CONTAMINATION OF WOOD CHIPS WITH MINERAL SOIL – FUEL QUALITY AND COMBUSTION BEHAVIOUR

Claudia Schön[1], Carina Kuchler[1], Daniel Kuptz[1], Elisabeth Rist[1], Elke Dietz[2], Markus Riebler[2], David Zimmermann[2], Robert Mack[1], Uwe Blum[2], Herbert Borchert[2], Hans Hartmann[1]

[1]Technology and Support Centre in the Centre of Excellence for Renewable Resources (TFZ)
Schulgasse 18, D-94315 Straubing, Germany, Tel.: +49-9421-300-152, Fax: +49-9421-300-211
Email: Claudia.schoen@tfz.bayern.de
[2] Bavarian State Institute of Forestry (LWF), D-85354 Freising, Germany

ABSTRACT: Careful operation during fuel production is essential to avoid highshares of mineral soil inwood chips leading to contamination of the biofuels. This can result in elevated gaseous and particulate emissions, corrosion or slag formation during combustion in the biomass boiler. To investigate this effect, stemwood and forest residue wood chip fuels were contaminated with mineral soil at two different ratios. Contamination was done using three typical forest soils from Bavaria (soil A, B and C). Total particulate matter (TPM) emissions increased for wood chips that when contaminated with soil A and C, compared to the reference fuel, but emissions for wood chips contaminated with soil B remained constant. Carbon monoxide (CO) and organic gaseous carbon (OGC) emissions decreased for contaminated wood chips. For NO_X emissions, no clear effect was observed. Overall, the contamination of woody biomass had a noticeable effect on pollutant emissions and should be avoided.
Keywords: boiler, combustion, emissions, quality, wood chip, soil contamination

1 INTRODUCTION

A proper fuel quality is essential for failure-free and low emission wood chip combustion in automatically stoked biomass boilers. The contamination of wood chipsby mineral soil during harvesting and fuel production might have a substantial impact on the combustion behavior due to the impact on its chemical fuel composition.

Critical elements in terms of woody biomass combustion are, for example, nitrogen (N), sulphur (S) and chlorine (Cl) leading to increased emissions of NO_X, SO_X or HCl. Other elements such as potassium (K), sodium (Na), lead (Pb), zinc (Zn) and to a certain degree S and Cl belong to the aerosols forming elements influencing the level of TPM emission [1]. High temperature corrosion can be an issue if S and Cl is present in the fuel but can be typically neglected for woodybiomass[2]. In addition, elements such as silicon (Si), K, magnesium (Mg), calcium (Ca) and aluminium (Al) can influence the slag formation during fixed bed combustion.The concentration of these elements is typically low in wood as they mainly occur in other organic (e. g. needles, bark) or inorganic sources (e. g. mineral soil) [3,4].

Contamination of wood chips with mineral soil of up to 10 w-% has been reported in some studies [5-7]. This contamination increases the concentration of critical elements such as Si, Al, K and Na leading to elevated TPM emission and slag formation.

Furthermore, soil adhesion to the fuel will raise mechanical stress in moving parts of the boiler and will thus increase mechanical wear. The aim of this study was therefore to evaluate the combustion behaviour of coniferous wood chips, which were contaminated with about 5 and 10 w-% of mineral soil (dry basis, d. b.). The study included the identification and evaluation of the environmental impact (gaseous and TPM emissions) andof slag formation.

2 MATERIAL AND METHODS

2.1 Selection of wood and mineral soils

The project area was focusing on the federal state of Bavaria in Germany. Three different types of mineral soil (soil A, B and C) were selected to represent large forest growing regions with Norway spruce (*Picea abies*) which is known for high wood chip production in Bavaria, Germany (Figure 1).
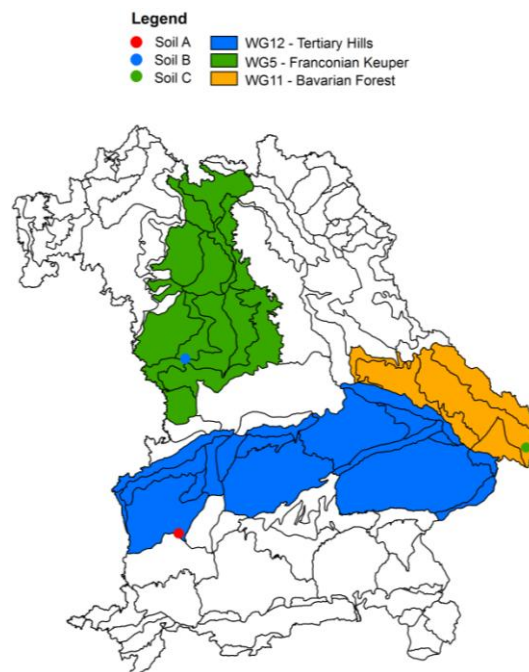

Figure 1: Location of three different soil types. Each soil is representative for the considerable parts of the marked region [8].

Forest regions with a high amount of rocks were excluded because contamination with mineral soil is not very likely in these areas. The following soils/regions were selected:
- Soil A: waterlogged loess/clay from tertiary

hills,

- Soil B: podsol brown soil above sandy-loam Franconian Keuper from northwest Bavaria,
- Soil C: brown earth from weathered granite and gneiss substrates from the Bavarian Forest.

The mineral soils were taken from the upper 30 cm, excluding the layer of humus. After sampling, each soil was air-dried indoors at room temperature. After drying, each soil was homogenized manually. A representative subsample of every soil was obtained by sample reduction. The respective subsamples were crushed manually using a heavy concrete roller. The roller was wrapped in cling film to avoid contamination and rolling was done on a tarpaulin covered floor. Each soil was then screened mechanically to a grain size of 2 mm using a self-made vibrating screen. This granulate diameter corresponds with the geological fraction-limit between fine soil and coarse soil fraction [9].

Wood chips were produced using stemwood (SW) and forest residue (FR) of coniferous wood from Norway spruce (*Picea abies*) which was cut in the region where the mineral soil A originated. Each wood fuel used in the trials was produced from the same raw material batch. All wood chips were technically dried to a uniform moisture content of about 15 w-% so that the influence of soil addition to the fuel could be investigatedwithout moisture impact, as claimed in [10].

2.2 Contamination of wood chips with soil

By means of preliminary tests, different procedures of soil addition to wood chips were investigated, in order to achieve undisturbed results. These pre-tests revealed that the best reproducible method was to add the mineral soil to the wood chips immediately before combustion by using a separate dosing screw (Figure 2), which feeds the soil into the horizontal conveyor screw between storage tank and boiler. The dosing screw was placed on a scale to adjust the soil dosing rate according with the desired mixing ratio of soil material and wood chips. Two different contamination levels (ca. 5 and 10 w-%) were consistently realized for all three soil types. In total,14 different fuel qualities were thus created and tested in the wood chip boiler (Table I).
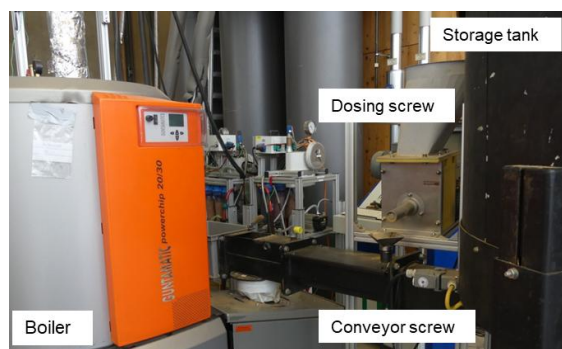

Figure 2: Contamination of wood chips with a dosing screw into the screw conveyor before boiler entrance

Table I: Nomenclature of fuels generated and combusted, SW – stemwood chips, FR – forest residue chips

Fuel	Contamination
Stemwood chips:	
SW-Ref	Reference fuel, no soil added
SW-A5	5.3 w-% mineral soil A
SW-A10	10.5 w-% mineral soil A
SW-B4	4.3 w-% mineral soil B
SW-B11	10.8 w-% mineral soil B
SW-C6	6.2 w-% mineral soil C
SW-C11	11.0 w-% mineral soil C
Forest residue chips:	
FR-Ref	Reference fuel, no soil added
FR-A3	3.3 w-% mineral soil A
FR-A9	8.8 w-% mineral soil A
FR-B5	5.0 w-% mineral soil B
FR-B9	8.8 w-% mineral soil B
FR-C4	4.0 w-% mineral soil C
FR-C9	8.6 w-% mineral soil C

2.3 Fuel properties

Before combustion, fuel properties were determined according to international standards for solid biofuels. Fuel moisture content was determined gravimetrically according to ISO 18134-1 using a drying cabinet ($n = 3$) (FED 720, Binder GmbH) immediately prior to the combustion tests. Determination of particle size distribution was done according to ISO 17827-1. Ash content ($n = 3$) was determined according to ISO 18122 in a muffle furnace (Nabertherm GmbH). Bulk density ($n = 3$) was determined according to ISO 17828. Net calorific value was determined using a calorimeter (C 2000 basic, IKA) according to ISO 18125. After acid digestion all chemical analyses were done by ICP-OES and ICP-MS analysis for the pure fuels and the three different soils were analyzed according to HFA B3.2.3 (German handbook for forest analysis) that corresponds largely with ISO 16967 and ISO 16968. For the contaminated fuels, the elements were calculated using the ICP results from the pure fuels and the soils in the appropriate contamination levels. The samples were taken directly from the screw conveyor of the boiler immediately before and after the respective combustion trial, and then homogenized to get a representative sub-sample for the whole batch. For ash content, net calorific value and chemical analysis, the samples were milled to a diameter of < 0.5 mm in one step using a cutting mill (Pulverisette 19, Fritsch GmbH) with heavy metal-free cutting tools. Based on the element concentrations, specific fuel indexes were calculated in order to predict the ash melting behaviour (molar (Si+P+K)/(Ca+Mg)-ratio), the theoretical risk for aerosol formation (Σ(K, Na, Pb, Zn)), NO_X-emissions (N-content of the fuel) and K-release to the flue gas (molar Si/K-ratio)[11,12].

2.4 Combustion tests and experimental setup

All fuels listed in Table I were combusted in a moving grate boiler (GUNTAMATIC Heiztechnik GmbH, Powerchip 20/30, constructed in 2010) which has a lateral fuel insertion (Figure 2, left). The combustion tests lasted for at least 8 hours including a pre-heating phase lasting for about 2 hours, which was followed by a 6 h full load operation before shutdown. The ash is removed via the moving grate to a screw conveyor which transports the ashes into the ash box. A round storage

tank with a flat spring agitator and a screw conveyor was used as a fuel feeding system. To determine the fuel consumption during combustion, the storage tank was placed on a platform scale (Mettler-Toledo GmbH, MT KD600) with a resolution of 0.005 kg. Figure 3 (right) shows a schematic drawing of the test rig and the arrangement of the measurement devices. The heat consumption was permanently regulated to a nominal load of 30 kW following DIN EN 303-5. The gaseous components CO, CO_2 and O_2 were determined using a single component analyzer (ABB Automation GmbH ABB AO2020), NO_X by a chemiluminescence detector (Eco Physics GmbH CLD 822 Mhr Analyzator) and for water vapour content, SO_X, HCl and CH_4 an FTIR-analyzer (Ansyco GmbH FTIR DX4000N) was used. The recording interval for the continuous measurement was set to 10 seconds. The total particulate matter (TPM) was measured following VDI 2066-1 applying a filtration temperature of 160 °C during sampling and filter post-treatment. Also,solid depositions in the sampling line were collected after each measurement day by washing with acetone and subsequent evaporation. The boiler was operated at constant flue gas draught of -15±2 Pa as it is suggested by the boiler manufacturer. The diameter of the flue gas duct and the connecting pipe was 150 mm. Flue gas velocity was continuously measured using a vane anemometer (Höntzsch GmbH, ZS25/25-ZG4) positioned in a narrowed section of the measurement section with a diameter of 100 mm (Figure 3, right). Prior to each trial, the combustion chamber, the heat exchanger and the fuel feeding system were completely cleaned using a vacuum cleaner, a brush and pressurized air. The storage tank was filled with enough fuel and the boiler was started and heated up to steady state operation at nominal load (30 kW) within approx. 2 h. Then the measurements were performed over 6 h at nominal load operation. Within this time, the gaseous emissions were continuously recorded, but were evaluated only for the duration of the TPM measurements. Five TPM measurements wereperformed evenly distributed over the whole duration of 6 h each lasting for 30 minutes. All reported emissions refer to dry flue gas at 0 °C and 1,013 hPa and (standard testing conditions - STC) are based on 13 % O_2. All residues of the combustion tests were carefully removed from the boiler and were assessed regarding slag formation.
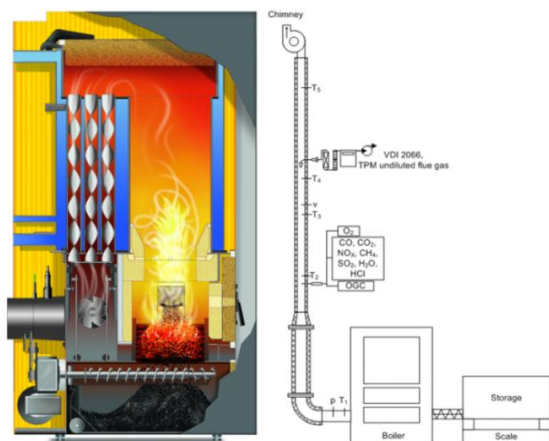

Figure 3: Schematic drawing of the boiler (source: Guntamatic, left) and a schematic drawing of the test stand (right). T1 – T5=temperature measurement points, v=velocity measurement, p=pressure measurement.

3 RESULTS AND DISCUSSION

3.1 Fuel properties

The results on physical fuel properties are summarized in Table II.

Table II: Physical fuel properties of investigated wood chips, MC – moisture content, AC – ash content, BD – bulk density, P class – particle class according to ISO 17225-4, a.r. – as received, d.b.– dry basis

Fuel	MC w-%, a.r.	AC w-% d.b.	BD kg/m³ a.r.	Fines w-% a.r.	P class - -
SW-Ref	15.8	1.0	214	8.6	P31s
SW-A5	15.2	5.7	225	9.7	P31s
SW-A10	12.7	10.1	233	16.9	none
SW-B4	14.7	5.7	230	9.0	P31s
SW-B11	13.3	10.9	248	15.9	none
SW-C6	14.5	5.2	228	12.3	none
SW-C11	11.7	12.7	242	20.5	none
FR-Ref	16.5	2.0	270	20.4	none
FR-A3	13.1	5.4	267	7.3	none
FR-A9	15.1	10.5	278	21.8	none
FR-B5	15.0	5.1	271	11.8	none
FR-B9	15.6	9.4	284	34.2	none
FR-C4	15.4	6.2	276	19.4	none
FR-C9	14.9	9.4	285	30.7	none

Due to the previously performed technical drying of all wood chips, the moisture content of the wood fuel used in the combustion trials was in a rather narrow range between 11.7 w-% (SW-C11) and 16.5 w-% (FR-Ref). All fuels largely differed in ash content ranging from 1.0 w-% for SW-Ref for uncontaminated stemwood to 12.7 w-% for SW-C11 with 11 m-% addition of soil C to stemwood. As expected, the ash content of contaminated fuels was in the range of 5.1 to 12.7 w-% (d. b.) due to the addition of inert mineral soil and was thus much higher than the reference fuel. The bulk densities of FR-B9 and FR-C9 were significantly higher than the reference fuel (p ≤ 0.05, single ANOVA (Tukey)). The bulk density of the other contaminated fuel portion was constant or higher. All values of the reference fuel made from stemwood met the requirements of ISO 17225-4 fuel class A1. All other fuels met the requirements for class B. The contaminated wood chips cannot be assigned to any class of the mentioned standard due to high ash content. The fraction of fines increased from 8.6 w-% to a maximum of 20.5 w-% for stemwood chips if soil was added to the fuel. In contrast to that the content of fines in the reference fuel for forest residue chips was already on an elevated level of 20.4 w-%. The reason for the observed decrease in fines of contaminated FR fuels at the lower contamination level although soil was added to the fuel might be that the small particles remained in the fuel storage tank and did not enter the feeding screw where the fuel sample wastaken.

The chemical composition of the reference fuels produced from stemwood and forest residue are summarized in Table III and show typical concentrations on the elements [5,13]. Moreover, the concentrations for the contaminated fuels as well as the three different soil types are shown in Table III. The nitrogen content was at 0.1 w-% for stemwood and at 0.34 w-% for forest residue. The addition of soil had almost no effect on the nitrogen content in the fuel, only some effect of dilution

Table III: Elemental concentration of the wood chip assortments and mineral soil as well as fuel indexes

Fuel	N	Al	Ca	K	Na	Mg	Si	P	(Si+P+K)/(Ca+Mg+Al)	Si/K	K+Na+Zn+Pb
	w-%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mol/mol	mol/mol	mg/kg
SW-Ref	0.11	239	1,847	638	32	335	1,563	84	1.1	3.4	691
SW-A5	0.09	3,782	1,883	1,378	266	648	15,106	101	2.7	15.3	1,669
SW-A10	0.09	7,258	1,918	2,104	496	934	28,394	117	3.0	18.8	2,628
SW-B4	0.12	2,234	1,812	1,750	88	486	16,420	86	4.3	13.1	1,862
SW-B11	0.09	5,249	1,758	3,431	174	685	38,878	88	5.5	15.8	3,631
SW-C6	0.09	5,322	2,029	1,519	370	1,248	16,259	113	2.1	14.9	1,917
SW-C11	0.10	9,257	2,170	2,201	632	1,940	27,636	136	2.2	17.5	2,866
FR-Ref	0.34	714	4,298	1,467	71	574	3,904	298	1.2	3.7	1,578
FR-A3	0.28	2,904	4,239	1,900	216	749	12,259	302	2.0	9.0	2,158
FR-A9	0.29	6,555	4,142	2,623	457	1,040	26,185	307	2.6	13.9	3,124
FR-B5	0.27	3,010	4,134	2,719	135	716	21,062	290	3.4	10.8	2,895
FR-B9	0.30	4,755	4,010	3,670	184	823	34,103	283	4.2	12.9	3,896
FR-C4	0.29	3,974	4,317	2,002	288	1,141	13,291	309	1.8	9.2	2,334
FR-C9	0.30	7,724	4,340	2,617	537	1,794	24,087	321	2.0	12.8	3,202
Soil A	0.05	67,090	2,521	14,600	4,452	5,872	257,144	397	3.4	24.5	19,052
Soil B	<0.05	46,630	1,025	26,500	1,349	3,407	347,073	122	6.9	18.2	27,849
Soil C	0,12	82,220	4,783	14,840	5,488	14,760	239,594	558	2.4	22.5	20,328

with inert material was observed for the forest residues.

The addition of soil increased the concentrations of Al, K, Na and Si considerably for both fuel assortments having an influence on the combustion behaviour.

One important fuel index regarding the combustion performance is the ash melting tendency which can be estimated from the molar ratio of (Si+P+K)/(Ca+Mg+Al), i.e. the "slagging index". The indexes are usually used for pure wood fuels. In contaminated fuels, the Al concentration might be very high due to high Al concentration in the added soil while ash melting temperatures might be increased. With regard to the Al content of the soils (soil A: 67,090 mg/kg, soil B: 46,630 mg/kg and soil C: 82,220 mg/kg) the (Si+P+K)/(Ca+Mg+Al)-ratio might be preferred for predicting ash melting behaviour of Al containing fuels [15].

This slagging index should be below 2.5 to avoid severe slagging [11,14,15]. For contaminated wood chips the index is higher than for the reference fuel being above or close to the threshold value of 2.5. The highest risk for slag formation is predicted for contamination with soil B while almost no risk of slag formation is predicted for the addition of soil C using this index. The slagging index of fuel with 10 w-% contamination is always higher than for the lower contamination level of 5 w-%, regardless which soil was used for contamination. From this calculation, a lower ash melting temperature is to be expected when contamination increases.

Regarding the sum of aerosol forming elements (K+Na+Zn+Pb) the reference fuel from stemwood contained 691 mg/kg whereas the fuel from forest residue contained 1,578 mg/kg. The contaminated fuels were partly in the same range as the reference fuel and partly considerably higher. The highest value was observed for both fuel assortments when soil B was added, ranging between 2,866 and 3,202 mg/kg and indicating elevated formation of particulate matter emission.

Regarding the expected K-release, the contaminated wood chip fuels showed increasing molar Si/K ratios compared to reference wood chips, where the ratio was always above the threshold value of 2.5 which indicates that more K is captured in the ash and not released to the gas phase. All tested soils have a high content of Si, therefore this effect on the index was expected [16].

Thus, under such circumstances the total particulate emission when using contaminated fuels may be expected to be reduced although the sum of aerosol forming elements increases. This hypothesis was to be verified in the performed combustion trials.

3.2 Combustion trials

CO is the leading indicator for incomplete combustion. The CO emissions were highest when the reference fuel was used being as high as 102 and 134 mg/m³ for stemwood and forest residue, respectively (Figure 4). The lowest values were measured using the fuel which was contaminated with 10 w-% mineral soil A (13 and 19 mg/m³ for stemwood and forest residue, respectively). All contaminated fuels had lower CO emissions than the reference fuel (mean 13 − 97 mg/m³). Thereby, increasing levels of contamination with every soil had a decreasing effect on the CO emissions.
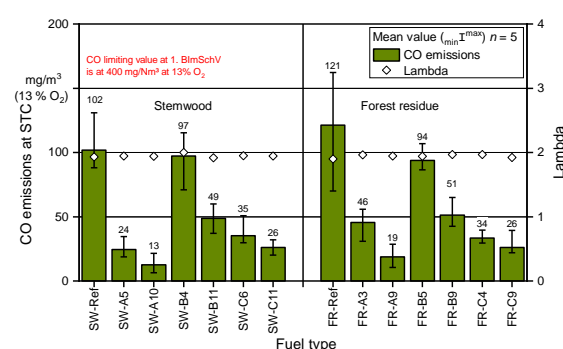

Figure 4: Mean CO emissions during combustion of wood chips without and with soil contamination in a 30 kW wood chip boiler ($n = 5$, whiskers indicate minimal and maximal values). SW stemwood, FR forest residue

The emissions of the organic gaseous carbon (OGC) are shown in Figure 5. The highest OGC emissions were detected for FR-Ref (2.4 mg/m³). The lowest value was measured for stemwood chips contaminated with 5 w-% and 10 w-% of soil A and with 11 w-% with soil C being as low as 0.2 mg/m³. For the contaminated wood chips, no clear trend was observed between the 5 or 10 w-%

contaminated fuels or the different soils. This was also due to the generally very low level of OGC as it is typical for automatically fed boilers. The values are in the bottom range of the FID.
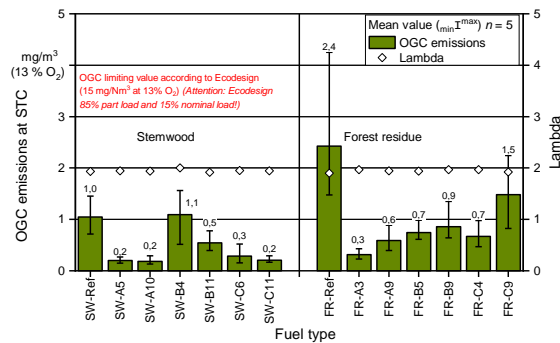

Figure 5: Mean OGC emissions during combustion of wood chips without and with soil contamination in a 30 kW wood chip boiler. SW stemwood, FR forest residue

NO_X emissions were lower for the combustion of stemwood chips varying between 138 and 144 mg/m³ (Figure 6). Almost twice as high were the NO_X emissions released during combustion of forest residue chips ranging between 244 and 276 mg/m³. No impact of soil contamination is observed. The slightly higher NO_X variation observed for forest residue chips can be attributed to higher inhomogeneity of the fuel, while stemwood chips are obviously highly homogeneous concerning the nitrogen content in the fuel.
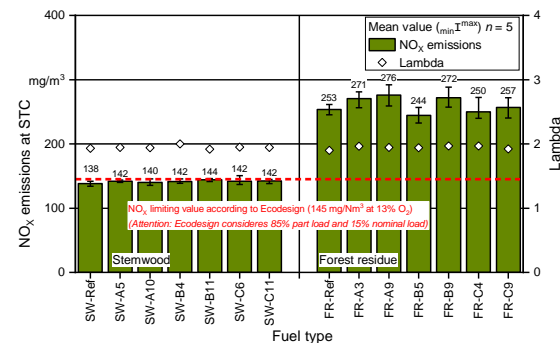

Figure 6: Mean NO_X emissions during combustion of wood chips without and with soil contamination in a 30 kW wood chip boiler. SW stemwood, FR forest residue

Total particulate matter (TPM) emissions are summarized in Figure 7. The combustion of the reference fuels led to 35 and 58 mg/m³ of TPM during full load operation for stemwood and forest residue, respectively. These values clearly reflect the differences in the content of aerosol forming elements (Table III). Both emissions exceed the German threshold of 20 mg/m³ for TPM emission as defined in 1. BImSchV[17].

However, when regarding the contaminated fuels, the content of aerosol forming element is not any more the decisive parameter for TPM emissions. The highest TPM emissions were detected for wood chips contaminated with 10 w-% of soil C for both wood chip types. Interestingly, the TPM emission for the contaminated stemwood chips was as twice as high as for the forest residue wood chips contaminated with the same soil (237

and 122 mg/m³) although the sum of aerosol forming elements (Table III) was highest for forest residue wood chips contaminated with soil B. The lowest increase of TPM emission was caused with fuel where soil B was added.

The reason why the typical correlation between the sum of aerosol forming elements and TPM emission cannot be found in this investigation could be seen in the increased Si/K ratio, which can leadto an intensified capturing of potassium into the ash. Another reason may be the entrainment of fine soil particles with the flue gas leading to the observed increase in TPM emission. This entrainment could have been triggered by the fact that the contamination was performed by adding fine powdered soil particles via a dosing screw, this might be untypical for soil contaminations which could also be highly incorporated into the fuel or could also occur as larger adhesive agglomerates.
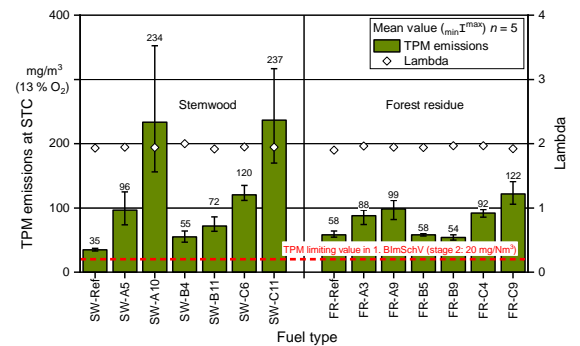

Figure 7: Mean TPM emissions during combustion of wood chips without and with soil contamination in a 30 kW wood chip boiler. SW stemwood, FR forest residue

4   SUMMARY AND CONCLUSION

The following conclusions can be drawn from this investigation:

- Careful operation during fuel production, e.g. during logging, chipping or transportation, is essential to avoid the contamination of wood chips and, thus, to reduce problems during combustion. All trials with wood chips that were contaminated with mineral soil resulted in a high amount of boiler ash and, according to the indexes, elevated slag formation is enhanced (data not shown). The boiler provided 30 kW constant full load operation during every trial. However, severe slagging and too high shares of ash might be problematic for boilers without a moving grate and can even result in a boiler shut down.
- The CO emissions decreased with addition of mineral soil. No contamination induced impact in NO_X emissions is observed. For CO, the legal require-ments of the current national emission thresholds of the German Federal Emission Control Act (1. BImSchV) were met.
- The TPM emissions increased with soil contamination (soil A and C) or remained constant. To date it remains unclear whether this effect is completely caused by thermochemical effects in the fuel conversion process or if it might also be explained by any direct entrainment of soil particles into the flue gas stream.

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