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Variables affecting emission measurements from domestic wood combustion

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Abstract

Wood heating is an important worldwide source of emissions of particulate matter, comprising black and organic carbon. In Norway, woody biomass combustion is a significant source of particle emissions. In 2013 about 1.2 billion tons of wood logs were burned, according to the response from annual questionnaires made by statistics Norway. About 1.0 million tons were burned for household heating. About 54% of the wood was burned in stoves with new combustion technology (in 550 000 stoves) while the remaining wood was burnt in old stoves (in 420 000 stoves).
The motivation of this investigation is to highlight the impact of some of the most important variables inherent to two different wood stove test standards, i.e. the EN 13240 DIN+ with heated filter method and the NS3058-59 full flow dilution tunnel method with ambient particle sampling, regarding the total amount of measured particulate matter collected gravimetrically on standard filters supported in standardized filter holders.

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Keywords: Domestic Wood Combustion Stove Approval Standards, Particle emissions

1. Introduction

The current paper includes results from particulate matter measurements performed by SP Fire Research Norway in cooperation with SINTEF Energy Research, as part of a project funded by the Norwegian Environment Agency. The purpose of this paper is to highlight the influence of some of the most important variables, inherent to EN 13240 DIN+ HF method [1] and the NS3058-59 FFDT method [2] with ambient particle sampling, regarding the total amount of measured particulate matter (TSP) collected gravimetrically on standard filters supported in standardized filter holders. Previous work has been criticized when performing similar experiments, by not performing measurements on HF and FFDT filter simultaneously, to ensure the exact same flue gas conditions. With this in mind, the current experimental

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campaign performed simultaneous particulate matter measurements on HF (⩾ 70°C) sampled from the chimney and on conditioned (⩽ 35°C) non-heated filters sampled from the FFDT. The difference when performing successive, as opposed to parallel, measurements is the relatively large variation in operational conditions due to the batch combustion principle and using wood logs. This is further explained in this work and quantified based on the current results.

Wood heating appliances such as wood stoves and fireplace inserts have been identified as significant sources for emissions to air. Hence, several countries have introduced emissions requirements for domestic heating with wood. Each stove, which comes on the European market, has to be approved according to the common EU standard EN 13240. This standard sets regulations for safety, efficiency and CO emissions, but not particle emissions. Some countries have established emission limits also for particles and developed measurement methods. A European Committee for Standardization, CEN/TC 295 WG05, has for several years worked on a common method for particle measurement. Three established methods are still described in a technical specification, CEN/TS15883:2009, the Austrian and German particle test method (DIN+), the Norwegian particle test method (NS3058-1/2) and the UK particle test method. The two most commonly used measurement methods for particles in Europe are the Norwegian Standard for Enclosed wood heaters (NS3058-1/2) sampling particles in a dilution tunnel and the DIN+ certification scheme sampling directly in the chimney. These two methods will result in variation in measured particle emission levels, mainly due to variation in the mass of condensable matter collected due to differences in the test procedures and filter temperature.

Nomenclature

TSP	Total Suspended Particulate matter, airborne particles or aerosols less than 100 micrometres
FFDT	Full Flow Dilution Tunnel
HF	Heated Filter

1.1. Standards for approval of enclosed wood heaters

Since 1998, enclosed wood heaters must be approved for sale and use in Norway according to the Norwegian standard NS3058-59. All stoves and fireplaces have to meet the emissions requirements described in NS3059 [3] with 20 g/kg (dry basis) as maximum allowable emission for each test and 10 g/kg as maximum weighted mean value (up to 4 loads, low to max). The collected particles are recorded gravimetrically and reported in g/kg dry wood. To put these requirements in perspective, Denmark introduced emission limits for wood stoves in 2008 where stoves must be tested according to either NS3058-59 or the EN 13240 DIN+ certification scheme. Recently updated Danish emission limits from 2015 is 5 g/kg according to NS 3058-59 and 40 mg/Nm3 according to 13240 DIN+ and from 2017, 4 g/kg and 40 mg/Nm3, respectively. In comparison, the Nordic Swan Ecolabel, a voluntary positive Ecolabelling of products and services, requires 3 g/kg as maximum weighted mean value (up to four loads, low to max) with 6 g/kg as maximum allowable emission for each test in 2014-2017, with 2 g/kg and 5 g/kg as max in 2017-2019.

NS3058-1 describes the test facility, fuel and heating patterns. NS3058-2 gives criteria for the determination of particles sampled in a FFDT.

1.2. Differences in standards and methods

The standards and methods differ in several ways. The most significant differences are which emissions that are measured, test facility, sampling location, sampling temperature, sampling period, fuel load and type of fuel. Fig. 1 (h) shows the main differences between particles sampled according to NS3058 and DIN+ (which includes particle measurements in contrast to EN 13240). Sampling temperature (solid particles for DIN+ 13240 versus solid particles + condensables) and location (in chimney for DIN+ 13240 versus near the end of the dilution tunnel) influences the kind of particles collected. DIN+ measurements in the hot undiluted flue gas result in collection of the solid fraction of particles mainly. However, stoves operated under poor conditions show a high share of condensable particles of organic substances. To collect all particulate matter, the filtration temperature needs to be reduced. By application of NS3058-59, dilution of the flue gas with ambient air in addition mimics the natural secondary particle formation mechanisms right after the flue gas exits the chimney, giving a more close to real-world picture of the total particles emitted [4]. In general, at close to nominal burn rates, the dilution tunnel measurements in line with the Norwegian standard produce at least around 2.5 times more TSP. At unfavorable conditions, the ratio has been measured to increase by a 10 fold [5]. The dilution tunnel measurements might on the other hand result in over-estimation of TSP due to re-evaporation of VOC from the particles by consecutive dilutions with increasing dilution ratio. This may occur when exhaust gas is diluted with ambient air after leaving the chimney [6]. Emission factors according to NS are much higher than emission factors from other European countries using a different measurement method [5]. Differences are primarily due to testing at low load, and applying a dilution tunnel in which the particles are sampled. The choice of measurement method and test procedure have a major influence on the emission factors and can to a large degree explain why different countries report such varying emission factors. Particularly, Norway reports the highest wood stove emission factor in Europe with 1800 g/GJ [7] (corresponding to 36 g/kg as an average for birch and spruce, when converted with the simple tool developed in the current work) for old and new stoves. Germany reports an emission factor of 105 g/GJ for wood heating in households [8] (corresponding to 2.08 g/kg for birch when directly converted).

1.3. Factors affecting emissions from residential wood combustion

Over the years, much effort has been put into research regarding the factors, which affects emissions from wood log combustion in wood stoves, many of which are all well known and understood today. Some of the most important factors are; moisture, ash content, amount of gasifying substances, log size, firebox size, shape and materials, flue gas outlet dimensions, air supply, stack height, size and shape, natural draft, air supply and mixing, combustion rate, fuel loading and finally in many cases the most important one; operation habits.

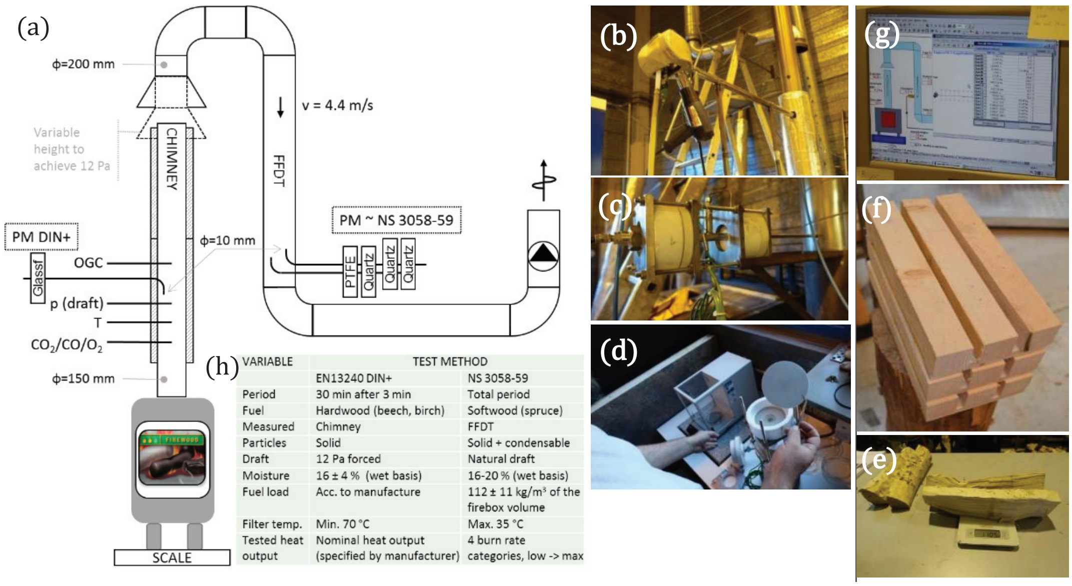
2. Experimental setup

The experimental setup in the current project is illustrated in Fig. 1, including a table showing the most important differences between DIN+ and NS. During all experiments, particulate matter was simultaneously sampled both on a hot filter and in the dilution tunnel. The setup can be run both in accordance with EN 13240 DIN+ as well in accordance with NS3058-59. When run as DIN+, the mass of fuel is given by the manufacturer's specification of nominal load for the selected stove, here 5 kW, calculated to 1.1 kg using the formula provided by the standard. When run as NS3058-59, the mass of the fuel is given by the dimension of the combustion chamber as 112± 11 kg/m_3 of the firebox volume.

The appliance selected for the current work was carefully chosen on the premises of being a modern, highly efficient low emission stove with a reasonable low nominal effect of 5 kW. The stove has a typical modern insulated combustion chamber using two-stage combustion, air preheating and window flushing from the top. It has been certified according to NS3058-59 with weighted emissions of 2.1 g/kg dry wood as a grade 2 stove. According to EN 13240 it has an efficiency of around 80%. Leakage at 25 Pa is about

10 m³ per hour. However, it is has a small peculiarity, i.e. slightly increasing particle emissions as the heat output increases from the nominal value.

Measurements results of particulate matter from EN 13240 DIN+ are given in mg/Nm3 (13% O_2), determined by the amount of mass collected on the hot filter divided by the volume of flue gas drawn through the filter by the pump. Results from the NS3058-59 FFDT are given in g/kg dry fuel. This necessitates conversion between the two emission units. DIN+ reports mg/Nm^3 at 13 vol % O_2 and reporting requires knowledge of average CO_2 or O_2. FFDT can report to g/hr, g/kg dry fuel, g/GJ or mg/Nm^3 but requires additional measurement to determine the average dilution ratio. To be able to compare results from the two methods they have been converted to a common basis in g/GJ. The conversion requires knowledge of the wood specie composition, ash content, and upper heating value. For birch and spruce the following values has been used for carbon content (%), carbon content in ash (%), hydrogen content (%) and higher heating value (kJ/kg); 50.2, 0.6, 5.1, 19805 and 50.8, 0.4, 5.3, 20268, respectively. For HF experiments in accordance with DIN+ organic gaseous compounds were not measured, as the tests were performed in accordance with FFDT. The moisture varied between 16-17% for birch and between 16-19% for spruce, on wet basis, which is within the requirements of both DIN+ and NS3058-59. The variation is believed to be sufficiently small to not affect the results in terms of moisture variation influence. When experiments were performed according to DIN+, sampling both on the HF and in the FFDT was started after 3 min. and stopped after 33 minutes. When sampling according to NS3058-59 the sampling was performed over the whole batch period. For each method tested, each class of heat output (nominal and high) and each type of wood species, three repeated experiments were performed to achieve a minimum of statistically sound values. For each series, the relative standard deviation (RSD), also known as the coefficient of variation (CV), was calculated.



VARIABLE	TEST METHOD	
	EN13240 DIN+	NS 3058-59
Period	30 min after 3 min	Total period
Fuel	Hardwood (beech, birch)	Softwood (spruce)
Measured	Chimney	FFDT
Particles	Solid	Solid + condensable
Draft	12 Pa forced	Natural draft
Moisture	16 ± 4 % (wet basis)	16-20 % (wet basis)
Fuel load	Acc. to manufacture	112 ± 11 kg/m³ of the firebox volume
Filter temp.	Min. 70 °C	Max. 35 °C
Tested heat output	Nominal heat output (specified by manufacturer)	4 burn rate categories, low -> max

Fig. 1. (a) Combined experimental setup simultaneous sampling on HF and in FFDT, (b) filter holder and probe for HF and (c) Ambient filters, (d) Weighing the filters, (e) EN 13240 DIN+ woody fuel, (f) NS3058-59 woody fuel , (g) Logging system, (h) main differences between NS3058-59 and EN 13240 DIN+

3. Experimental results and discussion

The experimental results in the current campaign were classified as low, nominal and high heat output cases given by; low < 1.4 kg/h, 1.4 ⩽ nominal < 1.75, high ⩾ 1.75. For all the tests the collected mass of TSP on the FFDT filters were found to be substantially higher than on the HFs. When compared on a common unit in g/GJ, about 4 and 8 times more was measured on the FFDT filter for birch and spruce, respectively. More mass due to condensation of organic gaseous compounds on the FFDT filter was expected and has been shown in literature, e.g. in [5]. In addition, spruce tends to volatilize faster than birch (both due to property differences as well as due to the smaller physical shape according to the FFDT method), especially at low and high burn rates were the combustion conditions normally are worse when compared to nominal burn rate. Overall, the amount of particles collected with the FFDT method was about 6.5 times higher than the amount of particles collected on the HF, when intermixing birch and spruce. Comparing only the nominal series, 7.6 times more particles were collected with the FFDT method, intermixing spruce and birch. At high load the difference were only 2.7 times more particles collected. This probably demonstrates that condensable matter to a certain degree also collects and/or adsorbs on the HF, although to a much lesser degree than when sampled in the FFDT. This effect is especially noticeable at high particle concentration in the flue gas. As with the approval tests, the selected stove showed increasing emissions when the heat output was increased above nominal, as well as the expected behavior of exponential increase at low load conditions.

As DIN+ requires a minimum of 30 minutes of sampling after 3 minutes, it was expected that when testing in accordance with NS, over the whole batch period, this would produce significantly more particulate matter on both the HF and the FFDT filter. However, the results are mixed. For the shortest periods (some shorter than 30 minutes due to high load), much particulate matter is produced probably due to lack of combustion air and insufficient residence time for proper burnout. At DIN+ conditions, with 30 min. of sampling, we see that only a small portion of the particles is captured on the HF relative to the amount on the FFDT filter. A further increase in the sampling period do not seem to increase the amount of captured particles on the HF. This effect might be explained by an increasing disproportion of the period when solid particles are formed relative to the total sampling time since the charcoal phase tends to produce very little solid particles.

Another factor affecting the particle emissions is the type of wood used during certification tests. The average values from the experiments for the nominal heat output series show that less particles are captured from spruce than from birch, both on the HF and in the FFDT filter when the experiments are performed in accordance with DIN+ sampling as 3+30 minutes. Common experience is that spruce will volatilize faster than birch and produce larger quantities of OGCs quite early in the combustion process. Restricting the sampling to 3+30 min. might therefore result in the escape of parts of the volatile matter, thereby producing less mass on the FFDT filter. Examining the amount of collected particles for birch and spruce when measured over the total batch in accordance with NS also shows slightly less particles captured for spruce at nominal burn rate. However, at high burn rates the emission from spruce surpasses that from birch. Although no measurements were performed for birch at low burn rate, the steep increase in emissions from spruce is assumed to surpass those from birch, at least when judged from previous experience. All-in-all, comparing all single experiments, an average of 3.9 times more mass per energy unit was captured on the FFDT filter when burning birch as compared to 9 times more when burning spruce, keeping in mind that no experiments were performed at low burn rate with birch.

In Fig. 2 the captured amount of particulate matter from all experiments, both on the HF and the FFDT filter is shown. We observe that the collection of particles on the HF increases as the combustion conditions deteriorate, but only towards higher loads. This might be due to an increased burn rate, higher flue gas flow, as well as an increase of the combustion chamber temperature producing more ash related condensables.

Also, worse burnout conditions might add to the condensables captured even on the HF. At loads below nominal, no experiments were performed as DIN+ and measurements were only performed with spruce. Collection of mass on the HF do not seem to be affected by lower loads as compared to the FFDT. The FFDT filter shows a typical behavior of exponential mass increment at low loads (although only proven here for spruce) as well as slightly increased emissions at the highest loads, the latter sometimes observed in newer stoves due to low/nominal load combustion chamber optimization.

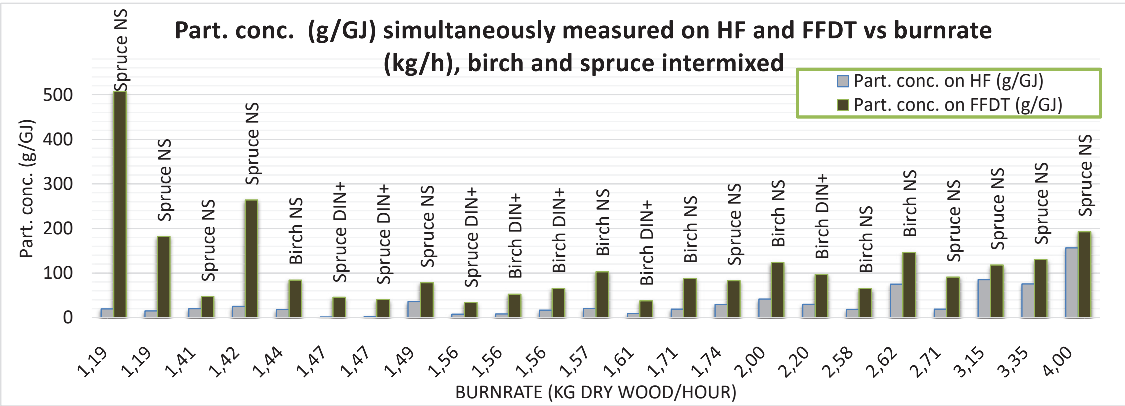


Fig. 2. All experiments, particulate matter collected on HF and in FFDT in g/GJ vs burn rate in kg dry wood per hour

Collected particulate matter both on the HF and on the FFDT filters increases for spruce when compared to birch. The increased emissions on the HF is probably due to increased capturing of condensables also on these filters. Both OGC as well as volatilized ash compounds adds to the increased mass of captured particulate matter. Performing the experiments in accordance with DIN+, using birch and increasing the fuel load from 1.1 kg (calculated nominal load according to DIN+) to 1.7 kg (calculated nominal load according to NS), results in a 3X increase in collected particulate matter on the HF filters as well as 2 times more on the FFDT filters. The official approval tests showed that the particle emissions increased at higher heat outputs, which is related to how the stove manufacturer has chosen to optimize the stove regarding the air supply variation and emissions. However, this illustrates the importance of a common agreement on how the mass of the fuel load for a given stove is defined.

When the stove is supplied with a higher initial fuel load (DIN+/1.1 kg vs NS/1.7 kg), going from reduced to full sampling period (30 min. vs whole batch), as well as deviating from nominal load (high for birch, and high and low for spruce), the particulate emissions will increase for both birch and spruce. On the HF filter the particle emissions from birch and spruce increases about 4 and 6 times, respectively, going from nominal to high heat output. Comparatively, FFDT sampling shows only a 2 and 3.7 times increase in the particle emissions for birch and spruce, respectively. A possible explanation for this is a significant increase in the production of condensables due to insufficient air supply, both from the ash and OGC, on the HF. Going from nominal to low load increases the emissions from spruce by 8.6 times on the FFDT filter.

The CV (coefficient of variation), also known as RSD (relative standard deviation), is a standardized measure of dispersion of a probability or frequency distribution. It is often expressed as a percentage, and is defined as the ratio of the standard deviation to the absolute mean. The CV or RSD is widely used in experimental science to express the precision and repeatability. To put the RSD in perspective, random probability results are those with a RSD > 50 %, putting the results from two of the current measurement series in this category. For the current experimental matrix counting all experiments, the average coefficient of variation for the HF and the FFDT method was 36% and 30%, respectively. This implies that if the measurements are not performed in parallel the results may vary with as much as ±36% and ±30%.

4. Conclusion

The current project has highlighted several factors affecting the particle emissions to different degrees. However, it must be emphasized that one should be careful when generalizing upon measurements performed on one single appliance. An important outcome is the quantification of the difference in the total amount of particles collected according to the two different methods, i.e. sampled simultaneously on heated and ambient filters. For all the tests, the total collected mass on the FFDT filters were found to be substantially higher than on the HFs. When compared on a common unit in g/GJ, about 4 – 8 times more mass was collected on the FFDT filter for birch and spruce, respectively. In average, the mass of particles collected with the FFDT method was about 6.5 times higher than the mass of particles collected on the HF, when intermixing birch and spruce.

Important recommendations from the current work is that when new test standards are developed one should give special attention towards choice of filter temperature and location, sampling period, fuel loading and burn rate(s). Measured organic gaseous carbon emissions from wood burning cover all gaseous hydrocarbons that might or might not contribute to the condensable fraction of the total particle emissions. Using a dilution tunnel will enable test laboratories to at least account for the condensable organic gaseous carbon fraction by mimicking the effect of secondary reactions influencing the particle emission level. Hence, the addition to any new method, of a dilution tunnel or a similar device, will provide a more realistic picture of the actual particle emissions to the atmosphere.

Acknowledgements

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Biography

Morten Seljeskog, born in 1964 – holds a Doctor of Engineering (Dr.ing) from the Norwegian University of Science and Technology defended in 2002 on the topic of shock tubes and cold plasma experiments. He is currently employed, since 1998, as a researcher at SINTEF Energy Research.