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Report

Factors affecting emission measurements from residential wood combustion

Simultaneous gravimetric filter sampling of particulate matter in flue gas from chimney and diluted flue gas from dilution tunnel, on hot filter (≥ 70 ˚C) and on ambient filter (≤ 35 ˚C) respectively, to determine to which extent variables inherent to EN 13240 DIN+ and NS3058-59 affect the amount of measured particulate matter

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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 purpose of this investigation is to highlight the influence of some of the most important variables, inherent to two different wood stove test standards, i.e. the EN 13240 DIN+ HF (heated filter) method and the NS3058-59 FFDT (Full Flow Dilution Tunnel) method, regarding the total amount of measured particulate matter (PM_t) collected gravimetrically on standard filters supported in standardized filter holders. An important outcome is the quantification of the difference in the total amount of particles collected according to the two different methods, using HF and FFDT. 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 4X and 8X 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 6.5X higher than the mass of particles collected on the HF, when including both birch and spruce.

When developing a new test standard 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 woodburning 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.

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1 Introduction

The current report includes results from particulate matter measurements performed by SP Fire Research Norway in cooperation with SINTEF Energy AS, as part of a project funded by the Norwegian Environment Agency. The purpose of this report is to highlight the influence of some of the most important variables, inherent to EN 13240 DIN+[1] HF (heated filter) method and the NS3058-59[2] FFDT (Full Flow Dilution Tunnel) method, regarding the total amount of measured particulate matter (PM_t) 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 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 report 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, 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, as described in the following.

1.1 Norwegian Standard for Enclosed wood heaters NS3058-1/2, NS3059

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] and shown in Table 1-1. Denmark also introduced emission limits for wood stoves in 2008 where stoves must be tested according to either NS3058-59 or the DIN+ certification scheme. The new Danish emission limits for 2015 and forward are given in Table 1-2. The Nordic Swan Ecolabel requires additional testing according to the Norwegian standard NS3058-59, with a stricter emission limit of 4 g/kg.

Table 1-1: Emission limits according to the current Norwegian Standard[2]

	Maximum allowable emission for one test (d.b.)	Maximum weighted mean value (d.b.)
Wood heaters	20 g/kg	10 g/kg

[1] DIN+ certification scheme: Room Heaters (Solid Fuel Stoves) with low-pollution combustion according to DIN EN 13240

[2] NORSK STANDARD, NS-3058 (1994), Enclosed wood heaters, Smoke emission

[3] NORSK STANDARD, NS-3059 (1994), Enclosed wood heaters, Smoke emission, Requirements

Table 1-2: New emission limits for Denmark

	PM according to NS3058 FFDT	Dust according to DIN+ HF	OGC DIN+ HF
From 2015	5 g/kg	40 mg/Nm^3	150 mg C/Nm^3
From 2017	4 g/kg	30 mg/Nm^3	120 mg C/Nm^3

NS3058-1 describes the test facility, fuel and heating patterns. NS3058-2 gives criteria for the determination of particles sampled in a FFDT. The approval must be performed with four tests at different burn rates (Table 1-3). The standard divides enclosed wood heaters in two grades; Grade 1 and 2. Grade 1 enfolds stoves and fireplace inserts which can be operated with very low burn rate, below 0.8 kg/h. These stoves are in general smaller units. Appliances in Grade 2 achieve the lowest burn rate below 1.25 kg/h but above 0.8 kg/h. The intention of testing the stoves at four different burn rates is to better reflect real-world firing habits and take into account that stoves should handle a range of burn rates without compromising particle emissions. NS3059 describes the final calculation of the four test runs with a specific weighting, depending on the grade and a probable burning pattern.

Table 1-3: Burn rate categories[2]

Burn rate category [Average burn rate kg/h dry]	1	2	3	4
Grade 1	< 0.80	0.80 – 1.25	1.26 – 1.90	> 1.90
Grade 2	< 1.25	1.25 – 1.90	1.91 – 2.80	> 2.80

The test fuel consists of air dried timbered spruce with moisture content between 16-20 % on wet basis and weight according to a filling density of 112 ± 11 kg/m^3 of the useable firebox volume. The geometry of the test fuel is shown in Figure 1. The test facility consists of a chimney with a height of about 4.5 m measured from the bottom of the stove to allow testing with natural draft. A dilution tunnel is installed to dilute the exhaust gas with ambient air and cooling the flue gas down close to room temperature. The tests are performed with natural draft (Figure 2). The particle measurement is taking place in the dilution tunnel and the gas is withdrawn isokinetically with constant volume flow. The filter holder contains two circular 10 cm in diameter plane filters in succession with a porosity of 1 µm. Due to the low filter temperature, plain glass fibre filters may be used.

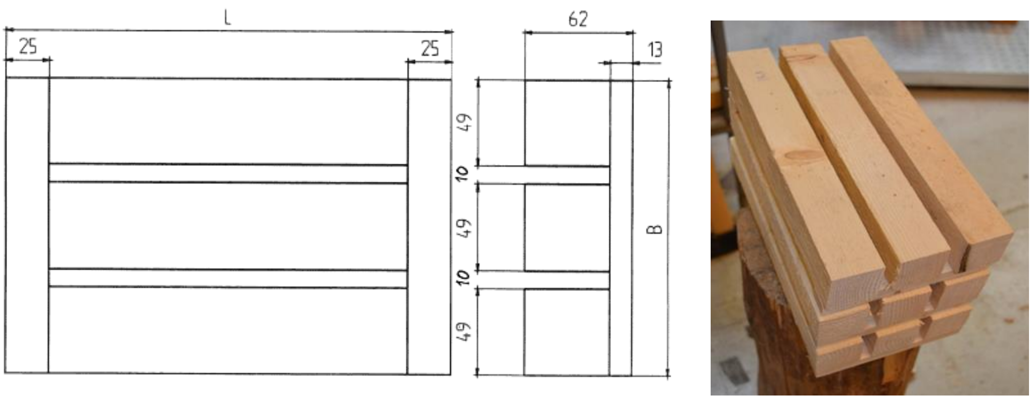

Figure 1: Test fuel geometry according to the Norwegian Standard[2]

The test is performed in a pre-heated stove, and the emissions are sampled over the whole batch of one fuel load. The requirements are that the pretest[2] shall last at least one hour with the desired air opening and shall give an amount of charcoal corresponding to 20 to 25 % of the test fuel weight. The average stove surface temperature shall not differ more than 70 °C from the start to the end of the test, to ensure that the stove is in thermal balance. The collected particles are recorded gravimetrically and reported in g/kg dry wood.

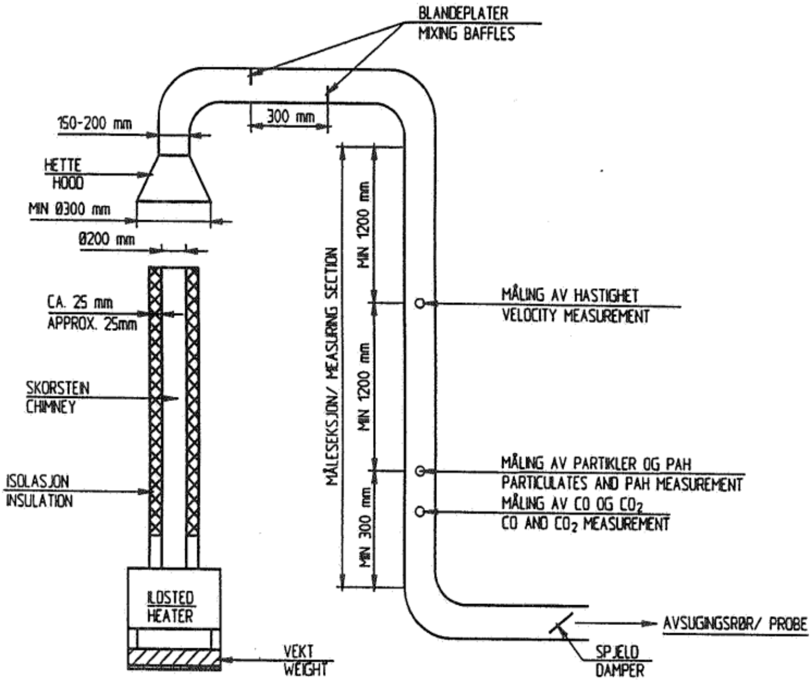

Figure 2: Dilution tunnel with wood heater and chimney (NS3058)

1.2 EN 13240 – Room heaters fired by solid fuel

All room heaters on the European market, including Norway, must be tested according to the standard EN 13240. It combines the basic requirements as with focus on manufacture, construction, safety, performance (efficiency, carbon monoxide emissions), instruction and labelling. It addresses manual feed boilers, stoves and fireplace inserts fired by solid fuels such as wood logs as well as mineral fuels and peat briquettes. The requirements on CO emissions are 1 vol % and the minimum efficiency is 50 % (see Table 1-4). EN 13240 does not contain requirements for particulate matter emissions. The standard describes the test method and test fuel. The test is performed at nominal heat output with a test fuel defined by the manufacturer with constant forced draught at 12 Pa. In addition to CO emissions, CO_2 levels in the flue gas are recorded. Before the test periods starts, the stove is preheated through an ignition and pre-test period. The following test period consist of three loadings with a minimum duration of 45 min.

Table 1-4: Requirements in EN 13240 Room heaters fired by solid fuel

	Limit value
CO	< 1 vol %
Efficiency	> 50 %

1.3 German method DIN+

The German method is based on the certification scheme DIN+ with stricter requirements than EN 13240 (room heaters), EN 13229 (inset appliances) and EN 12815 (residential cookers) and includes particle measurement in addition to nitrogen oxides and unburned hydrocarbons. The requirements are shown in Table 1-5. The particle sampling starts 3 min. after the fuel has been added and continues for 30 minutes. A constant volume is withdrawn during the test period. Due to the fixed pre-calculated volume, the sampling is also only approximately isokinetic. The temperature of the filter shall be kept ≥ 70 °C[1]. The tests are performed according to the described test procedure and test setup in the European standards EN 13240, EN 13229 and EN 12815.

Table 1-5: Requirements on wood stoves according to DIN+ certification

	Emission (at 13 % O_2) and efficiency limits
CO	1500 mg / Nm^3 (corresponds to 0.12 vol% at 13 % O_2)
NO_x	200 mg / Nm^3
C_nH_m	120 mg / Nm^3
Dust	75 mg / Nm^3
Efficiency	75 %

1.4 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. Table 1-6 gives an overview of the differences between particles sampled according to NS3058 and DIN+ (which includes particle measurements in contrast to EN 13240).

Table 1-6: Overview of the main differences between NS3058-59 and EN 13240 DIN+

	DIN+ 13240	**NS3058-59**
Emission unit	mg/Nm^3 at 13 % O_2	g/kg dry wood
Sampling period	30 min. after 3 min.	Time from charging the stove until complete combustion of test fuel
Fuel	Hardwood (beech, birch)	Softwood (spruce)
Sampling location	Chimney	FFDT
Particles collected	Solid	Solid + condensable
Draft	12 Pa forced	Natural draft
Moisture content	16 ± 4 % (wet basis)	16-20 % (wet basis)
Fuel load	According to manufacturer	112 ± 11 kg/m^3 of the firebox volume
Filter temperature	≥ 70°C	≤ 35°C
Filter diameter	90 mm	100-103 mm
Tested heat output	Nominal heat output (specified by manufacturer)	4 burn rate categories, low -> max

Sampling temperature (solid particles for DIN+ 13240 versus solid particles + condensable) 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, 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].

Sampling particles in the hot undiluted flue gas (DIN+) results in underestimation of particulate matter (PM) from wood stoves due to formation of aerosols of condensable matter in the flue gas when cooling it down to ambient temperature. The ratio of particles in the dilution tunnel to particles measured in the chimney depends on the combustion conditions. If the combustion is good, as at nominal conditions meaning almost complete burnout of particles and combustible gases, the difference between dilution tunnel and chimney measurements decreases. 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 PM_t. At unfavorable conditions, the ratio increases up to 10. Then 10 times more PM_t are collected in the dilution tunnel compared to the chimney.[5] The dilution tunnel measurements might on the other hand result in over-estimation of PM_t 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 on low load, and applying a dilution tunnel in which the particles are sampled. The Norwegian standard requires four tests, at four different burn rates. The stoves are tested also under less favourable combustion conditions, with reduced burn rates lower than 1.25 g/kg. This leads to higher emissions compared to tests performed only under the combustion condition for which the stove is optimized for, also referred to as nominal load. The dilution tunnel method captures condensed particles in addition to the solid particles. In conclusion, 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 project) 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).

1.5 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, which are all well-known and established today. Table 1-7 provided here[9] is a good example describing the factors, their characteristics and the effect on the emissions.

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4 Nussbaumer T, Czasch C, Klippel N, Johansson L, Tullin C. Particle emissions from biomass combustion in IEA countries- Survey on measurements and emission factors. International Energy Agency (IEA) Bioenergy Task 32; Swiss Federal Office of Energy; 2008

5 Nussbaumer, T.; Klippel, N.; Johansson, L. 2008; Survey on measurements and emission factors on particles matter from biomass combustion in IEA countries, 16th European Biomass Conference and Exhibition, 2–6 June 2008, Valencia, Spain – Oral Presentation OA 9.2

6 Nussbaumer T. Feinstaub-Emmisionsfaktoren von Holzheizungen: Übersicht aus Ländern der Internationalen Energie Agentur – Bioenergy Combustion Task. 10. Holzenergie-Symposium 12.09.2008

7 http://www.russianarcticbc.org/documents/presentations/2011_10_06/MYRTVEIT%20Norway%20Black%20Carbon%20Emissions.pdf

8 Struschka, M. et al. (2008), " Effiziente Bereitstellung aktueller Emissionsdaten für die Luftreinhaltung", Umweltbundesamt

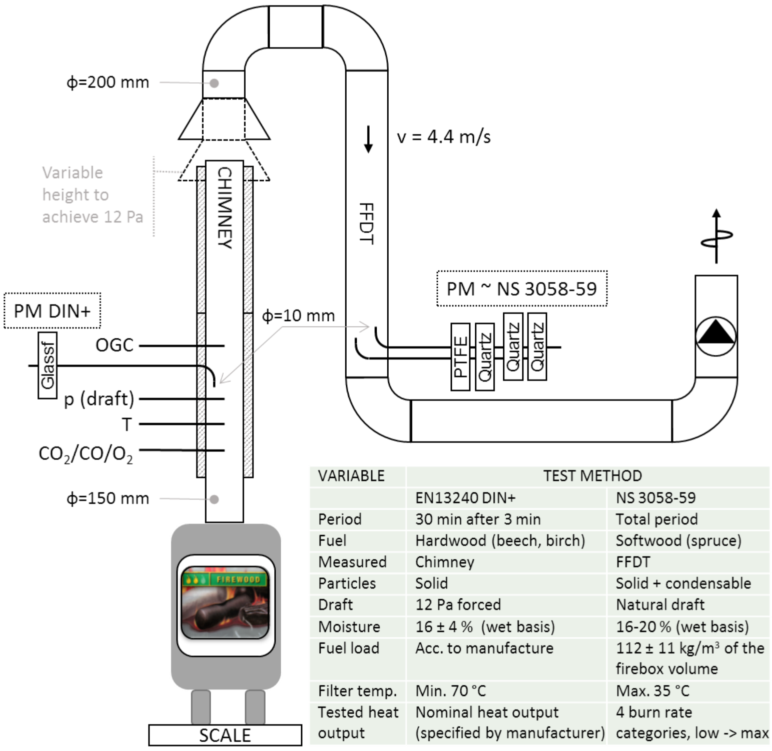
Table 1-7: Factors affecting emissions from residential wood combustion[9]

Factor	Characteristic affecting emissions	Effect
Fuel	Moisture	Lowers combustion temperature
	Ash content	Increases particle emissions
	Amount of gasifying substances	Pyrolysis control more difficult, flame needs a lot of space
	Log size	In continuous combustion affects how constant the combustion is. In batch combustion affects firing and gasification rate
Appliance	Firebox size, shape and materials	Affects draft conditions and combustion temperature
	Flue gas outlet dimensions	Affects draft conditions
	Air supply	Affects the amount and mixing of combustion air
Smokestack	Stack height, size and shape	Affects draft conditions
Combustion conditions	Natural draft Affects combustion control Flue gas residence time	Affects emission burnout
	Combustion temperature	Affects emission burnout
	Air supply and mixing	Affects flue gas and air mixing
Flue gas after treatment	After treatment appliances	Affects emission quantity, and appliance operation and use
Operating conditions	Combustion rate	Affects gasification rate and amount of combustion gases
	Fuel loading rate	Affects combustion rate and momentary power
	Control devices	Affects fuel, air and appliance power control
Appliance user	Operation habits, garbage burning	Affects several combustion factors

2 Experimental setup

The experimental setup in the current project is illustrated in Figure 3, 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.

9 Tissari J., Raunemaa T., Jokiniemi J., Sippula O., Hytönen K., Linna V., Oravainen H., Pyykönen J., Tuomi S., Vesterinen R., Taipale R., Kolsi A., Nuutinen I., Kouki J., and K. Vuorio K. Puun polton pienhiukkaspäästöot. loppuraportti, 2005



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

Figure 3: The combined experimental setup, simultaneous sampling on HF and in FFDT

Figure 4: Experimental setup for measurements of particle emissions according to DIN+. The flue gas is diluted further upstream, through the hood, for simultaneous FFDT sampling. A constant draft of 12 Pa was achieved by adjusting the distance between the chimney and the hood.

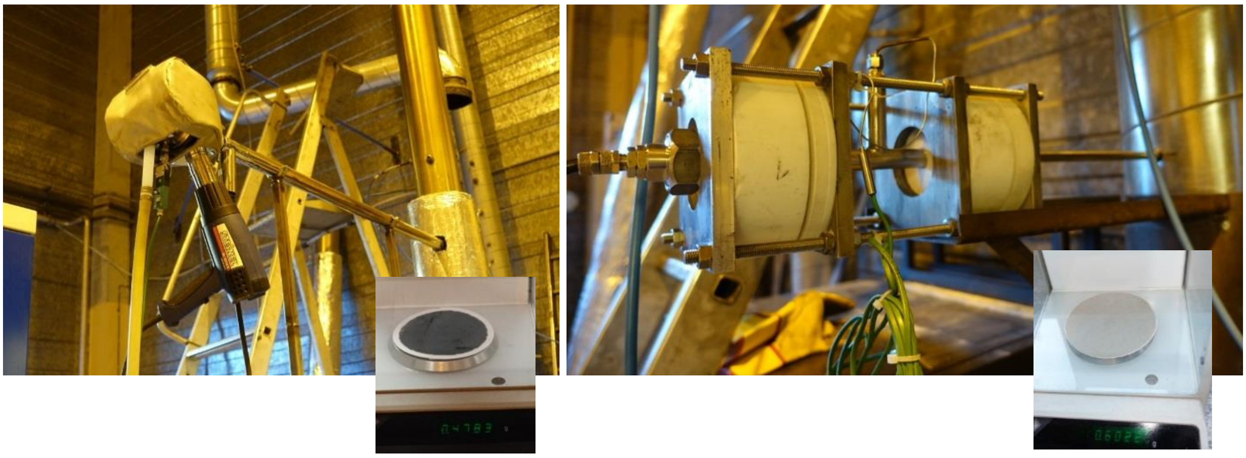


Figure 5: Experimental setup: close-up of HF and filter holder for FFDT, with appurtenant photo illustrating the typical filter colorization inherent each method.

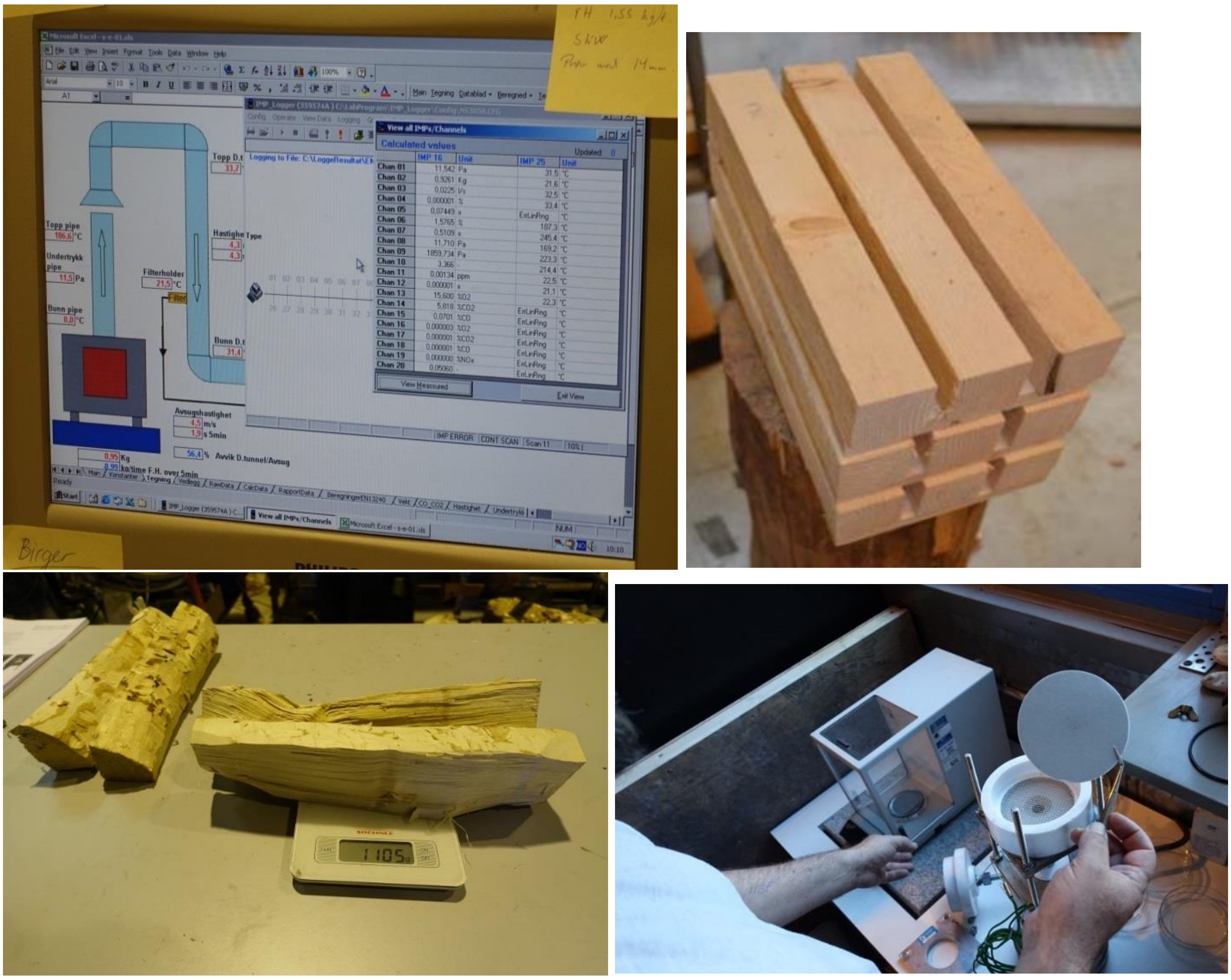


Figure 6: Experimental setup - software for data logging; spruce according to NS3058-59; birch without bark is used when performing tests according to DIN+; manual handling of filters for gravimetric analyses.

The appliance selected for the current project 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 m^3 per hour. However, it is has a small peculiarity, i.e. slightly increasing particle emissions as the heat output increases from the nominal value.

3 Experimental results and discussion

Measurements results of particulate matter from EN 13240 DIN+ are given in mg/Nm^3 (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. To perform this conversion the upper heating value, the stoichiometric flue gas volume at a given oxygen concentration as well as the elemental composition must be known. The upper heating value and the elemental composition is provided by certified laboratories for the fuels in question, here spruce and birch. The stoichiometric flue gas volume, including correction to a given oxygen concentration, can readily be calculated by applying a formula provided by EN 12952-15. The following emissions conversions explain how the conversion of the results from the simultaneous HF and FFDT measurements was performed in the current project.

3.1 Emission conversion

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. The following is a walk-through to explain the conversion scheme used in the current project to convert the measured particle emissions between both units. The method requires knowledge of the wood specie composition, given in Table 3-1, for the two types of wood commonly used at SP Fire Research Norway when performing certified tests:

Table 3-1: Composition of wood specie from analyses

	C	H	S	O	N	Ash
SPRUCE	50.8	5.3	0.015	43.4	0.12	0.4
BIRCH	50.2	5.1	0.018	43.8	0.25	0.6

..Normalizing:

Table 3-2: Normalized composition

	C	H	S	O	N	Ash
SPRUCE	50.782	5.298	0.015	43.385	0.120	0.400
BIRCH	50.216	5.102	0.018	43.814	0.250	0.600

..On ash-free basis:

Table 3-3: Composition on ash-free basis

	C	H	S	O	N
SPRUCE	50.986	5.319	0.015	43.559	0.120
BIRCH	50.519	5.132	0.018	44.079	0.252

With a known composition on ash-free basis, calculation of the flue gas volume can be performed as follows, according to EN 12952-15, as:

$$V_{Spruce,Birch} = 8{,}89 \times \frac{C_{S,B}}{100} + 20{,}97 * \frac{H_{S,B}}{100} + 3{,}32 * \frac{S_{S,B}}{100} - 2{,}64 * \frac{O_{S,B}}{100} + 0{,}78 * \frac{N_{S,B}}{100} \left[\frac{Nm^3}{kg\ daf}\right]$$

$$V_{Spruce} = 4{,}50 \left[\frac{Nm^3}{kg\ daf}\right], V_{Birch} = 4{,}41 \left[\frac{Nm^3}{kg\ daf}\right]$$

Recalculate to desired oxygen content, here 13% oxygen is used:

$$V_{Spruce} = 11{,}86 \left[\frac{Nm^3}{kg\ dry\ 13\%\ O_2}\right], V_{Birch} = 11{,}59 \left[\frac{Nm^3}{kg\ dry\ 13\%\ O_2}\right]$$

Further, knowledge of the upper heating value must be found from certified laboratory analyses:

$$UHV_{Birch} = 19{,}805 \left[\frac{MJ}{kg}\right], UHV_{Spruce} = 20{,}268 \left[\frac{MJ}{kg}\right]$$

From mg/Nm^3 to g/kg:

$$y \left[\frac{g}{kg}\right] = {}^{x} \left[\frac{mg}{Nm^3}\right] \times V_{S,B} \left[\frac{Nm^3}{kg\ dry\ 13\%\ O_2}\right] \Big/ 1000$$

From g/kg to g/GJ:

$$y \left[\frac{g}{GJ}\right] = {}^{x} \left[\frac{g}{kg}\right] \times 1000 \Big/ UHV_{S,B}$$

The calculation example given in Table 3-4 shows the peculiarity of having to provide limits for two methods, one applying a HF and one where the filter temperature is close to the surroundings. The example shows what a direct conversion between the two units, either for birch or spruce, would result in for the new Danish emission limits. Direct conversion of 30 mg/Nm^3 gives 0.35 g/kg and is approximately the same for birch and spruce. Direct conversion of 4 g/kg gives an average value of about 340 mg/Nm^3 for spruce and birch. Both the converted values are way off in both directions, meaning that setting such limits requires high experience and a thorough knowledge of what limits modern stoves are capable of achieving when measured according to either method.

Another example of conversion misuse is in the reported Norwegian emission inventory for wood stoves of 1820 g/GJ, which is way above what is reported by any other European country[10]. The reason is that this figure comes from the direct conversion of some estimated average Norwegian emissions based on an evaluation of lab test results according to the Norwegian standard versus real-life emissions. When directly converted we get 36 g/kg, which in 2011 was the emission factor estimate used for Norwegian real-life emissions. However, these figures cannot be compared to other countries' inventories just by converting it to comparable units as long as they are DIN+ based, since the measurement method is physically different.

[10] Black Carbon emissions, Norway (2011) Ingrid Myrtveit, Vigdis Vestreng, Hanne Aronsen, http://www.russianarcticbc.org/documents/presentations/2011_10_06/MYRTVEIT%20Norway%20Black%20Carbon%20Emissions.pdf

Table 3-4: Calculation example

Birch

PM converter professional ver. 12		
mg/Nm3	g/kg	g/GJ
30.00	0.35	17.55
345.16	4.00	201.97
345.16	4.00	201.97

Birch	11.59	Nm3/kg	dry at 13% vol O2
UHV	19.81	MJ/kg	Upper heating value

Spruce

PM converter professional ver. 12		
mg/Nm3	g/kg	g/GJ
30.00	0.36	17.55
337.32	4.00	197.36
337.32	4.00	197.36

Spruce	11.86	Nm3/kg	dry at 13% vol O2
UHV	20.27	MJ/kg	Upper heating value

The following tables, Table 3-6 to Table 3-9, are the experimental results from simultaneous measurements of particle emission on HF filters and on conditioned filters sampling from the FFDT. For HF experiments in accordance with DIN+ organic gaseous compounds were not measured, as the tests were performed in accordance with FFDT. In general, it can be seen that the combustion conditions are quite good, providing low levels of both particulate matter and carbon monoxide, with slightly increasing emissions at heat outputs above nominal output. The measured values from the current campaign corresponds well with the approval tests for the selected stove both with regards to CO and particle emissions. The heat output for the nominal cases varied between 5.3 - 7.7 kW and 4.9 - 6.5 kW for spruce and birch respectively, although the air vent regulator remained in the same position. For the high heat output cases, it varied between 7.2 – 10.3 kW and 8.2 - 16.8 kW (which is quite high compared to the declared maximum heat output of 9 kW from the producer) for birch and spruce, respectively, although the air vent regulator remained in the same position. The reason for this variation is probably due to the difference in properties for birch and spruce, spruce having the ability to release volatiles faster than birch. This is both due to density differences, spruce being less dense than birch, and the fact that spruce in accordance with NS is made up of furring strips of wood with a higher area being exposed to the surrounding incoming heat flux. Other variables, like how the wood is stacked, how fast it ignites, wood density, structure etc., will also influence the burn rate for the same air vent regulator position. The selected stove is listed from the producer to have a nominal heat output of 5 kW, with a minimum and maximum output of 4 kW and 9 kW respectively.

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 minutes and stopped after 33 minutes. When sampling according to NS3058-59 the sampling was performed over the whole batch period. The properties used for spruce and birch are shown in Table 3-5.

Table 3-5: Different properties for spruce and birch

	Spruce	Birch
C = Carbon content, %	50.8	50.2
C_r = Carbon content in ash, %	0.4	0.6
H = Hydrogen content, %	5.3	5.1
Higher heating value (kJ/kg)	20 268	19 805

3.2 Experimental results and discussion

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 as shown lowermost in each of the following tables, Table 3-6 to Table 3-9.

Table 3-6: Experimental results – low load FFDT, spruce

		NS Test	NS Test	Average NS Spruce		NS Test	NS Test	Average NS Spruce
Heat load		LOW-NOM	LOW-NOM	**LOW-NOM**		LOW	LOW	**LOW**
		s-e-26	s-e-27			s-e-28	s-e-29	
Wood specie		Spruce	Spruce	**Spruce**		Spruce	Spruce	**Spruce**
C_{OGC} = Organic gaseous compound in fluegas	**mg/Nm3 at 13 % O2**							
[THC] = total hydrocarbons in wet fluegas	**ppm (as C3H8)**							
CO, measured average	**vol%**	0.25	0.58	**0.41**		0.62	1.01	**0.81**
CO, measured average ajusted	**vol% at 13 % O2**	0.34	0.92	**0.63**		0.89	1.30	**1.10**
Heat output	**kW**	5.89	5.44	**5.67**		6.05	4.72	**5.39**
Moisture content wet basis	**%**	17.00	17.00	**17.00**		17.00	17.00	**17.00**
NS ajusted part. emissions, EAD	**g/t**	7.60	1.35	**4.47**		12.25	4.38	**8.31**
NS ajusted part. emissions, EAD	**g/kg dry wood**	5.35	0.96	**3.15**		10.27	3.69	**6.98**
Total sampling period	**min**	57.00	58.00	**57.50**		70.00	73.00	**71.50**
Total mass of wood consumed	**kg dry wood**	1.35	1.36	**1.36**		1.39	1.44	**1.42**
Burnrate	**kg dry wood / hour**	1.42	1.41	**1.42**		1.19	1.19	**1.19**
DIN+ Dust	**mg**	23.60	19.00	**21.30**		22.80	18.30	**20.55**
DIN+ Suction volume	**Nm3**	0.54	0.55	**0.55**		0.68	0.71	**0.70**
DIN+ Dust	**mg/Nm3**	43.40	34.42	**38.91**		33.38	25.63	**29.51**
		1,7 kg, 6 mm åpning				1,7 kg, 3 mm		
Part. conc. as DIN+ (g/GJ)	**g/GJ**	25.39	20.14	**22.77**		19.53	15	**17.27**
Part. conc. as FFDT (g/GJ)	**g/GJ**	263.96	47.37	**155.67**		506.71	182.06	**344.39**
Part. conc.as DIN+ SD (g/GJ)	**g/GJ**			2.63				2.27
Part. conc. as FFDT SD (g/GJ)	**g/GJ**			108.30				162.33
Part. conc. as DIN+ RSD (%)	**%**			12 %				13 %
Part. conc. as FFDT RSD (%)	**%**			70 %				47 %

Table 3-7: Experimental results – nominal load DIN+, birch and spruce

		DIN+ Test	DIN+ Test	DIN+ Test	Average DIN+ Birch	DIN+ Test	DIN+ Test	DIN+ Test	Average DIN+ Spruce	DIN+ Birch
Heat load		NOM	NOM	NOM	**NOM**	NOM	NOM	NOM	**NOM**	NOM
		s-e-07	s-e-08	s-e-09		s-e-10	s-e-11	s-e-12		s-e-23
Wood specie		Birch	Birch	Birch	**Birch**	Spruce	Spruce	Spruce	**Spruce**	Birch
C_{OGC} = Organic gaseous compound in fluegas	**mg/Nm3 at 13 % O2**									337.95
[THC] = total hydrocarbons in wet fluegas	**ppm (as C3H8)**									171.01
CO, measured average	**vol%**	0.04	0.05	0.04	**0.05**	0.03	0.04	0.04	**0.04**	0.13
CO, measured average ajusted	**vol% at 13 % O2**	0.08	0.11	0.10	**0.09**	0.06	0.09	0.07	**0.07**	0.15
Heat output	**kW**	5.16	5.16	4.83	**5.05**	5.82	5.34	5.52	**5.56**	7.18
Moisture content wet basis	**%**	16.00	16.00	16.00	**16.00**	18.00	18.00	18.00	**18.00**	17.00
NS ajusted part. emissions, EAD	**g/t**	1.62	1.19	2.01	**1.61**	1.07	1.36	1.20	**1.21**	4.22
NS ajusted part. emissions, EAD	**g/kg dry wood**	1.04	0.74	1.29	**1.02**	0.69	0.92	0.82	**0.81**	1.92
Total sampling period	**min**	30.00	30.00	30.00	**30.00**	30.00	30.00	30.00	**30.00**	30.00
Total mass of wood consumed	**kg dry wood**	0.75	0.78	0.75	**0.76**	0.75	0.71	0.71	**0.73**	1.06
Burnrate	**kg dry wood / hour**	1.56	1.61	1.56	**1.58**	1.56	1.47	1.47	**1.50**	2.20
DIN+ Dust	**mg**	3.40	3.50	6.70	**4.53**	3.30	0.60	1.10	**1.67**	14.80
DIN+ Suction volume	**Nm3**	0.25	0.22	0.24	**0.23**	0.25	0.25	0.24	**0.25**	0.29
DIN+ Dust	**mg/Nm3**	13.88	15.84	28.51	**19.41**	13.31	2.39	4.53	**6.74**	51.20
		Nominal mass, 1.1 kg, 3+30 min. in acc. with DIN+, 11 mm damper								*NS mass, 1.7 kg, 3+30 min. as DIN+, 11 mm damper*
Part. conc. as DIN+ (g/GJ)	**g/GJ**	8.12	9.27	16.68	**11.36**	7.79	1.40	2.65	**3.94**	**29.96**
Part. conc. as FFDT (g/GJ)	**g/GJ**	52.37	37.36	65.12	**51.62**	33.91	45.48	40.23	**39.87**	**96.95**
Part. conc.as DIN+ SD (g/GJ)	**g/GJ**				4.65				3.38	
Part. conc. as FFDT SD (g/GJ)	**g/GJ**				13.90				5.79	
Part. conc. as DIN+ RSD (%)	**%**				40.93%				86%	
Part. conc. as FFDT RSD (%)	**%**				26.93%				15%	

Table 3-8: Experimental results – nominal load FFDT, birch and spruce

		NS Test	NS Test	NS Test	Average NS Birch	NS Test	NS Test	NS Test	Average NS Spruce
Heat load		NOM	NOM	NOM	**NOM**	NOM	NOM	NOM	**NOM**
		s-e-13	s-e-15	s-e-16		s-e-14	s-e-17	s-e-18	
Wood specie		Birch	Birch	Birch	**Birch**	Spruce	Spruce	Spruce	**Spruce**
C_{OGC} = Organic gaseous compound in fluegas	**mg/Nm3 at 13 % O2**	234.12	148.69	49.74	**144.18**	73.73	123.45	136.85	**111.34**
[THC] = total hydrocarbons in wet fluegas	**ppm (as C3H8)**	70.92	58.42	19.44	**49.59**	22.88	58.28	85.07	**55.41**
CO, measured average	**vol%**	0.05	0.08	0.04	**0.06**	0.05	0.16	0.14	**0.11**
CO, measured average ajusted	**vol% at 13 % O2**	0.10	0.11	0.06	**0.09**	0.09	0.19	0.13	**0.14**
Heat output	**kW**	4.87	6.16	6.53	**5.85**	5.22	10.42	7.71	**7.78**
Moisture content wet basis	**%**	16.00	16.00	16.00	**16.00**	18.00	17.00	19.00	**18.00**
NS ajusted part. emissions, EAD	**g/t**	2.40	3.20	2.97	**2.86**	2.36	4.99	2.91	**3.42**
NS ajusted part. emissions, EAD	**g/kg dry wood**	1.66	2.04	1.74	**1.81**	1.58	1.84	1.68	**1.70**
Total sampling period	**min**	59.00	56.00	50.00	**55.00**	54.00	34.00	44.00	**44.00**
Total mass of wood consumed	**kg dry wood**	1.42	1.47	1.43	**1.44**	1.34	1.53	1.28	**1.38**
Burnrate	**kg dry wood / hour**	1.44	1.57	1.71	**1.57**	1.49	2.71	1.74	**1.98**
DIN+ Dust	**mg**	13.90	14.60	12.60	**13.70**	25.20	14.80	19.00	**19.67**
DIN+ Suction volume	**Nm3**	0.44	0.42	0.39	**0.42**	0.41	0.27	0.38	**0.35**
DIN+ Dust	**mg/Nm3**	31.31	34.68	32.64	**32.88**	61.17	32.60	50.50	**48.09**
		NS mass, 1.7 kg, complete periode in acc. with NS, 11 mm damper							

Part. conc. as DIN+ (g/GJ)	**g/GJ**	18.32	20.29	19.10	**19.24**	35.79	19.07	29.55	**28.13**
Part. conc. as FFDT (g/GJ)	**g/GJ**	84.06	102.78	87.69	**91.51**	78.11	90.78	82.89	**83.93**
Part. conc.as DIN+ SD (g/GJ)	**g/GJ**				0.99				8.45
Part. conc. as FFDT SD (g/GJ)	**g/GJ**				9.93				6.40
Part. conc. as DIN+ RSD (%)	**%**				5%				30%
Part. conc. as FFDT RSD (%)	**%**				11%				8%

Table 3-9: Experimental results – high load FFDT, birch and spruce

		NS Test	NS Test	NS Test	Average NS Birch	NS Test	NS Test	NS Test	Average NS Spruce
Heat load		HIGH	HIGH	HIGH	**HIGH**	HIGH	HIGH	HIGH	**HIGH**
		s-e-19	s-e-20	s-e-21		s-e-22	s-e-24	s-e-25	
Wood specie		Birch	Birch	Birch	**Birch**	Spruce	Spruce	Spruce	**Spruce**
C_{OGC} = Organic gaseous compound in fluegas	**mg/Nm3 at 13 % O2**	101.97	36.26	57.78	**65.34**	37.07	588.41		**312.74**
[THC] = total hydrocarbons in wet fluegas	**ppm (as C3H8)**	53.53	22.01	35.92	**37.15**	26.59	395.24		**210.92**
CO, measured average	**vol%**	0.13	0.08	0.02	**0.08**	0.13	0.34	0.13	**0.20**
CO, measured average ajusted	**vol% at 13 % O2**	0.15	0.07	0.02	**0.08**	0.10	0.28	0.12	**0.17**
Heat output	**kW**	7.50	10.30	10.30	**9.37**	12.39	16.75	11.78	**13.64**
Moisture content wet basis	**%**	16.00	16.00	17.00	**16.33**	19.00	18.00	18.00	**18.33**
NS ajusted part. emissions, EAD	**g/t**	4.87	7.59	3.34	**5.27**	7.52	15.63	7.67	**10.27**
NS ajusted part. emissions, EAD	**g/kg dry wood**	2.44	2.89	1.29	**2.21**	2.39	3.90	2.64	**2.98**
Total sampling period	**min**	44.00	36.00	34.00	**38.00**	27.00	20.00	30.00	**25.67**
Total mass of wood consumed	**kg dry wood**	1.47	1.57	1.46	**1.50**	1.42	1.33	1.46	**1.40**
Burnrate	**kg dry wood / hour**	2.00	2.62	2.58	**2.40**	3.15	4.00	2.91	**3.35**
DIN+ Dust	**mg**	32.10	46.50	10.80	**29.80**	38.30	54.20	38.30	**43.60**
DIN+ Suction volume	**Nm3**	0.45	0.36	0.34	**0.38**	0.26	0.20	0.30	**0.26**
DIN+ Dust	**mg/Nm3**	71.00	128.10	31.90	**77.00**	145.60	267.00	129.00	**180.53**
		NS mass, 1.7 kg, complete periode in acc. with NS, 34 mm damper							

Part. conc. as DIN+ (g/GJ)	**g/GJ**	41.55	74.96	18.67	**45.06**	85.19	156.21	75.47	**105.62**
Part. conc. as FFDT (g/GJ)	**g/GJ**	123.20	145.92	65.14	**111.42**	117.92	192.42	130.25	**146.87**
Part. conc.as DIN+ SD (g/GJ)	**g/GJ**				28.31				44.08
Part. conc. as FFDT SD (g/GJ)	**g/GJ**				41.66				39.93
Part. conc. as DIN+ RSD (%)	**%**				63%				42%
Part. conc. as FFDT RSD (%)	**%**				37%				27%

The experiments in the current campaign have been classified as low, nominal and high heat output cases given by; low < 1.4 kg/h, 1.4 ≤ nominal < 1.75, high ≥ 1.75 kg/h. For all the tests the collected mass of PM_t on the FFDT filters were found to be substantially higher than on the HFs. When compared on a common unit in g/GJ, about 4X and 8X 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 Nussbaumer et al., 2008[5]. In addition, spruce tends to volatize faster than birch (both due to property differences as well as 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 6.5X higher than the amount of particles collected on the HF, when intermixing birch and spruce. Comparing only the nominal series, 7.6X more particles were collected with the FFDT method, intermixing spruce and birch. At high load the difference were only 2.7X 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 behaviour 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, as can be seen in Figure 7. 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.

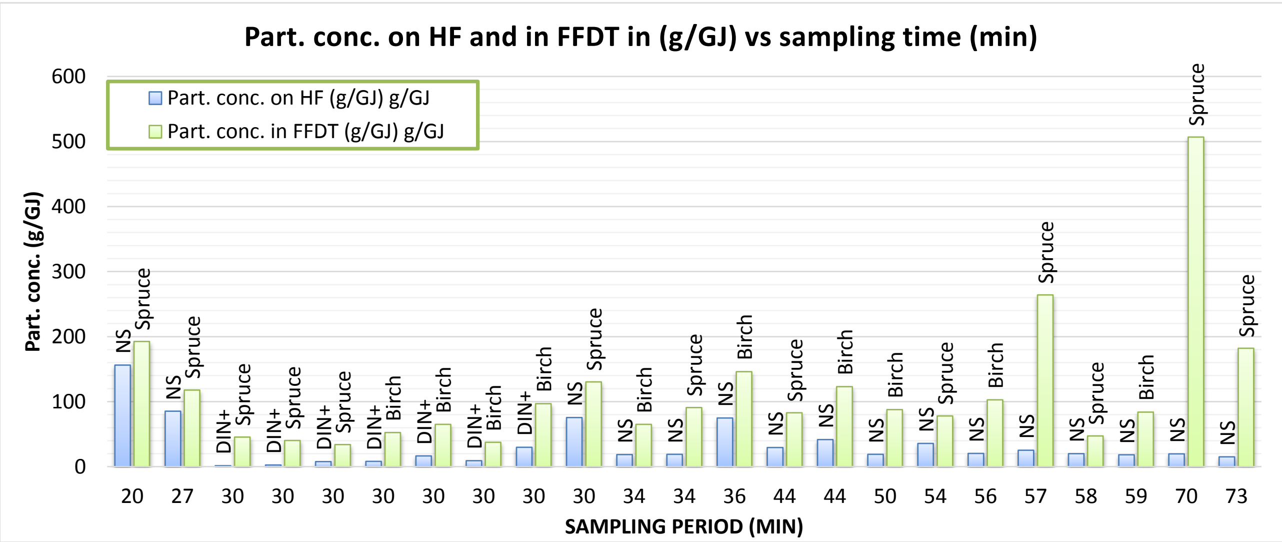


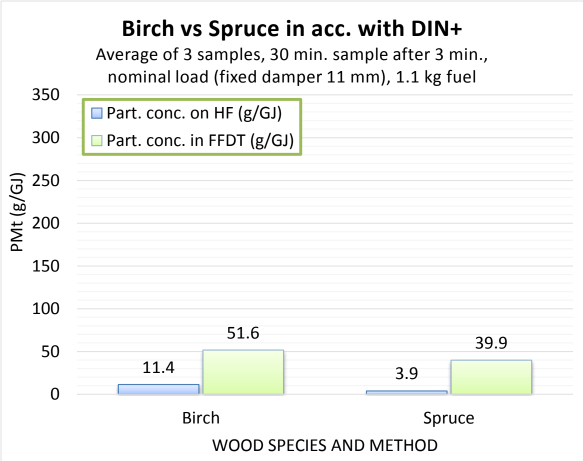
Figure 7: All experiments, particulate matter collected on HF and in FFDT in g/GJ vs sampling time according to either DIN+ or NS3038-59. The results measured according to each test method are grouped in double-columns according to test method and type of wood.

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.

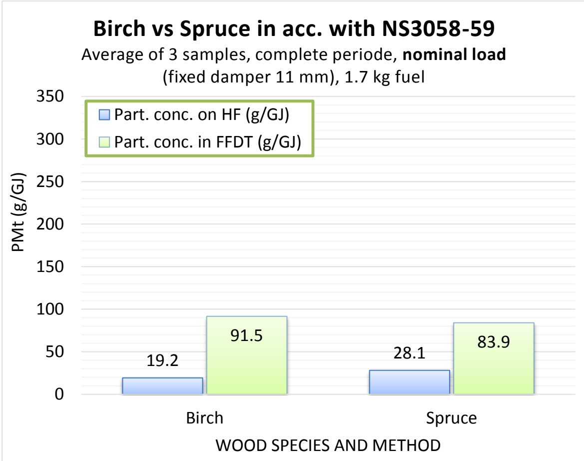
Another factor affecting the particle emissions is the type of wood used during certification tests. The average values from the experiments for the nominal heat output series as shown in Figure 8a, show that less particles are captured from spruce than from birch, both on the HF and in the FFDT filter, when the experiments are performed in accordance with DIN+ sampling as 3+30 min. 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. An example of OGC production from experiment # 23 illustrating this is shown in Figure 10. Examining the amount of collected particles for birch and spruce when measured over the total batch in accordance with NS, as in Figure 8b, also shows slightly less particles captured for spruce at nominal burn rate. However, at high burn rates Figure 8c shows that 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 (Figure 8e) is assumed to surpass those from birch, at least when judged from previous experience. All-in-all, comparing all single experiments, an average of 3.9X more particle mass was captured on the FFDT filter when burning birch as compared to 9X more when burning spruce, keeping in mind that no experiments were performed on low burn rate with birch.

As seen in Figure 8c, 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 2X on the FFDT filters (Figure 8d). Also, 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.

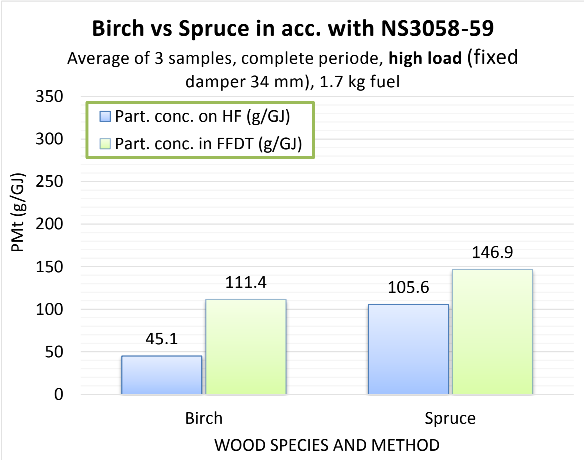
Examining the measurements of particle emissions in Figure 9 we see that when the stove is supplied with a higher initial fuel load (DIN+/1.1 kg vs NS/1.7 kg), going from reduced to full sampling period (30 min. vs whole batch), as well as deviating from nominal load (high for birch, and high and low 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 4X and 6X, respectively, going from nominal to high heat output. Comparatively, FFDT sampling shows only a 2X and 3.7X 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 8.6X on the FFDT filter.



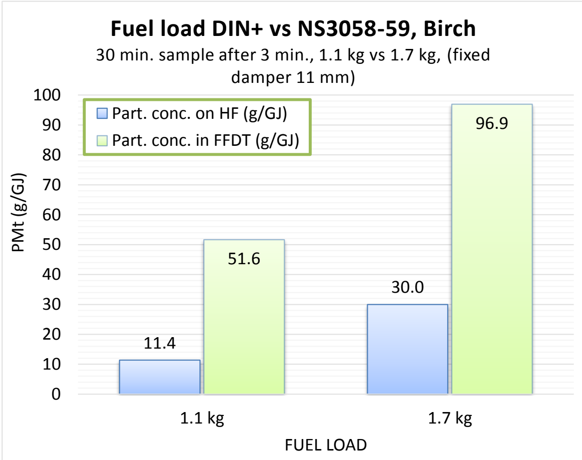
a)



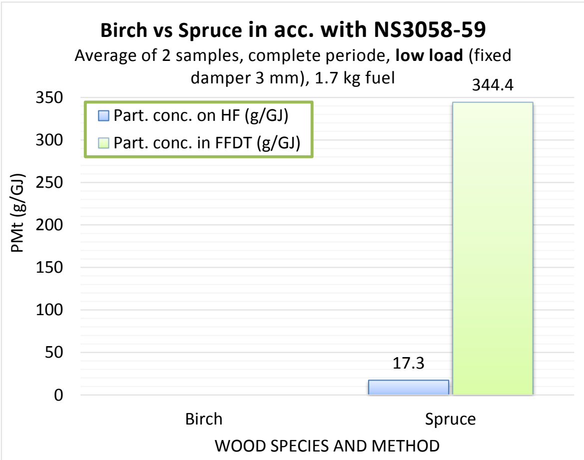
b)



c)



d)



e)

Figure 8: Averaged experimental results, comparing birch and spruce a) at nominal load as DIN+ b) at nominal load as NS c) at high load as NS d) comparing fuel load according to DIN+ and NS e) low load as NS f) high load as NS

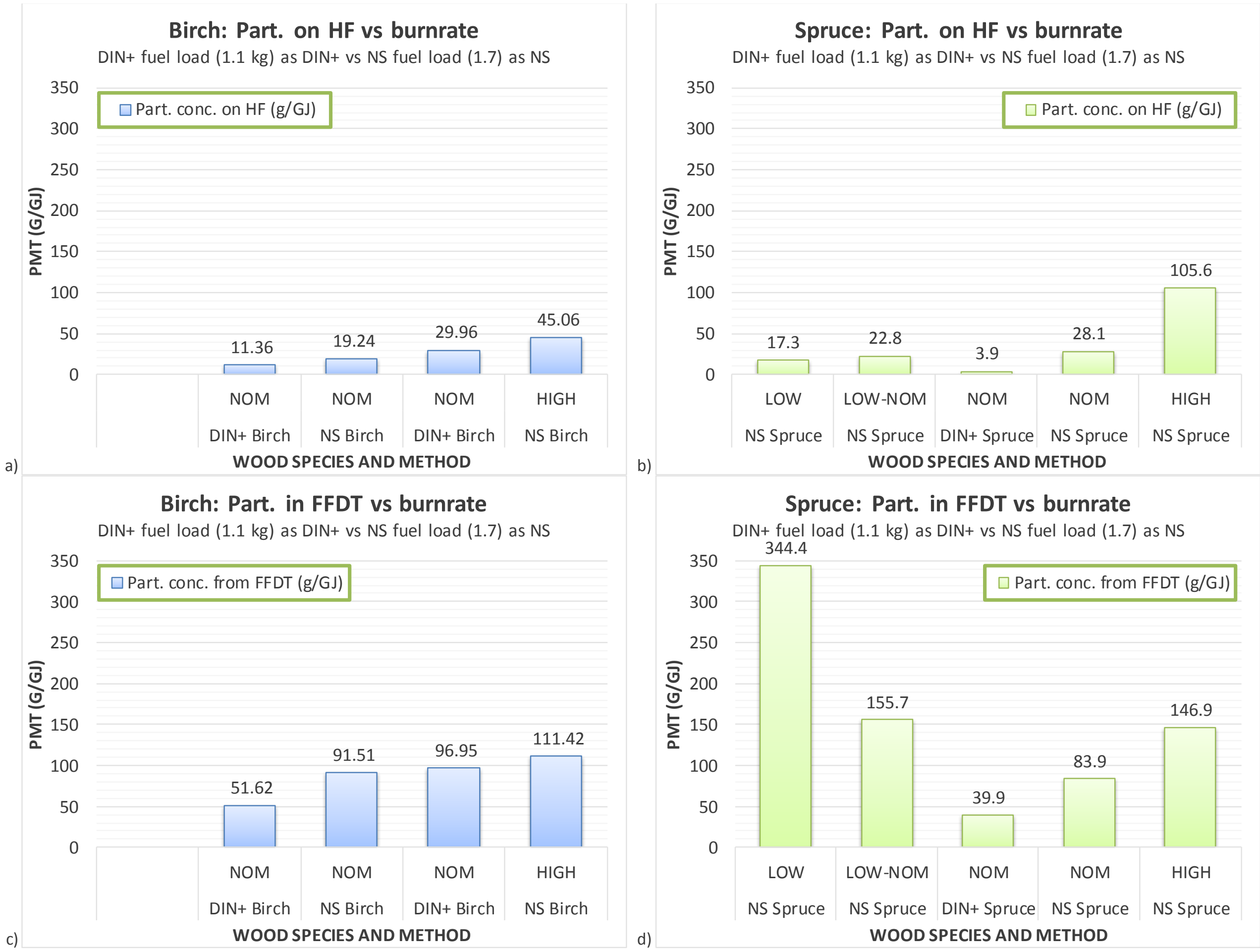


Figure 9: Particle emissions as a function of burn rate and fuel load (1.1 kg vs 1.7 kg), birch versus spruce and DIN+ versus NS

Figure 10 shows the OGC concentration measured in the chimney according to DIN+ with birch, versus time in one selected experiment (test #23) to illustrate what might escape in terms of particles when limiting the sampling to 3+30 minutes. The figure illustrates a typical batch combustion behaviour. High peaks in OGC is an indirect indication of bad combustion conditions and therefore known to be directly linked to particle production, i.e. OGC peaks = PM_t peaks. If the sampling period is limited to only 3+30 min. instead of the full combustion period, a certain amount of particles will not be captured, i.e. from the first 3 min. period of ignition and the charcoal transition phase. Test # 23 was performed to illustrate what happens with the emissions when the fuel load is increased (1.7 kg versus 1.1 kg) beyond the nominal fuel load given by the manufacturer. The difference in emissions, captured within the 30 min. sampling period, can be seen in Figure 8d. A fuel load of 1.7 kg gives 3X more emissions on the HF and 2X more on the FFDT filter, in spite of only sampling for 30 min.

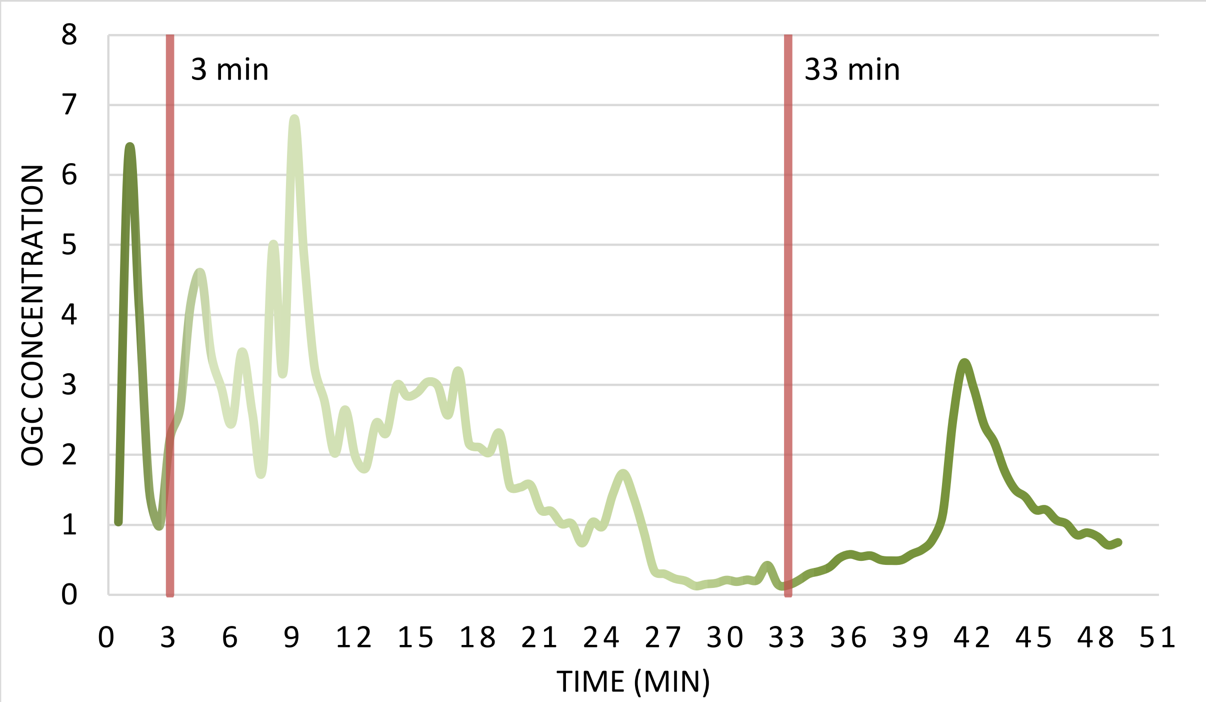


Figure 10: OGC production illustrating what escapes when limiting the sampling to 3 + 30 minutes

Figure 11 shows a plot of the average values for all series, nominal to high heat output, illustrating a possible relation for the current stove between the DIN+ and the FFDT method. Low loads have been omitted as measurements are lacking for birch. As discussed between experts several times over the years, this is merely a stove specific correlation which cannot be applied in general for any other stove.

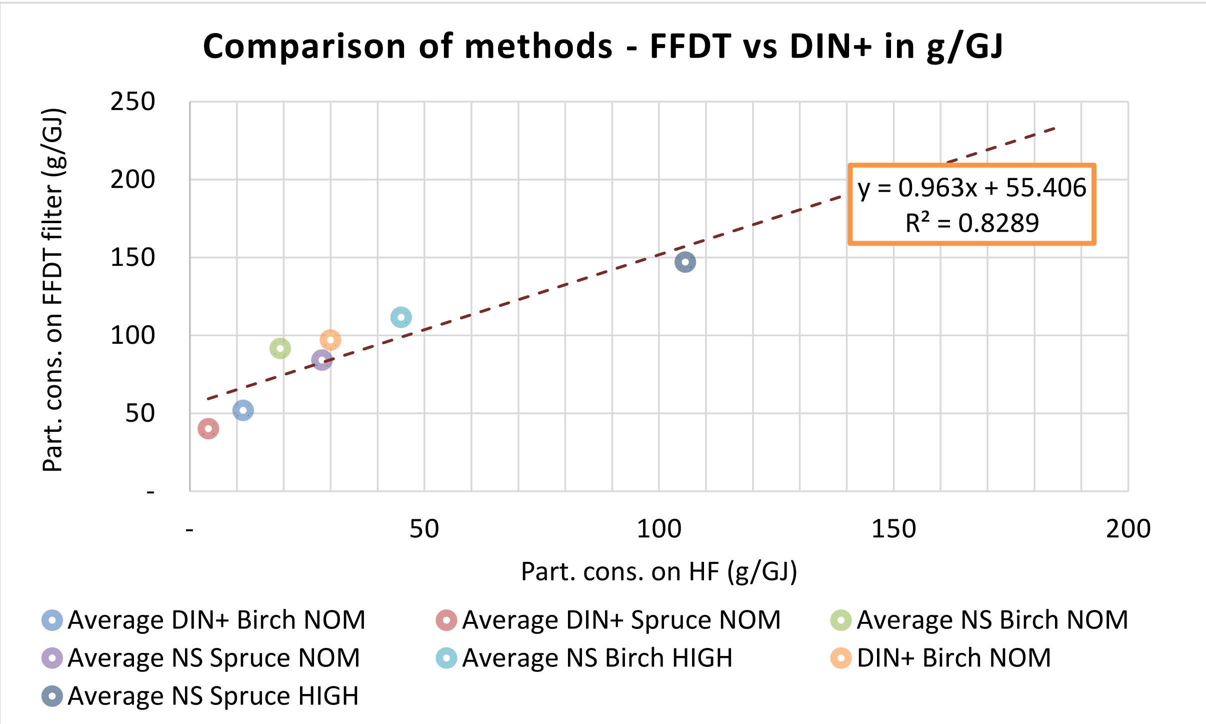


Figure 11: Comparison of methods, FFDT versus DIN+ in g/GJ

In Figure 12 the captured amount of particulate matter from all experiments, both on the HF and the FFDT filter is shown. Firstly, it can be observed 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 with 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 behaviour 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 optimisation.

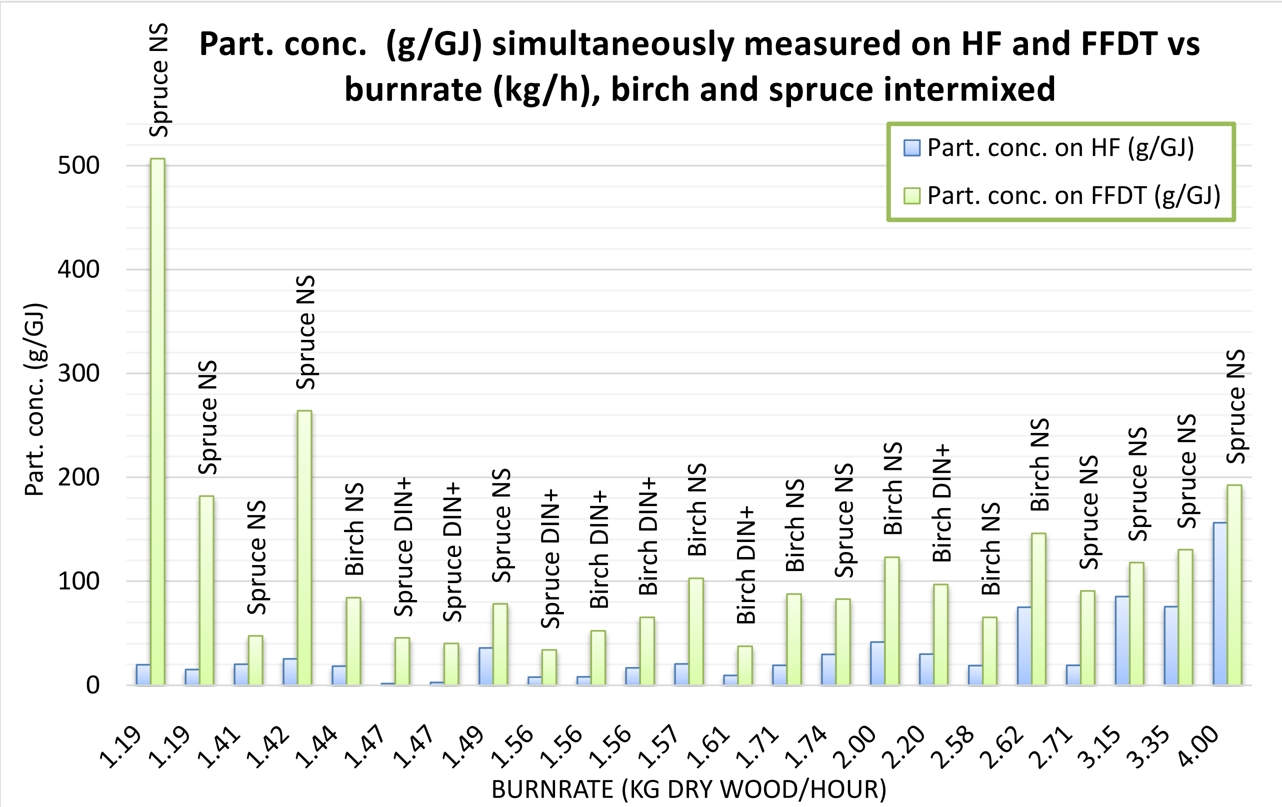


Figure 12: Collected particle emissions on HF and for FFDT for all experiments in g/GJ

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. Both series belonged to results measured with the HF. In general, the lower the RSD is the better the precision and repeatability becomes. Comparing the variation between the two methods under investigation, DIN+ and the FFDT, it can be observed that the variation is less pronounced for the FFDT than for the HF method. The most probable explanation for this is that the FFDT collects more particulate mass (both solid and condensables, due to dilution with ambient air), and is sampled over the whole batch period and therefore is less vulnerable to deviations due to fuel type and sampling period. It might also be that captured particle mass on HF is more vulnerable to rapid changes in the combustion conditions due to sampling location closer to the combustion chamber and thereby capturing closer to real time the changes in particles production due to natural changes in combustion conditions than the dilution tunnel method. The relatively long retention time in the dilution tunnel might possibly smoothen out some chemical changes in particulate composition before being captured on the FFDT filter.

The difference when performing successive, as opposed to parallel particulate measurements, is the relatively large variation in conditions between successive experiments typical for biomass batch combustion of larger wood logs. 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%

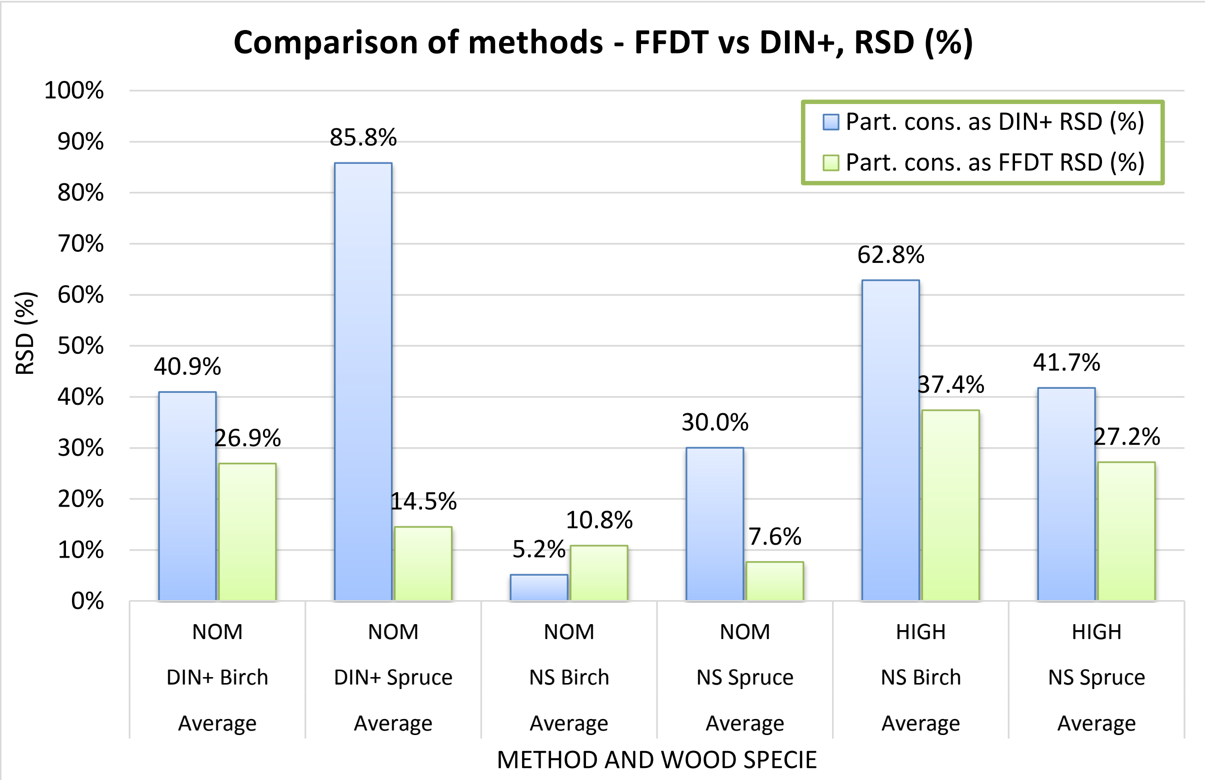


Figure 13: Comparison of methods, RSD

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4 Summary and conclusion

The current project has highlighted several factors, which more or less affect the measured particle emission. However, it must be emphasized that one should be careful when generalizing upon measurements performed on one single appliance.

Overall, the combustion conditions during all tests were rather good, providing low levels of both particulate matter and carbon monoxide, with slightly increasing emissions at heat outputs above nominal output. Rather typical conditions for a modern stove. The heat output for the nominal cases varied between 5.3 - 7.7 kW and 4.9 – 6.5 kW for spruce and birch respectively, although the air vent regulator remained in the same position. For the high heat output cases, it varied between 7.2 – 10.3 kW and 8.2 - 16.8 kW for birch and spruce respectively, although the air vent regulator remained in the same position. The current measurements are also well in line with the values measured for both CO and particulate matter during the certified approval tests.

Heated (≥ 70 ˚C) or conditioned ambient filter (≤ 35 ˚C): An important outcome of this project is the quantification of the difference in the amounts of particles collected according to the two different methods, being HF and FFDT. For all the tests the collected mass of PM_t on the FFDT filters were found to be substantially higher than on the HFs. When compared on a common unit in g/GJ, about 4X and 8X 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. In addition, spruce volatizes more rapidly due to its physical shape given by the standard, being especially pronounced at low and high burn rates where the combustion conditions normally are worse when compared to nominal burn rate. Overall, the amount of particles collected with the FFDT method was about 6.5X higher than the amount of particles collected on the HF, when intermixing birch and spruce. Comparing only the nominal series, 7.6X more particles were collected with the FFDT method, intermixing spruce and birch. At high load the difference were only 2.7X more particles collected. This probably demonstrates that some condensable matter, possibly inorganics, 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 behaviour of exponential increase at low load conditions. The measurement campaign illustrates the importance of arriving at one single test standard which do not necessitate a comparison of “apples and pears”.

Test period: As DIN+ requires only 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 were mixed. For the shortest periods, much particulate matter is produced because of insufficient amounts of combustion air, as well as too low temperature and residence time for proper burn-out. At DIN+ conditions, with 30 min. of sampling, only a marginal portion of the particles is captured 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 periods when solid particles are formed relative to the total sampling time.

If the sampling period is limited to only 30 min. after the first 3 min. period instead of the full combustion period, a certain amount of particles will not be captured, i.e. from the first 3 min. period of ignition and the charcoal transition phase.

Fuel load: The current experiments indicate that fuel load is an important factor, which actually affects significantly the particle emissions. A fuel load of 1.7 kg, as opposed to 1.1 kg given by the manufacturers specification of nominal load, produces 3x more emissions on the HF and 2x more on the FFDT filter, in spite of only sampling for 30 min. Any new method should therefore take into consideration how the mass of the test fuel is defined, like in NS3058-59, rather than following the manufacturers recommendation.

Burn rate: A peculiar aspect of the selected stove is the increased emissions of particles, as the combustion conditions deteriorate when increasing the heat output above the nominal. Increasing the burn rate and thereby the deterioration of the combustion, increasing amounts of particulate matter are captured on both the HF and the ambient filter. A possible explanation for this is an increase in the collection of condensables, both from the ash and OGC, more so on the HF than on the ambient filter. 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.

Repeatability: Comparing the variation between the two methods under investigation, DIN+ and NS3058-59, it can be observed that the variation is much less pronounced for the FFDT than for the HF method. The most probable explanation for this is that the FFDT collects more particulate mass, and is therefore less vulnerable to deviations due to fuel type and sampling period. It might also be that captured particle mass on HF is more vulnerable to rapid changes in the combustion conditions due to the sampling location.

4.1 Added value to the current CEN standardization process, BeReal and the EN-PME-TEST project

The current project has highlighted the effect of several parameters affecting the sampling of particulate matter that should be taken into consideration when selecting and/or developing a new standard, which includes gravimetric sampling from small-scale heating appliances. Parameters that should be given special attention are;

1. **Filter temperature**

   Results from the current project showed that on the average for all tests, 5.6 times more mass was collected on the ambient filter. At nominal and high load, the increased mass on the ambient filters where 7.2 and 2.1 times higher, respectively. Our recommendation is that any new proposed method should include PM sampling at ambient temperature either by applying dilution tunnel or other dilution alternatives, to be able to account for the condensable part leaving the chimney.

2. **Fuel load**

   The results from the current project strongly suggest that any new method should provide a given procedure to derive the fuel load for any given stove, based on some selected parameters given by the stove's physical design. The main idea is to avoid incongruity between the stove's physical size and its nominal heat output provided by its manufacturer.

3. **Sampling period**

   The results obtained in the current project regarding sampling period, suggests that a new common standard also should include a test protocol where sampling over at least one full burn cycle is described, or even better, over several consecutive cycles preferably with varying heat output. The current DIN+ HF is not currently able to capture the ignition face, and in many cases neither the transition to charcoal phase.

4. Burn rate

A recommendation from the current work is to include at least one low heat output test, if the stove in question is physically able to operate at reduced airflow, possibly as part of a test procedure using several consecutive test cycles.

Regarding burn rate and the peculiarity of the stove tested in the current project, with increasing emissions at heat outputs above nominal, the results cannot be used directly to provide specific recommendations. However, it is a well-known inherent property that every stove which physically allows variation of the airflow into the combustion chamber exhibits optimum combustion conditions only within a limited range of the total allowable airflow rate. Above and below this window combustion conditions change, resulting in inherent changes affecting both gaseous and particle emissions. A typical behaviour for most stoves is an exponential increase in particle emissions at burn rates below nominal heat output. At burn rates above nominal heat output emissions normally tends to further decrease. However, there are some exceptions, where the emissions actually significantly increases if the stove is operated close to or at maximum heat output. There is always a fine balance between the amount of airflow allowed into the combustion chamber and its inherent acceleration of the volatilization and the stove's burnout capabilities. As shown in the current project, some stoves exert an increase in emissions above nominal heat output.

Several of the above-mentioned factors are still under investigation or have to a certain degree already been researched, within both EN-PME-TEST as well as in the BeReal project. One of the key objectives in the BeReal project is to develop an advanced test protocol for biomass room heating appliances in order to better reflect real life operation by sampling during several test cycles, including one cold start-up and a final low heat output cycle. In EN-PME-TEST, the intention is to develop a single PM-test method that could possibly replace all currently existing test methods by one single method. The proposed test protocol is that from the BeReal project. EN-PME-TEST proposes one short-term method where PM and OGC are measured. In the proposed long-term method only one value could be measured capable of reflecting both PM and OGC. In order to prevent over- or underestimation of organic compounds, PM and OGC are proposed sampled at the same temperature (180°C). Neither the BeReal nor the EN-PME-TEST project propose to collect the condensable part of the PM_t as achieved by the FFDT, sampled gravimetrically at ambient temperature (≤ 35°C as described in NS3058-59).

Concerning accuracy and variability of a test method

To put the RSD in perspective, random probability results are those with a RSD > 50%, placing the results from two of the current measurement series in this category. Both series belonged to results measured with the HF. In general, the lower the RSD is the better the repeatability becomes. Comparing the variation between the two methods under investigation, DIN+ and the NS3058-59, it can be observed that the variation is much less pronounced for the former than for the latter method.

However in the US, the EPA's test method 28 which equals the NS3058-59 (except for the user behaviour weighted emissions), has been scrutinized for accuracy and has been found to consistently result in a RSD in excess of 40%. Analysis of existing data has shown that the entire emissions testing and certification process is subject to a substantial precision problem. There are evidence demonstrating that emission test results using the ASTM E2780/EPA M28 method cannot be reliably replicated within a range that is roughly equal to or even greater than the proposed Step 1 emissions limits (wood stove = 4.5 g/h)[11]. Keeping in mind that

[11] http://www.intertek.com/uploadedFiles/Intertek/Divisions/Commercial_and_Electrical/Services/Building_Products/
Forms/White%20Paper%20-%20Hearth%20-%202015%20NSPS%20-%20BPWPNA01-1.pdf

emission limits in the US are given in g/h, the currently available methods are such that if a wood stove is able to produce emissions rates of 2 g/h or less, there is significant probability that any single test will result in an emission rate as high as 5 or 6 g/h.

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