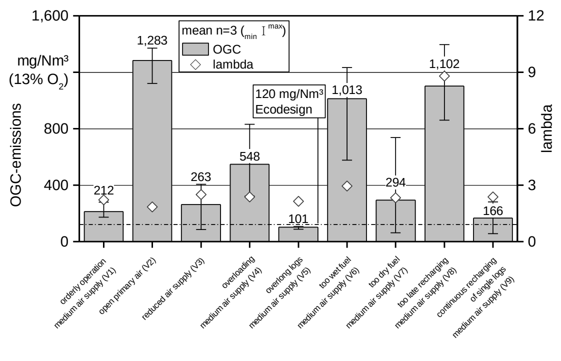

Figure 15: OGC-emission of all recharging and operational modes using the Spartherm Sino L stove

On the other hand several operations lead to rather similar and low OGC-levels, these cases are the standard "orderly operation" (V1: 212 mg/m^3), the "reduced air supply" (V3: 263 mg/Nm^3) and the "too dry fuel" (V7: 294 mg/m^3).

A continuous recharging of single logs (V9) was surprisingly quite low for OGC-emissions (166 mg/m^3), which indicates the benefits of steady combustion conditions as they are achieved in automatically charged furnaces. But the lowest OGC-emission of all trials was observed when using of overlong wood logs (V5: 101 mg/m^3). However, this variant also provided the highest mean flue gas temperatures (Figure 14) among those trials were otherwise the same fuel mass and medium air settings had been applied. This phenomenon may thus explain why V5 yielded unexpectedly positive results; usually those cases with long and inclined logs that have no contact to the ember are known to cause excessive smoke formation. It may be that for this particular case some beneficial effects were generated by possibly increased turbulences in the combustion chamber due to long logs partly blocking the gas paths which could thus enhance mixture of gases and improve burnout. Also the combustion chamber of this stove had been constructed in a relatively high and slim geometry, this may have avoided any negative impact from overlong logs as it would mostly be expected in rather flat and wide combustion chambers. Such observations had previously been made in another study [7].

In biomass combustion NO_x-emissions are usually following the variable nitrogen content in the fuel, and no larger impact from the thermal conditions in the combustion chamber is usually given. In this study the applied fuel had been homogeneously chosen from the same origin, thus no larger variation of N-content can be assumed. As the N-content in wood is generally quite low, no excessive NO_x-emission was seen which could possibly violate the upcoming limit of 200 mg/m^3 as specified in the European Ecodesign directive.

However, for some variants significant NO_x-emission differences were observed within the overall range of 67 und 131 mg/m^3 (Figure 16), In particular NO_x-concentration was low for the variants V2, V3 and V4. This may be attributed to the fact that nitrogen conversion into harmless N_2 is favoured under conditions of oxygen depletion where any NO_x-precursors undergo reducing conditions [10]. It is believed that local oxygen depletion was also enhanced in the depicted low-NO_x variants (particularly V2 and V4), where oxygen is assumed to be low in the secondary combustion space around the upper flames. When exhaust fumes are here not fully burnt out, a higher CO-concentration is promoted, too. High CO-concentrations can additionally benefit the reaction of nitrogen-monoxide (NO) towards elementary nitrogen (N_2); this is explained by the homogeneous NO-consuming reaction given in formula (1), a reactions which occurs at temperatures higher than 1000 K [10].

$$2\,NO + 2\,CO \rightarrow 2\,CO_2 + N_2 \qquad (1)$$

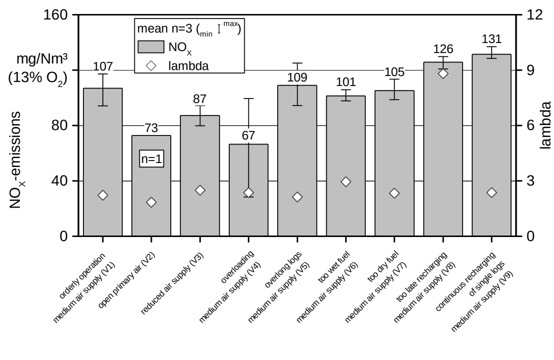

Figure 16: Total NO_x-emission of all recharging and operational modes using the Spartherm Sino L stove

Total PM-emissions from the chosen room heater remained in the standard case and even in some irregular cases below the German emission limits of 1.BImSchV [6] where PM limits are set at 40 mg/m^3 for results from type testing. However, as mentioned above, such comparison to type testing limits is not fully permissible due to incompatible testing methods.

During the orderly operation (reference case V1) the total dust release was at 22 mg/m^3 (Figure 17), but even lower dust formation was observed when the “quasi-continuous recharging” mode was chosen (V9: only 12 mg/m^3). Exceedance of emission limits was observed at open primary air flaps (V3: 142 mg/m^3), with "too wet fuel" (V6: 94 mg/Nm3) und at "late recharging" (V8: 87 mg/m^3).

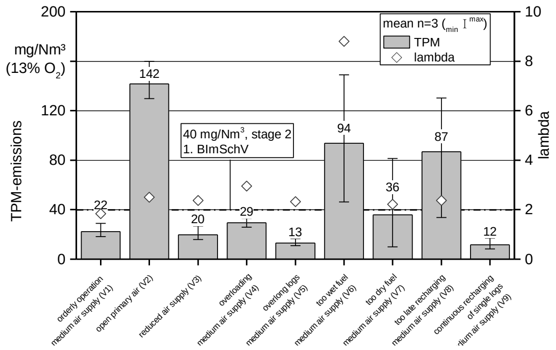

Figure 17: Total PM-emission of all recharging and operational modes using the Spartherm Sino L stove

Under conditions of open primary air flaps the high PM emissions can be explained by high fuel conversion rate and high volume flows which lead to particle formation through incomplete combustion (see explanation given for CO and OGC). Consequently lower retention times of exhaust fumes as well as inevitably lower oxygen availability in the flame zone are believed to have caused high soot formation.

For "too wet fuel" (V6) and "late recharging" (V8), temperature in the flue gas was relatively low (Figure 14), which indicates that combustion chamber temperatures had been low, too, and they could thus not accelerate the burnout. For V8 ("late recharging") it may also be stated that a long smouldering phase before flame ignition (15 to 20 minutes) was observed during all 3 replications, and the formation of unburnt hydrocarbon is believed to have contributed to primary aerosol discharge.

5 CONCLUSIONS

The results confirm that the stove operator has a big influence on the level of emissions from firewood room heaters. This applies for the start-up phase (i.e. correct ignition), the stove recharging operation and the correct air settings. From the results presented here, a number of respective conclusions can be drawn.

- The general advantage of the usually promoted "top down" compared to the "bottom up" ignition mode is not confirmed in this study. This is true for both, natural draught as well as controlled chimney draught conditions.
- Consequently, manufacturers should develop precise manuals that describe the best ignition mode specifically for each stove type or geometry.
- The use of suitable starter blocks and proper kindling material is essential for achieving low emissions at cold start conditions. No crumpled newspaper shall be used. Otherwise the pollutant discharge in the initial (cold starting) batch can easily double, for OGC even quadruple.
- Wrong air settings can dramatically deteriorate emission behavior. Easily made mistakes such as the "forgotten" closure of primary air supply through the grate after the cold start batch, can dramatically increase pollutant discharge (except for NO_x) by about six times. Manufacturers could avoid such operating "accidents" by integrating simple air control technology, based on temperature signals which trigger motor based air flap adjustments.
- The use of overlong (inadequate) logs, which need to lean against refractory lining, can be unproblematic when the stove is properly designed and is having a high and slim geometry.
- The use of "too dry" fuel (here M=7 %) can be unproblematic when the stove is properly designed with only little leakage air flow.
- Too "wet fuel" (here: M=30 %) can hardly be compensated by advances in stove design; the emission level for CO, OGC and PM was around 2.5- to 5-times higher than with proper fuel.
- Extremely late recharging without short term primary air adjustment for rapid re-ignition shall be avoided. Such short term flap opening for grate air supply (e.g. for 15 to 30 seconds) could easily be accomplished by a simple air control technology which should be integrated by the manufacturer.
- Although the user is identified as a decisive factor for air pollution from log wood stoves, user instructions are often poor or even misleading. This should best be avoided by creating a (standardized) "quick-user-guide" which should be based on experimental evaluation performed by the manufacturer.
- The potential for emission reduction by introducing automatically controlled combustion air supply in comparison to manually operated stoves should be addressed in future studies where in particular realistic user behavior should be taken into focus.

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