INFLUENCE OF IGNITION AND OPERATION TYPE ON PARTICLE EMISSIONS FROM RESIDENTIAL WOOD COMBUSTION

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ABSTRACT: The particulate matter (PM) emissions from wood stoves and boilers, i.e. particle mass, particle size and chemical composition, strongly depend on the type of operation and the fuel properties. Investigations under real-life conditions show a relevant influence of the method applied for the initial fuel ignition and of the start-up from cold conditions on total PM emissions. Ignition from the top enables a reduction of total PM emissions by 50% to 80% in comparison to traditional ignition from the bottom. The measurement of condensables in addition to the measurement of solid particles sampled on a filter at 160°C according to VDI 2066 shows that the condensable fraction can exceed the mass of solid particles by up to a factor of five.
Keywords: Aerosols, combustion, emissions, emission reduction.

1 MOTIVATION

Particulate matter smaller than 10 microns (PM_{10}) is most relevant for the health impact of airborne pollutants in the ambient air [1, 2]. Increased concerns about PM emissions and their cardiopulmonary health risk motivate detailed emission measurements of combustion appliances. While large scale automatic combustion plants achieve high combustion quality and low emissions of unburnt carbonaceous particles, manually operated wood combustion often cause high emissions of unburnt carbon such as soot (elemental carbon, EC) and hydrocarbons (HC). In addition, automatic combustion plants are often equipped with fine particle removal equipment.

Consequently, residential wood combustion is considered to contribute significantly to the particulate matter (PM) in the ambient air, especially during winter and in areas where wood is traditionally used for heating. Measurements in Switzerland revealed, that during wintertime about 80% of the organic carbon in the ambient air in an alpine valley near the motorway originated from wood combustion [3], which is hence far more relevant than the Diesel soot from the transit traffic at the investigated location.

2 OBJECTIVES

The objectives of the present investigation are:

1. To identify the influence of operation and differences between type-test and real-life conditions on PM emissions of different wood stoves and boilers. In particular, the following parameters shall be investigated:

    - relevance of the start-up phase
    - type of ignition
    - warm start (as performed according to type-test standards for residential wood combustion devices) versus cold start
    - batch size, fuel humidity, log size.

2. To assess total PM in the ambient, not only solid particles (SP), but also condensables and volatile organic compounds (VOC, measured by FID) shall be investigated, since they can contribute to secondary organic aerosols (SOA) by condensation and photochemical oxidation.

3. To deduce recommendations for optimum ignition and optimum operation in practice.

4. To deduce recommendations to improve future type-test conditions to reward design principles that avoid poor operation in practice.

3 METHODOLOGY

This paper presents results from field-measurements and laboratory tests. PM emissions from different wood stoves and boilers were measured, i.e., different conventional wood stoves, a tile stove, a chimney stove and a log wood boiler as shown in Table 1. In addition, a prototype wood stove with two stage combustion was investigated earlier and is reported here as comparison.

Table 1: Overview on investigations on PM emissions.

Combustion devices	Field measurements	Laboratory measurements
Wood stoves (conventional design)	x	x
Wood stove with two stage combustion	–	x
Tile stove	x	–
Chimney stove	x	–
Log wood boiler	x	ongoing
Pellet stove	–	ongoing
Pellet boiler	–	ongoing

The comparison of different ignition modes included the conventional ignition of the fire from the bottom and ignition from the top. Ignition from the top is realized by putting a so-called "ignition module" on the top of a batch of logs as illustrated in Figure 1. The ignition module consists of four small logs of dry softwood with the dimensions of about 3 cm x 3 cm x 15 cm. The ignition module is ignited by some wax-covered wood wool. As test fuel beech wood was chosen.

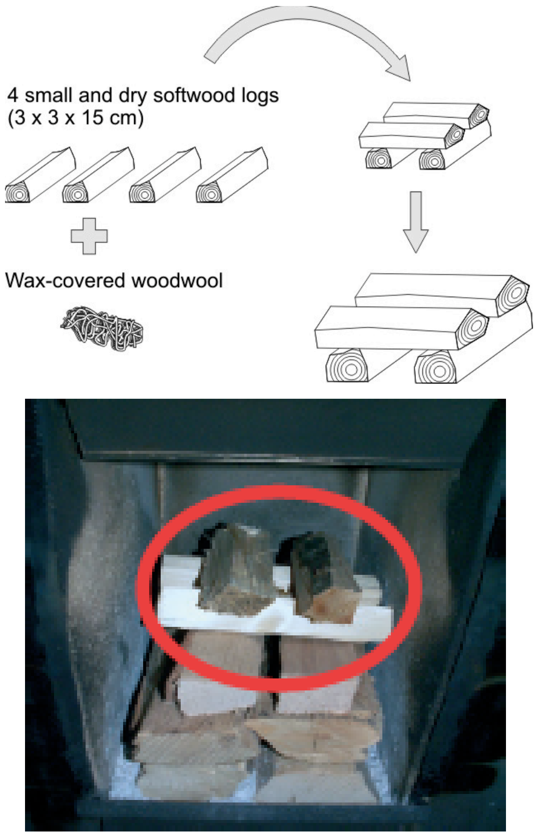

Figure 1: Illustration of the ignition module construction used for ignition from the top

For the field-measurements, a portable instrument Wöhler SM 96 was used for gravimetric PM detection and an Anapol EU-5000 for the gas composition.

In the laboratory of the Lucerne University of Applied Sciences, PM emissions were monitored according to the German norms (VDI 2066), i.e. isokinetic sampling on a filter probe heated to 160°C. Thus the solid particle fraction (SP) of PM was determined gravimetrically. Furthermore, condensable organic compounds in the flue gas were sampled by water-filled impingers at temperatures close to 0°C according to the EPA method 5H. After condensation in the cooled impingers, TOC analyses of the samples were conducted by an accredited laboratory. Emission measurements were performed and separately determined during the start-up phase, during stable operation and during burnout. Additionally, gaseous emissions of carbon monoxide, hydrocarbons (measured by FID) and nitrogen oxides as well as O_2 and CO_2 were continuously analyzed.

Besides a series of parameters, PM emissions can also be influenced by the chimney draft. According to European type-tests, wood stoves are operated with constant chimney draft of 12 Pa. However, the chimney draft under real-life conditions strongly depends on the flue gas temperature and can additionally be influenced by the atmospheric conditions. Hence wood combustion devices operated with natural draft (i.e., without ventilator) are strongly influenced by the chimney draft, which depends on the chimney characteristics, the flue gas temperature, the weather conditions, and several other parameters. To gain information on differences in PM emissions between type-test and real-life conditions, natural chimney draft is simulated in laboratory experiments. For this purpose, a first series of measurements of the flue gas temperature in the stack, chimney draft and weather conditions were conducted in a real-life wood stove with a metal chimney. Figure 2 shows an example of the measured chimney draft as function of time and illustrates, that operation at a constant chimney draft of 12 Pa as performed during type-test does not reflect real-life conditions. As illustrated in Figure 3, the chimney draft during start-up is strongly correlated to the flue gas temperature.

To enable measurements with conditions similar to real-life for natural draft, the chimney draft in the laboratory is electronically controlled as function of the flue gas temperature based on a linear correlation, i.e.:

$$p(T) = a\,T - b \quad [\mathrm{Pa}]$$

where T is the flue gas temperature in [°C]. For the presented example, a = 0.0671 and b = 0.287 is found with $R^2 > 0.99$ and used in the present test for the investigated stove. The illustrated example achieves a maximum draft which is slightly higher than 12 Pa. However, under real-life conditions, the maximum draft at high flue gas temperatures can also exceed this value by more than 100%, since the flue gas temperature can further increase depending on fuel amount, chimney insulation and other parameters. Hence the burning rate and the excess air ratio and consequently the resulting emissions can vary from the example with moderate chimney draft described here and thus the influence of natural draft and constant draft needs further investigation.

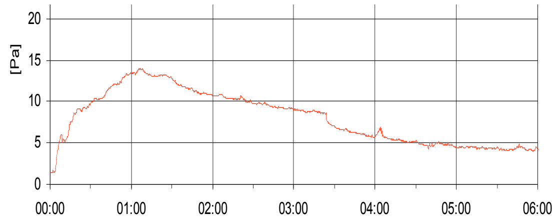

Figure 2: Natural chimney draft of a wood stove in the field as a function of time for one batch in a wood stove.

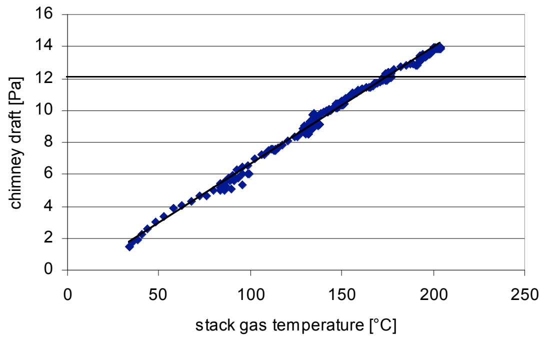

Figure 3: Natural chimney draft of a wood stove during field-measurements as function of the flue gas temperature in the stack.

4 RESULTS

4.1 Influence of start-up phase

The contribution of different phases of an entire burning cycle is exemplarily shown in Figure 4 and demonstrates the relative importance of the start-up phase, not only by PM concentrations in the flue gas, but especially by the cumulated loads. During the first 20 minutes, which corresponds to approximately 7% of the burning cycle, roughly 50% of the total PM emissions are emitted, whereas the role of the burnout is negligible, which illustrates the strong influence of the start-up phase on the total PM emissions.

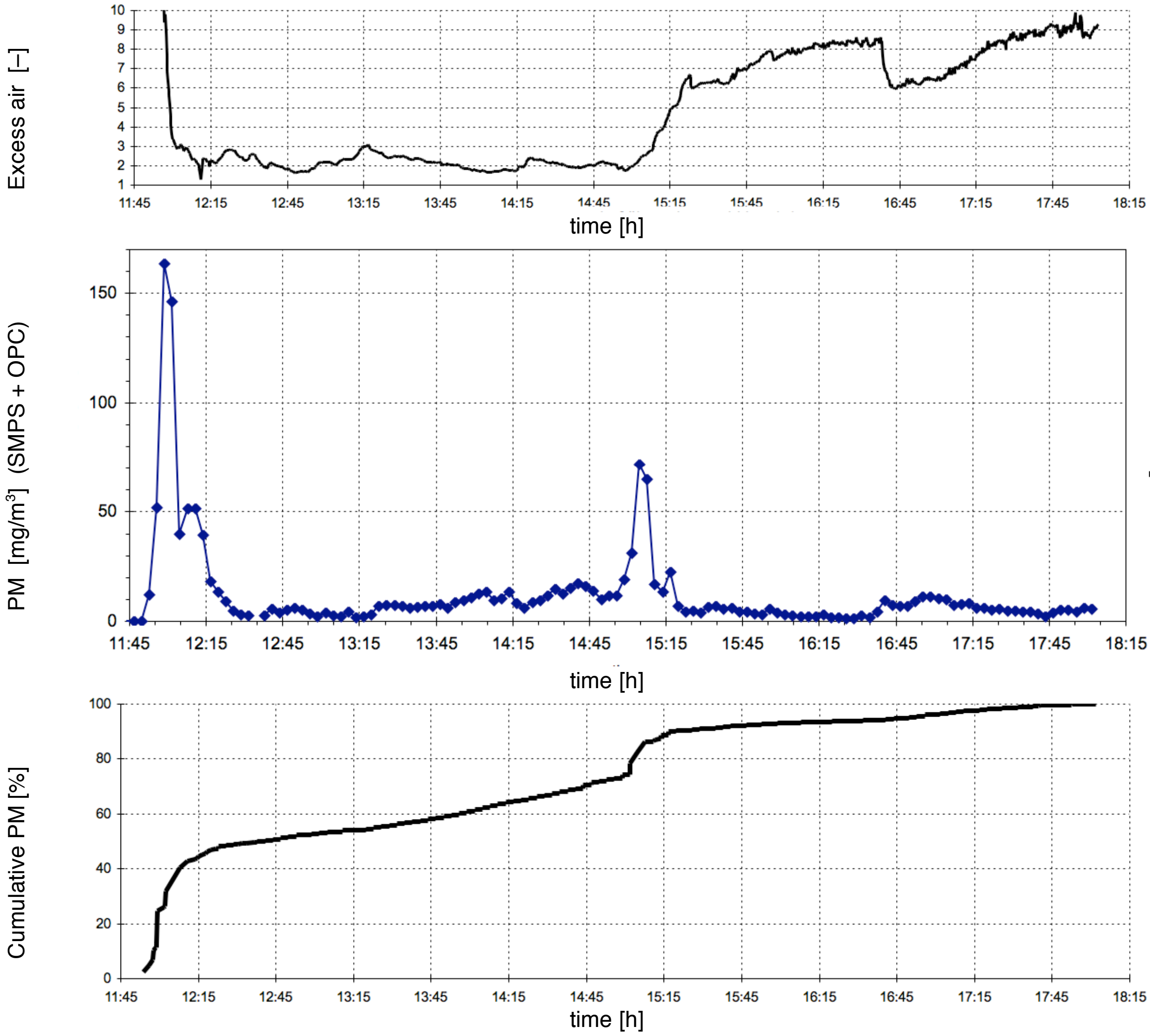

Figure 4: Excess air ratio, PM, and cumulative PM (from top to bottom) as function of time during an entire burning cycle in a manually operated wood combustion device. The shown example is performed for a two-stage combustion wood stove, which enables an operation of approximately 6h with a start-up phase of approximately 20 minutes. Hence the start-up phase is shorter than 10% of the entire cycle. The PM emissions are measured by SMPS and OPC and transformed to mass concentration, the data in the graph refer to PM concentrations not normalized to O_2 as the data are then integrated to calculate the cumulative PM mass during the entire cycle [4]. The cumulative PM emissions are integrated during the entire cycle and weighed with the flue gas volume flow according to the methodology described in [5].

4.2 Influence of ignition mode

The comparison of different ignition modes, which is visualized in Figure 5, reveals that ignition from the top results in significantly lower PM emissions than ignition from the bottom. The conventional ignition from the bottom causes the hole batch to burn simultaneously, which results in a high burning rate and leads to zones with lack of oxygen and incomplete combustion. Additionally, the flame can be cooled by the logs above. At the same time high concentrations not only of PM but also of CO and hydrocarbons are observed. In contrast, igniting the wood from the top leads to a stepwise and a more complete combustion. Consequently, ignition from the bottom enabled a reduction of total PM emissions by 50% to 80% in comparison to traditional ignition from the bottom.

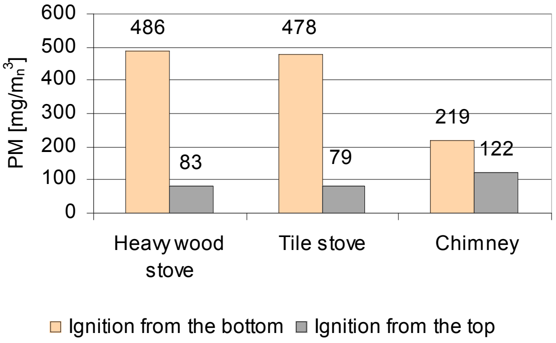

Figure 5 PM emissions in three different combustion devices operated with ignition from the bottom and ignition from the top using an ignition module [6].

4.3 Influence of operation type

The particle emissions under different operation conditions varied between 20 mg/m^3 at 13% O_2 and up to 5000 mg/ m^3 for a stove operated under very bad conditions [4]. Conventional updraft stoves achieved particle emissions of 20 – 50 mg/m$_n^3$ at 13% O_2 including start-up emissions, when operated ideally. An ideal operation is achieved by using a small amount of small dry logs and by igniting the fire from the top. When a glow bed is available, two small logs of dry wood (2 x 750 g at w = 12%) are added. Even lower particle emissions were achieved in a prototype of an advanced two stage combustion stove operated with dry wood resulting in 10 mg/m$_n^3$.

If the conventional stoves were operated under typical heating conditions with more than 50% filled fuel chamber and using wood logs of 1.5 kg, the emissions increased by a factor of 5 to 10 due to incomplete combustion, presumably as a consequence of insufficient mixing and too short residence time in the hot zone. On the other side, the two-stage combustion stove can be operated with fully filled fuel chamber. Here, the instantaneous heat output and the residence time in the combustion chamber are not affected by the level of logs used in the fuel chamber. Hence the two-stage combustion achieves a relevant advantage under typical heating conditions. If the conventional stoves are operated under very bad conditions, i.e., by closing the air inlet after start-up to prolong the combustion time, the emissions increase by another factor of 10. Such an operation is not possible in the two-stage combustion stove. When wet fuel is used and/or the combustion air is closed, the fire in the two-stage combustion stove extinguishes and hence increased emissions occur only during a limited time period, while conventional wood stoves can be operated with excessively high emissions during hours.

4.4 Influence of natural draft

First measurements simulating natural chimney draft in the laboratory were performed and compared to measurements at a constant draft of 12 Pa according to type-test conditions. Results shown in Figure 6 indicate higher PM emissions during the ignition phase and similar emissions during stable burning. The natural draft is low during the start-up which leads to an extended ignition phase with rather low temperature in the combustion chamber. Consequently, the formation of products of incomplete combustion is enhanced and leads to higher PM emissions. However, the reproducibility of natural draft experiments is lower than applying type-tests conditions.

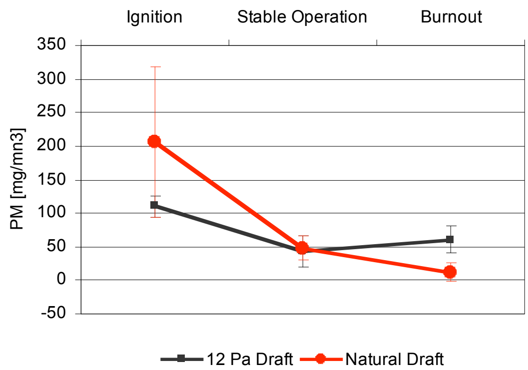

Figure 6: Comparison of PM emissions at 13 vol.-% O_2 under type-test and natural draft conditions.

4.5 Contribution of condensables to total PM emissions

The fraction of organic condensables under cold start conditions is by a factor 1.3 to 5 higher than the fraction of solid particles (SP) measured at 160°C. In Figure 6 the contributions of C and SP during the ignition phase are shown. Similar distributions of both fractions are observed during stable operation, but they are about a factor of 10 smaller. On the other hand the situation is different for type test conditions where logs are put on a glow bed: the condensable fraction is about 50% of PM in the investigated case. It is likely that the formation of condensable organic compounds is influenced by the combustion chamber temperature and enhanced by low temperatures. First measurements of HC by FID are in the same order of magnitude as C determined by impingers.

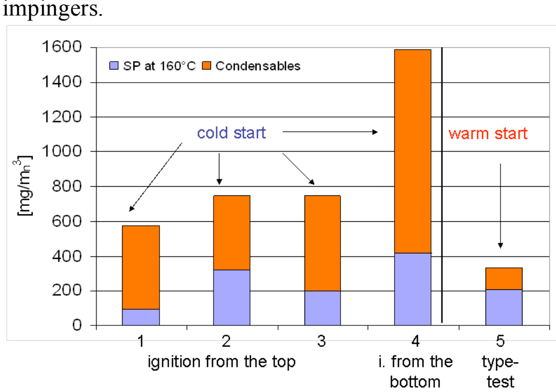

Figure 7: Fractions of solid particles SP and Condensables under different operation conditions.

5 CONCLUSIONS

- The start-up phase contributes over proportionally to the total PM emissions in manual wood combustion, but is not considered in nowadays type-tests.
- For conventional wood stoves, igniting the fire from the top can reduce PM emissions in practice during start-up and during the whole batch.
- For manual wood combustion, the operation type strongly influences the PM emissions.
- For typical conditions in wood stoves, high concentrations of organic condensables are emitted which are not trapped in hot filter sampling. The concentration and their contribution to the total PM expected in the ambient can vary in a wide range. The mass concentration of condensables can exceed the solid particles sampled on hot filters by a factor of up to 5 or even more.
- Preliminary results indicate lower concentrations of condensables for warm start than for cold start. It is likely, that organic condensables (hence hydrocarbons) can be reduced by high combustion temperature.
- Preliminary measurements indicate a good correlation between hydrocarbons measured by FID and condensables trapped in impingers. This is expected since hydrocarbons except methane and other low molecular compounds are likely to be trapped in the impingers. Hence for emission limit values, solid particles sampled on a hot filter and VOC detected in the hot flue gas might be a good choice as they reflect the airborne emissions from wood stoves and boilers which are health relevant as primary aerosols and as potential precursors of secondary organic aerosols.
- The correlation between condensables and hydrocarbons measured by FID is further investigated.
- The use of emission factors to predict PM_{10} in the ambient air by considering solid particles trapped on hot filters only can significantly under-estimate the contribution of residential wood combustion, since secondary organic aerosols (SOA) from condensation of condensables and from photochemical oxidation of VOC can highly exceed the mass of primary solid particles.

6 LITERATURE

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