Residential Electrostatic Precipitator - Performance at efficient and poor combustion conditions

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SP Sveriges Tekniska Forskningsinstitut

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Abstract

The performance of a pilot residential electrostatic precipitator R_ESP (Applied Plasma Physics AS), was investigated at laboratory. Measurements of TSP (Total Suspended Particles), content of organic and elemental carbon, and mass size distribution of particles upstream and downstream of ESP were performed. Values for PM1 (particles < 1 µm) were calculated from the particle size distributions. Concentrations and size distributions with respect to particle numbers were measured in separate tests. Gas concentrations, temperatures and boiler parameters were also measured. The TSP concentrations upstream of the R_ESP were varied in range of 15-390 mg/mN3. Up to concentrations of about 300 mg/mN3, the TSP-concentrations out from the ESP were less than 20 mg/mN3, which is well below the German emission limit for wood stoves. The removal efficiencies with respect to mass were about 87% at efficient combustion and 93% at poor combustion. Corresponding values with respect to number concentrations were about 97% at efficient combustion and almost 99% at poor combustion. The better performance at poor combustion may be explained by lower flue gas temperature, leading to longer residence time in the ESP. High removal efficiencies were also found with respect to particulate organic and elemental carbon.

Key words: Residential ESP, biomass combustion, particle emissions

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Sammanfattning

Luftföroreningar från förbränningsprocesser för energiproduktion och långväga transporter är de viktigaste källorna för PM2,5 (partiklar < 2,5 µm) i omgivningsluften i Sverige. PM2,5 från eldstäder kan orsaka akuta lungproblem, innehåller cancerframkallande organiska föreningar, och dessutom finns det risk att höga koncentrationer ultrafina partiklar leder till hjärt- och kärlsjukdomar. På marknaden, eller nära marknadslansering, finns ett fåtal anordningar avsedda att rena rökgaser från eldstäder i bostäder för att kunna möta framtida utsläppsgränser. I denna studie undersöktes prestandan hos ett småskaligt elektrostatiskt filter (ESP) som är nära marknadslansering.

Elektrofiltret i denna studie (R_ESP, Applied Plasma Physics AS) är avsett att monteras ovanpå en skorsten, utomhus på taket. I föreliggande studie undersöktes ett pilot-R_ESP under två veckors drift. Spänningen i elektrofiltret var 38 kV under de flesta mätningarna. Studien omfattar två olika förbränningsfall; Det första var effektiv träpelletsförbränning i en pelletspanna. Det andra fallet var dålig förbränning av träpellets (i samma panna som föregående fall). Elektrofiltret monterades på en skorsten i lab-miljö (ca 20°C i omgivningsluft). I denna uppställning genomfördes parallella mätningar av TSP (total mängd suspenderade partiklar) och masstorleksfördelningar av partiklar (0,3-10 µm) både uppströms och nedströms elfiltret. Utvalda prover av TSP analyserades med avseende på elementärt och organiskt kol. PM1 (partiklar < 1 µm) beräknades utifrån storleksfördelningen av partiklar. Separata tester med en ELPI (Electrical Low Pressure Impactor) gjordes för att få en bild av antalskoncentrationen och storleksfördelningen (0,007-8 µm). ELPIn användes för mätningar nedströms ESP-filtret varvid koncentrationen uppströms filtret simulerades genom att elektrofiltret slogs av och på med några minuters mellanrum. I samtliga fall utfördes även mätningar av O2, CO2, CO och TOC (Total Organic Carbon), temperaturer och pannparametrar.

Koncentrationen av TSP uppströms R_ESP var ca 15-390 mg/mN3 torr rökgas, normaliserat till 10 % O2. Upp till TSP-värden på ca 300 mg/mN3 i gasen in i ESP-filtret var TSP-värdena ut från ESP mindre än 20 mg/mN3 vid 10 % O2. Detta är långt under den tyska utsläppsgränsen för vedkaminer (~ 29 mg/mN3 vid 10 % O2/ 40 mg/mN3 vid 13 % O2). Avskiljningsgraden med avseende på partikelmassa var ca 87 % vid effektiv förbränning och ca 93 % vid dålig förbränning. Motsvarande värden med avseende på antalsreduktion var ungefär 97 % vid effektiv förbränning och nästan 99 % vid dålig förbränning. Den bättre avskiljningsgraden vid dålig förbränning kan möjligtvis förklaras av den lägre rökgastemperaturen in i elektrofiltret, vilket leder till en längre uppehållstid. Elektrofiltret presterade bra under den två veckor långa provtagningsperioden men långtidstester bör utföras för vidare utvärdering.

Summary

Traffic exhausts, combustion processes for energy production and long-distance transports are the main sources of PM2.5 (particles < 2.5 µm) in the ambient air in Sweden. PM2.5 from residential combustion contains carcinogenic organic compounds and may, at high concentrations, cause acute lung problems and heart- and cardiovascular diseases. To meet future emission limits there are a few residential devices for cleaning of flue gas available, or close to market. In this work the performance of a residential electrostatic precipitator (ESP), close to market, is investigated.

The residential ESP in this study (R_ESP, Applied Plasma Physics AS) is designed to be mounted on a rooftop chimney. In this work the performance of a pilot-R_ESP was investigated during two weeks of different measurements. The ESP-voltage was 38 kV in most measurements. The study includes two combustion cases. The first case is efficient pellets combustion, achieved by optimal combustion of wood pellets in a pellets boiler. The second case is poor combustion of wood pellets (in the same boiler as used for the first case). The ESP was mounted on a chimney inside a laboratory. Concentrations of TSP (Total Suspended Particles) and mass size distributions (0.03-10 µm) were measured simultaneously upstream and downstream of the ESP. Subsequently, TSP-samples were analysed with respect to elemental and organic carbon. Concentrations of PM1 (particles < 1 µm) were calculated from the particle size distributions. Separate tests were performed using an electrical low pressure impactor (ELPI, 0.007-8 µm) to determine number concentrations and size distributions. The ELPI was installed downstream of the ESP and the upstream concentrations were simulated by switching off the ESP. The ESP was toggled on and off with intervals of a few minutes. During all the tests, gas concentrations of O2, CO2, CO, TOC (Total Organic Carbon), temperatures and boiler parameters were measured.

The concentrations of TSP upstream of the R_ESP were in range of 15-390 mg/mN3 dry flue gas, normalized to 10% O2. Up to TSP-concentrations of about 300 mg/mN3, the concentrations out from the ESP were less than 20 mg/mN3 at 10% O2. This is well below the German emission limit for wood stoves (~29 mg/mN3 at 10% O2 / 40 mg/mN3 at 13% O2). The removal efficiencies with respect to mass of particles were about 87% at efficient combustion and about 93% at poor combustion. Corresponding values with respect to number of particles were about 97% at efficient combustion and almost 99% at poor combustion. The better performance at poor combustion may be explained by the lower flue gas temperature into ESP, which lead to longer residence time. The R_ESP performed well during two weeks of laboratory tests. The long term performance needs to be further investigated.

1 Introduction

Traffic exhaust, combustion processes for energy production and long-distance transports are the main sources of PM2.5 into the ambient air of Sweden [1]. PM2.5 denotes particles smaller than 2.5 µm. Such particles constitute a risk for public health. Residential combustion may locally cause acute lung problems, and the particles contain carcinogenic organic compounds. High number concentrations of ultrafine particles can lead to heart- and cardiovascular diseases.

The limit of PM2.5 in the air is 25 µg/m3, as a mean value over a year, in Sweden as well as in whole EU[2]. This limit is problematic to fulfil in many areas with extensive wood burning.

1.1 Background

One way to reduce the emissions of particles from wood burning is to use secondary removal devices. This may also be an alternative to meet stricter emission limits in the future. In the project FutureBioTec (in program ERA-NET Bioenergy) 12 residential electrostatic precipitators (ESPs), 2 catalytic converters, one ceramic filter and one condensing heat exchanger were identified as on the market or close to the market [3]. ESP seem to be the most promising technology, and three products can already be found on the market. In this project the residential electrostatic precipitator R_ESP (Applied Plasma Physics AS) is studied. It is one of the residential ESPs identified as close to the market.

1.2 Aim

In this work the performance of the residential electrostatic R_ESP is investigated. The removal efficiency has been investigated with respect to particle concentration, size distribution and the content of inorganic particles, organic carbon and soot (elemental carbon).

2 Theory

A general description of the processes of electrostatic precipitation of flue gas particles is presented in this chapter.

2.1 Dust precipitation by electrostatic force

Electrically charged particles in a flue gas can be precipitated by an applied electrical field, perpendicular to the direction of the flow, in which particles are attracted by the electrode of opposite polarity. The strength of the force acting on a single particle depends on the applied electrostatic field strength as well as the charge of the particle. However, particles in a flue gas are generally not sufficiently electrically pre-charged when entering a flue gas cleaning system. Thus, the first task of an electrostatic precipitator is to charge the flue gas particles, and the second task is to collect the particles on dust collection surfaces.

In most industrial applications, the charging and collection of particles are achieved in the same chamber. The charging of particles is a much faster process than collecting them on the collection surfaces.

To charge the particles, the gas needs to be ionized. This is accomplished by the discharge electrode (as opposed to the other electrode which work as collector surface) shaped in such a manner that the local electric field strength becomes very high close to the electrode. For instance, a relatively thin wires or a string with needle points can be used. Typically, the field strength near the discharge electrode is in the range of 5 to 10 MV/m. At such high field strengths, free electrons are rapidly accelerated to energies that can ionize gas molecules when colliding. At ionization, even more free electrons are released. In turn, they accelerate, collide, and ionize more gas molecules. This continuous process creates a corona around the discharge electrode. It may be formed all along the wire or at isolated spots, depending on the design and other conditions. It has been found that the electrostatic precipitator process works best when the discharge electrode is chosen to be of negative polarity. Thus, positive ions formed in the corona migrate towards the wire where they are discharged. The electrons, on the other hand, are repelled by the discharge electrode and move away from it. In the lower electric field strength outside the corona region, the energies of electrons are not anymore sufficient to ionize gas molecules. The free electrons moves towards the collection surfaces, but on their way they can be captured on particles present in the flue gas. Consequently, the particles in the flue gas becomes negatively charged and are forced towards the collection surfaces by the electric field force.

For relatively large particles (>0.15 um) the dominant charging mechanism is “field charging”, which could be explained as capture by any particle in the pathway of the electron. However, while a particle becomes increasingly charged, approaching electrons will be more and more repelled by the charge of the particle, implying that there is a limit on how charged one particle will get. The maximum charge for a particle depends on the particle size, the dielectric constant of the particle and the local field strength. Very small particles (<0.15um) are also charged, but by another mechanism, called “diffusion charging”, in which electron-gas molecule collisions are considered [4].

In the electric field of an electrostatic precipitator, the charged particles are accelerated towards the collection surfaces by the electrostatic force. As the particle gain velocity relative to surrounding gas, the counter-acting drag force increases. The average migration velocities of particles (w) can be estimated by assuming the drag force equal to the electrostatic force. This drift velocity depends on the average field strength E and on particle diameter (D) as:

$$w \propto DE^2 \tag{1}$$

The average field strength is commonly approximated as the voltage divided by the distance between the discharge electrode and the collection surface. From, Eq. 1, it follows that the migration velocities of particles in the precipitator increase with higher voltage between electrodes. In practice, the field strength is limited by sparking (similar to thunderbolts in a thunder storm). At high field strengths, an ionized path (electric arc) might form between the electrodes. To prevent overload of the transformer and to restore the electric potential between electrodes, such electric arcs must be extinguished. Usually, the control system of an ESP detects such a flashover by the increased current and falling voltage, and reacts by shutting of the current for a moment. After the electric arc is quenched, the voltage between electrodes will be restored. The frequency of flashover will increase with the electric field strength. At flashovers, the field strength is momentarily lost and sparks can detach dust from collection surfaces, reducing collection efficiency. That is, the collection efficiency of an ESP is improved by raised voltage between electrodes until the frequency of sparks become too high. The control system of an ESP may use a pre-set value of desired sparks per minute when controlling the voltage. If no sparks at all, the ESP is probably not working at its optimum.

It should be mentioned, however, that this is not always true; if the dust has very high resistivity, a phenomena called “back corona” may occur on the collection surfaces, deteriorating the collection efficiency. Under such circumstances, more complex control algorithms have to be used to find optimum performance.

In the ESP, charged particles are deposited on collection surfaces. How hard the dust sticks to these surfaces depends on its resistivity. ESPs have been found to work best with medium resistive dust, in the range of approximately 107 to 1010 ohm cm. If the dust has too low a resistivity, for instance if containing a lot of black carbon, the dust will readily discharge on the collection surfaces, leaving very low electrostatic force to hold the dust cake on to the surface. This results in a high re-entrainment of particles which reduces the performance of the precipitator for low resistivity dust. Too high resistivity creates problems with “back corona”, as mentioned, and falling electrostatic field strength in the gas, while the dust may stick so hard on the surfaces that it can be difficult to remove. The resistivity of the dust is affected by its temperature, so the performance of the ESP also depends on the operating temperature.

The collection surfaces have to be cleaned regularly to maintain the efficiency of the precipitator. In large-scale ESPs, the cleaning is usually accomplished by rapping on the surfaces by hammers. During rapping, deposits are mechanically detached from the surface and most of it falls down into hoppers, while a fraction is entrained into the flue gas.

The relation between the collection efficiency of an ESP and the migration velocity (w) is commonly described by Deutsch formula:

$$\eta = 1 - e^{-\frac{wA}{Q}} \tag{2}$$

In which A is the total surface area of collecting surface and Q is the gas flow through the precipitator. As can be seen from Eq. 1, the actual migration velocity (w) depends on particle sizes. Generally, flue gases contain particles of various sizes. The size distributions depends on the process where they are formed. Thus, in practice, the average migration velocity is usually expressed as an apparent value for the process, calculated from a measured efficiency of the ESP. Such an apparent migration velocity (w) depends not only on particle size distribution, but among other things also on the dielectric properties and resistivity of the particles.

2.2 Industrial electrostatic precipitators

Electrostatic precipitators (ESP) are commonly used in industrial applications and in heat and power plants, with collection efficiencies often above 99.5 %. A sketch of a partition of a typical large ESP is given in Figure 1. In this sketch, the discharge electrodes are made of wires and the collection surfaces are steel plates. The gas flows between the plates. The voltage between electrodes is supplied by high voltage rectifiers, commonly in range of 20 to 80 kV.

The charged particles loose most of their charge at the collection plates, but they tend to agglomerate to each other, forming a dust cake. The dust cake on the plates are periodically removed by rappers striking the plates. The impact should be just hard enough to detach sheets of dust, not causing unnecessary re-entrainment of dust into the gas. Most of the dust cake falls into hoppers below the plates, but some is always re-entrained. Usually, an ESP consists of at least two systems in series, and also some in parallel for large gas flows. Each system is individually controlled with separate power transformers. Most of the dust, by mass, is in the larger particle size fractions, which are most easily captured by the precipitator. Therefore, the first system collects most dust and needs the most frequent rapping. Most of the dust re-entrained from the first system is recaptured by the next system, which collects less dust and needs less frequent rapping. In this sense, the dust emission due to rapping is reduced with increasing number of systems in series. An increased number of systems increase the performance of the ESP, but it will of course affect the investment cost of the installation. Since the particle concentration falls along the direction of the gas flow, the electrical current between electrodes is highest in the first system. The high presence of electrical charged particles in the first system usually implies that the frequency of sparks is highest in this system.

The cross-sectional area of the ESP is usually chosen to provide an average gas velocity of less than about 2 m/s, in order to provide sufficient residence time and to reduce re-entrainment. Uniform cross-sectional distribution of the gas flowing though the precipitator is very important in order to maximize its collection efficiency. The need for even gas distribution, which could be accomplished by a series of screens and baffles, has to be evaluated against the desire to keep the power loss from pressure drop as low as possible.

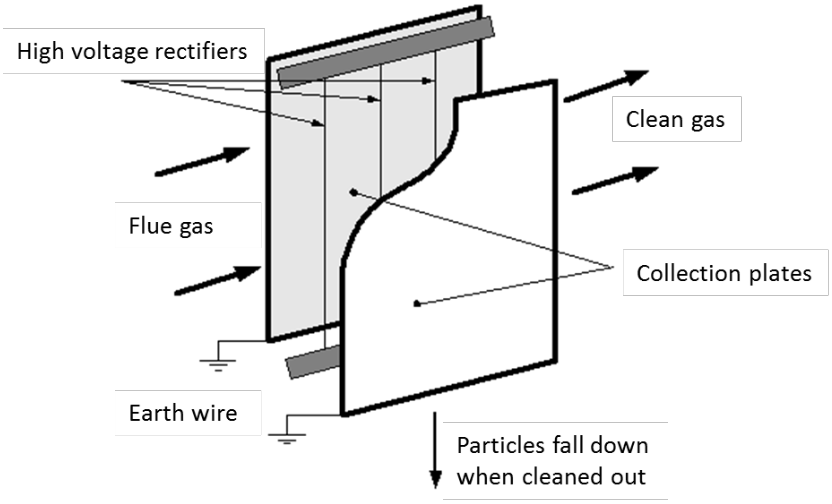

Figure 1: The principle of an ESP.

3 Method

The performance of a residential ESP was investigated by measuring the concentrations of particles in the flue gas upstream and downstream of the ESP and from that calculating removal efficiency. Particles were characterised with respect to total mass concentration, mass size distribution and number concentration and size distribution. The experiments were performed during combustion of wood pellets.

A pellets burner were used in combination with a boiler at SP Energy Technology combustion laboratory. A chimney was installed on the boiler and the ESP was mounted directly on the chimney, see Figure 5

Combustion cases

1. Efficient pellets combustion
2. Poor combustion of wood logs, simulated by poor combustion of pellets

3.1 Electrostatic Precipitator R_ESP

The electrostatic precipitator R_ESP is relatively compact, designed for direct mounting on chimneys of residential houses. Figure 2 shows a photograph of the R_ESP specimen used in this project. The R_ESP is installed on top of the chimney where the flue gas exits but an electrode also reaches down into the chimney. The R_ESP, according to the manufacturer, needs to be maintained at regular intervals with soot cleaning, preferably at the same intervals as the chimney is swept.

The R_ESP needs access to a grounded electrical outlet of 220 V, secured up to 16 A. The maximum power is 105 W while normal operation is at 60 W. In this work the ESP-voltage was 38 kV if not stated otherwise. A cross-view of the R_ESP showing the various parts inside the filter is shown in Figure 3. The voltage is applied through a cable in the centre of the filter and electric fields are formed in two parts of the R_ESP: 1) In the parts inside the chimney between the electrode in the centre and the chimney wall, and 2) In the part sticking out above the chimney, between the electrode and the metal wall. In the electric field the flue gas particles are negatively charged. The exterior part of the R_ESP is grounded and constitute the positive electrode, attracting the particles to be collected on the walls.

Figure 2: A photograph of the E_ESP.

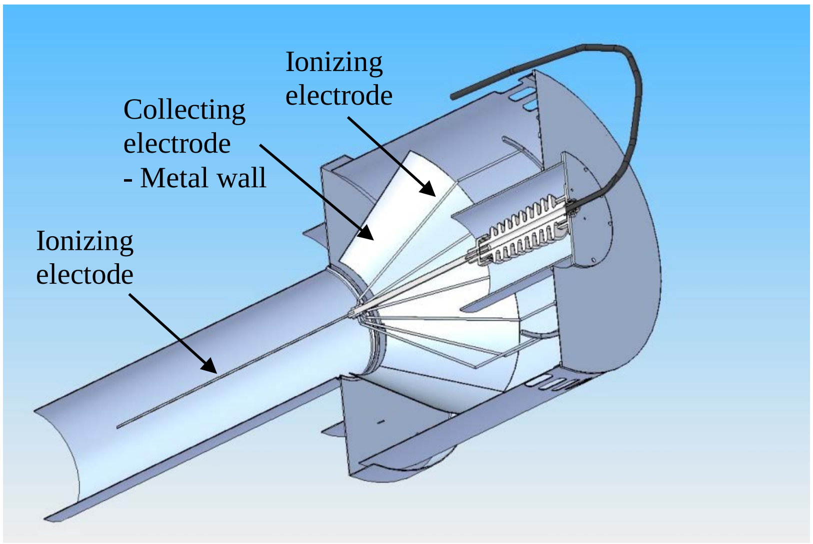

Figure 3: A cross-view of the R_ESP.

3.1.1 Particle separation

The particle removal efficiencies of the R_ESP were calculated from measured particle concentrations. The initial concentration, before the R_ESP, (C_{in}) and the concentration after the R_ESP (C_{out}) give the particle removal efficiency η_{filter} as

$$\eta_{filter} = \frac{C_{in} - C_{out}}{C_{in}} \tag{3}$$

3.2 Boiler

The boiler and the burner used in the experiments are from Janfire, model NH, see Figure 4. The burner is fully automatic and self-cleaning. A patented moving base in the burner cleans and feeds any slag and impurities from the grate into the ash pan. The burner is automatically cleaned at set intervals or when the boiler thermostat starts.

Figure 4: NH-Burner and boiler from Janfire used in the project.

3.3 Fuel

Standard wood pellets were used as fuel for all experiments. A description of the pellets can be found in Table 1.

Table 1: Fuel analysis

Chemical composition of the standard wood pellets		
Moisture content	wt-%	7
Carbon	wt-%	50.3
Oxygen	wt-%	43
Hydrogen	wt-%	6.1
Nitrogen	wt-%	0.07
Sulphur	wt-%	0.01
Ash	wt-%	0.4
Lower heating value	MJ/kg	18.8

3.4 Measurements

Parallel measurements of TSP (Total Suspended Particles) and mass size distribution of particles (0.03-10 µm) upstream and downstream of ESP were performed. PM_1 (particles < 1 µm) was calculated from the particle size distributions. Number concentrations and size distributions were determined in separate tests using an electrical low pressure impactor (ELPI). In addition, gas concentrations of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), Total Organic Carbon (TOC), temperatures and boiler parameters were measured during all tests.

3.4.1 TSP (Total Suspended Particles)

TSP was measured simultaneously upstream and downstream of the ESP. The European standard EN 13284-1 [5] was used to determine the particle concentrations. This standard is originally intended for low particle concentrations (< 50 mg/m_N^3) but it works well also at higher concentrations. A partial flow was drawn out from the centre of the chimney through a heated probe (160 ºC). The sampling was isokinetic, i.e. the velocity in the probe tip was the same as in the chimney during sampling, achieved by using a zero-difference-pressure probe. The particles were collected on two 90 mm planar filters in parallel (weighed in advance), which after sampling were dried and weighed. The gas volume drawn through the filter during sampling was controlled, enabling calculation of mass concentration of particles. The filters were dried at 105 ºC and stored in a desiccator before and after sampling. Finally, analyses on the contents of organic carbon (OC) and elemental carbon (EC) in the particles on the filters were performed by thermal-optical carbon analyser (Sunset inc.), according to the NIOSH method 5040 [6]. Samples from downstream of the ESP were analysed directly from the filter substrate while samples from upstream of ESP were analysed from particle sample scraped from the filters. This procedure was carried out due to the high amount of material on the filters and it leads to higher uncertainty than in the direct analysis. Therefore the upstream results should be considered as indicative.

3.4.2 Particle Size Distribution and PM_1

Particle size distribution, with respect to mass, was measured simultaneously upstream and downstream of the ESP. Two Dekati Low Pressure Impactors (LPI) were used for the measurements. LPI gives the size distribution in 12 stages in the range of 30 nm – 10 µm. The concentrations of PM_1 were calculated from mass collected on the stages of the impactor with cut-off $\leq$ 1 µm. During sampling, the probe and LPI were heated to 105-110 °C to avoid condensing water vapour.

3.4.3 Number Concentration and Size Distribution

Separate tests were performed with an Electrical Low Pressure Impactor (ELPI, 0.007-8 µm) to determine number concentrations and size distributions. The ELPI was installed downstream of the ESP. Upstream concentrations were simulated by switching the ESP off. The ESP was regularly toggled on and off with a few minutes intervals during the ELPI-tests.

Particles to the ELPI were sampled by a heated probe and a two-steps dilution system, designed to avoid uncontrolled condensation and particle growth. The first dilutor was a porous tube dilutor, and the second an ejector dilutor. The first dilution step was heated to 160 °C (both the dilutor and the dilution air were heated), while the second dilution step was unheated. The diluting gas consisted of filtered and dried pressurised air.

3.4.4 Gaseous compounds, temperature and boiler parameters

The combustion conditions were monitored by gas concentrations measured in the flue gas. The concentrations of CO and hydrocarbons were used as indicators of the quality of combustion; The higher the concentrations, the poorer the combustion. CO_2 and O_2 were measured to control the excess air. Conventional gas analysers for on-line measurements were used for this purpose. CO/CO_2-instruments works on the principle of detection of non-dispersive infrared light and O_2-instruments on the principle of paramagnetism. Hydrocarbons were measured with a flame ionization detector that was calibrated with propane gas. This gives the primary hydrocarbon emissions as propane equivalents which can be recalculated into TOC, a measure of the concentration of pure carbon in gaseous hydrocarbon emissions.

TSP sampling

- **90 mm planar filters, quartz fiber (heated to 160°C)**

PM1-sampling

- **Dekati Low Pressure Impactor (DLPI), 30 nm – 10 µm (heated to 105°C)**

Number concentration and size distribution

- **Dekati Low Pressure Impactor (DLPI), 30 nm – 10 µm (heated to 105°C)**

Electrical Low Pressure Impactor (ELPI), 7 nm – 8 µm

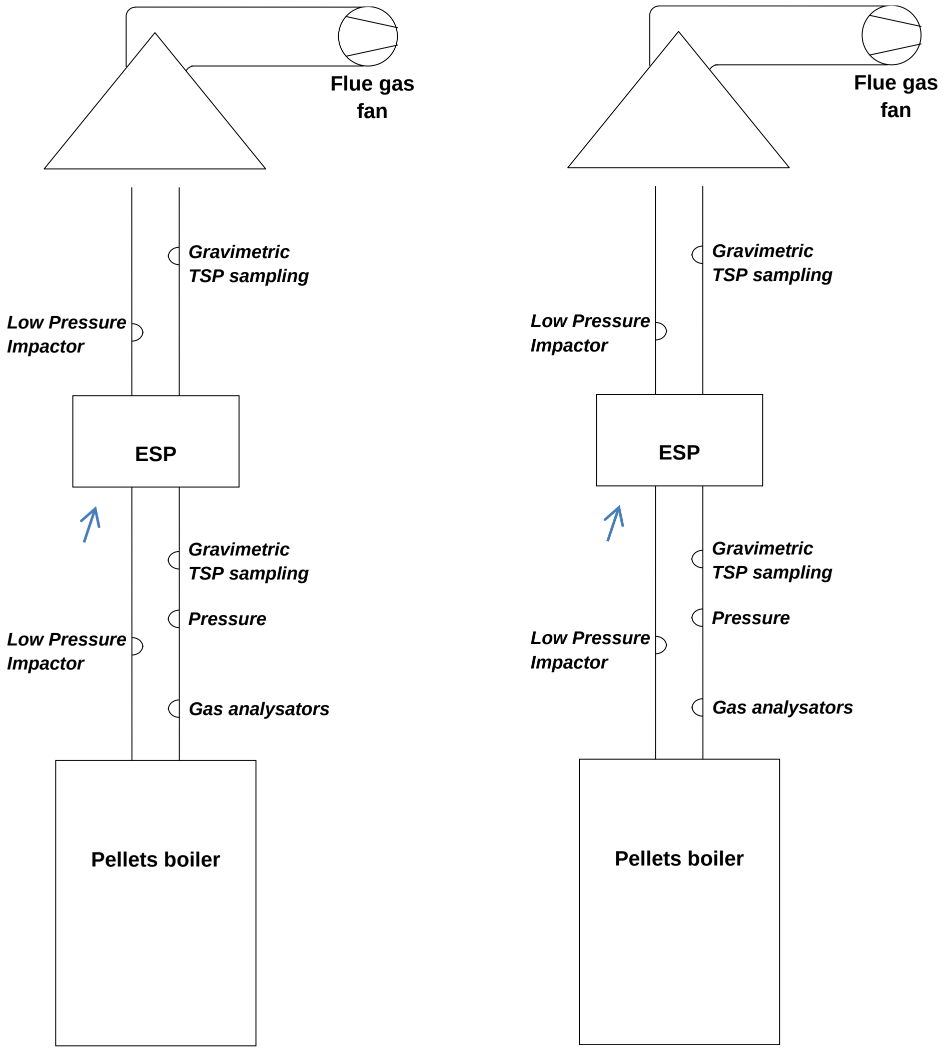

Figure 5: Left: Measurement set-up at gravimetric measurements of TSP and PM_1. Right: Measurement set-up at on-line measurements of number concentration and size distribution.

4 Results

4.1 Measurement overview

The removal efficiencies of the ESP has been calculated from the measured concentrations of particles upstream and downstream of the ESP. In some cases mass concentrations were measured (by DLPI or filter) and in other cases the number concentrations were measured (on-line by ELPI). The measurements performed are listed in Table 2. First the performance of R_ESP was investigated under efficient combustion conditions and thereafter at poor combustion. The voltage of the ESP was 38 kV, except for some cases of 35 kV at efficient combustion.

Table 2: Overview of measurement cases

	ESP (kV)	Date	Measurement method for particles
Efficient combustion			
E _DLPI_a	38	February 15	Dekati Low Pressure Impactor
E_Filter	38	February 18-22	Filter
E_DLPI_b	38	February 18-21	Dekati Low Pressure Impactor
E_ELPI_a	38	March 21	Electrical Low Pressure Impactor
E _ELPI_b	38	March 21	Electrical Low Pressure Impactor
E _ELPI_c	38	March 21	Electrical Low Pressure Impactor
E35 _ELPI_d	35	March 21	Electrical Low Pressure Impactor
E35 _ELPI_e	35	March 21	Electrical Low Pressure Impactor
E35 _ELPI_f	35	March 21	Electrical Low Pressure Impactor
E35 _ELPI_g	35	March 21	Electrical Low Pressure Impactor
Poor combustion			
P _Filter	38	March 24	Filter
P _DLPI	38	March 24	Dekati Low Pressure Impactor
P _Filter_b	38	March 28	Filter
P _Filter_c	38	March 29	Filter
P_DLPI_b	38	March 28-29	Dekati Low Pressure Impactor
P _ELPI_a	38	March 21	Electrical Low Pressure Impactor
P _ELPI_b	38	March 21	Electrical Low Pressure Impactor
P _ELPI_c	38	March 21	Electrical Low Pressure Impactor
P_ELPI_d	38	March 21	Electrical Low Pressure Impactor
P_ELPI_e	38	March 21	Electrical Low Pressure Impactor
P_ELPI_f	38	March 21	Electrical Low Pressure Impactor
P_ELPI_g	38	March 21	Electrical Low Pressure Impactor
P_ELPI_h	38	March 21	Electrical Low Pressure Impactor
P_ELPI_i	38	March 21	Electrical Low Pressure Impactor
P_ELPI_j	38	March 21	Electrical Low Pressure Impactor

4.2 Boiler output and gas upstream of ESP

The efficient combustion was characterized by concentrations of carbon monoxide between 140 and 270 mg/m_N^3 (at 10% O_2) and organic gaseous carbon between 3 and 7 mg/m_N^3 (at 10% O_2), shown in Table 3. The corresponding oxygen concentrations were 11.3-11.9 %, except for the first measurement when O_2-concentration was 12.8 %. During these measurements the boiler output was 7.8-8.2 kW, except for one first measurement when the boiler ran at 5.9 kW (Table 3). The flue gas temperature upstream of the electrostatic precipitator was 76-82 °C and the chimney draught (negative pressure) was 11-13 Pa.

Table 3: Boiler output, flue gas temperature, draught and gaseous compounds at efficient combustion, in gas upstream of the ESP

	Boiler output (kW)	**Flue gas temp. (°C)**	**Draught (Pa)**	**O_2 (%)**	**CO (mg/m_N^3) ***	**OGC (mg/m_N^3) ***
E _DLPI_a	5.9	76	13	12.8	270	6
E_Filter	7.8	77	13	11.9	220	4
E_DLPI_b	8.1	77	12	11.7	180	3
E_ELPI_a	8.2	82	11	11.8	170	6
E _ELPI_b	7.9	81	11	11.5	170	6
E _ELPI_c	8.0	81	11	11.6	170	6
E35 _ELPI_d	8.1	81	11	11.3	180	7
E35 _ELPI_e	8.1	81	11	11.3	140	5
E35 _ELPI_f	7.9	81	11	11.5	160	5
E35 _ELPI_g	8.1	81	11	11.6	160	5

**at 10% O_2*

In Table 4 the characteristics of “poor combustion” cases are shown. During poor combustion, concentrations of CO were 16900-27900 mg/m_N^3 (at 10% O_2) and OGC 830-1970 mg/m_N^3 (at 10% O_2). The corresponding concentrations of O_2 were between 5.6 and 6.6%. The boiler output was 7.2-8.1 kW, i.e. somewhat lower than in the case of efficient combustion. The flue gas temperature varied between 62 and 67 °C and draught varied between 6 and 10 Pa.

Table 4: Boiler output, flue gas temperature, draught and gaseous compounds at poor combustion, in gas upstream of the ESP

	Boiler output (kW)	**Flue gas temp. (°C)**	**Draught (Pa)**	**O_2 (%)**	**CO (mg/m_N^3) ***	**OGC (mg/m_N^3) ***
P _Filter	7.4	62	7	6.2	26200	1700
P _DLPI	7.5	62	8	6.2	27000	1790
P _Filter_b	7.9	65	7	5.6	24600	1480
P _Filter_c	8.1	64	7	6.0	24900	1580
P_DLPI_b	7.7	63	7	5.9	25800	1700
P _ELPI_a	7.2	65	9	6.6	22900	1970
P _ELPI_b	7.7	67	8	6.3	16900	830
P _ELPI_c	7.9	67	6	5.8	20200	890
P_ELPI_d	7.4	66	7	5.8	24900	1250
P_ELPI_e	7.6	65	8	6.1	27900	1460
P_ELPI_f	7.5	65	8	6.3	26700	1480
P_ELPI_g	7.3	65	9	6.5	25000	1440
P_ELPI_h	7.7	65	10	6.6	21600	1190
P_ELPI_i	7.6	64	9	6.5	22700	1190
P_ELPI_j	7.5	64	9	6.5	25400	1370

**at 10% O_2*

During efficient combustion, the measured concentrations of TSP were in range of 15-22 mg/m_N^3 (at 10% O_2). The two cases investigated for PM_1 showed that 95-96% of the particles were PM_1 (Table 5). The number concentration of PM_{10} was 5.0 – $5.8 \cdot 10^6$ particles/cm^3 (at 10% O_2), and at least 98% of the particles were of size 1 µm or smaller.

Table 5: Particle concentrations at efficient combustion, in the gas upstream of the ESP

	TSP(Filter) (mg/m_N^3) *	**TSP (DLPI) (mg/m_N^3) ***	**PM_1 (mg/m_N^3) ***	**PM_{10} Number $(1/cm^3)$ ***	**PM_1 Number $(1/cm^3)$ ***
E _DLPI_a	x	16.0	15.3	x	x
E_Filter	22	x	x	x	x
E_DLPI_b	x	14.9	14.2	x	x
E_ELPI_a	x	x	x	5.4E+06	5.4E+06
E _ELPI_b	x	x	x	5.5E+06	5.5E+06
E _ELPI_c	x	x	x	5.2E+06	5.1E+06
E35 _ELPI_d	x	x	x	5.0E+06	5.0E+06
E35 _ELPI_e	x	x	x	5.8E+06	5.8E+06
E35 _ELPI_f	x	x	x	5.4E+06	5.4E+06
E35 _ELPI_g	x	x	x	5.3E+06	5.2E+06

**at 10% O_2*

During the poor combustion conditions, the TSP was found to be 199 – 394 mg/m_N^3 (at 10% O2). In one case TSP was measured to 294 mg/m_N^3 and the corresponding PM_1 concentration 268 mg/m_N^3 and in another case the TSP and PM_1 were 199 and 189 mg/m_N^3 respectively· Thus, PM_1 constitute 91 and 95% of TSP in these two cases. The number concentration of PM_{10} was 2.1 – 4.9 · 10^7 particles/cm^3 (at 10% O_2), and at least 97% of the particles were of size 1 µm or smaller.

Table 6: Particle concentrations at poor combustion, in the gas upstream of the ESP

	TSP(Filter) (mg/m_N^3) *	**TSP (DLPI) (mg/m_N^3) ***	**PM_1 (mg/m_N^3) ***	**PM_{10} Number $(1/cm^3)$ ***	**PM_1 Number $(1/cm^3)$ ***
P _Filter	358	x	x	x	x
P _DLPI	x	294	268	x	x
P _Filter_b	372	x	x	x	x
P _Filter_c	394	x	x	x	x
P_DLPI_b	x	199	189	x	x
P _ELPI_a	x	x	x	2.6E+07	2.6E+07
P _ELPI_b	x	x	x	4.9E+07	4.9E+07
P _ELPI_c	x	x	x	4.6E+07	4.6E+07
P_ELPI_d	x	x	x	2.6E+07	2.6E+07
P_ELPI_e	x	x	x	2.1E+07	2.1E+07
P_ELPI_f	x	x	x	3.7E+07	3.7E+07
P_ELPI_g	x	x	x	3.8E+07	3.7E+07
P_ELPI_h	x	x	x	4.0E+07	4.0E+07
P_ELPI_i	x	x	x	4.1E+07	4.1E+07
P_ELPI_j	x	x	x	4.0E+07	4.0E+07

**at 10% O_2*

4.3 Gas downstream of ESP

Downstream the ESP the mass concentrations of TSP and PM_1, and number concentrations of PM_{10} and PM_1 were measured (see Figure 5). Particle results from efficient combustions are presented in Table 7 and from poor conditions in Table 8. At efficient and poor conditions the TSP concentrations downstream of the ESP were 2-3 and 13-96 mg/m_N^3 respectively. The corresponding removal efficiencies were found to be 82-89 % and 74-96 % respectively. Further, the PM_1 removal efficiency was 86-90 % at efficient combustion and 97-99 % at poor combustion.

PM_{10} number concentrations downstream of the ESP were 1.7–1.8·10^5 particles/cm^3 at efficient combustion and 0.8-1.1 10^5 particles/cm^3 at poor combustion, at an ESP voltage of 38 kV. The removal efficiencies based on number concentrations of particles were 97 % and 98-99 % at efficient and poor combustion conditions respectively. During efficient combustion, an ESP voltage of 35 kV was also tested, leading to 2.6-2.9 · 10^5 particles/cm^3 downstream of the ESP, corresponding to a removal efficiency of 95 %.

Table 7: Particle concentrations at efficient combustion, in the gas downstream of the ESP

	TSP(Filter) (mg/m_N^3) *	**TSP (DLPI) (mg/m_N^3) ***	**PM_1 (mg/m_N^3) ***	**PM_{10} Number (1/cm^3) ***	**PM_1 Number (1/cm^3) ***
E _DLPI_a	x	2.9	2.1	x	x
E_Filter	2.8	x	x	x	x
E_DLPI_b	x	1.6	1.4	x	x
E_ELPI_a	x	x	x	1.8E+05	1.8E+05
E _ELPI_b	x	x	x	1.8E+05	1.8E+05
E _ELPI_c	x	x	x	1.7E+05	1.7E+05
E35 _ELPI_d	x	x	x	2.7E+05	2.7E+05
E35 _ELPI_e	x	x	x	2.9E+05	2.9E+05
E35 _ELPI_f	x	x	x	2.8E+05	2.8E+05
E35 _ELPI_g	x	x	x	2.6E+05	2.6E+05

**at 10% O_2*

Table 8: Particle concentrations at poor combustion, in the gas downstream of the ESP

	TSP(Filter) (mg/m_N^3) *	**TSP (DLPI) (mg/m_N^3) ***	**PM_1 (mg/m_N^3) ***	**PM_{10} Number (1/cm^3) ***	**PM_1 Number (1/cm^3) ***
P _Filter	40	x	x	x	x
P _DLPI	x	13	3.9	x	x
P _Filter_b	96	x	x	x	x
P _Filter_c	25	x	x	x	x
P_DLPI_b	x	15	4.8	x	x
P _ELPI_a	x	x	x	1.0E+05	1.0E+05
P _ELPI_b	x	x	x	1.1E+05	1.1E+05
P _ELPI_c	x	x	x	1.1E+05	1.1E+05
P_ELPI_d	x	x	x	1.1E+05	1.1E+05
P_ELPI_e	x	x	x	9.9E+04	9.8E+04
P_ELPI_f	x	x	x	1.0E+05	1.0E+05
P_ELPI_g	x	x	x	9.4E+04	9.3E+04
P_ELPI_h	x	x	x	8.9E+04	8.8E+04
P_ELPI_i	x	x	x	8.4E+04	8.3E+04
P_ELPI_j	x	x	x	8.3E+04	8.3E+04

**at 10% O_2*

Table 9: ESP's removal efficiencies

	η_{TSP} (%)	η_{PM1} (%)	$\eta_{PM10\ Number}$ (%)	$\eta_{PM1\ Number}$ (%)
Efficient combustion				
E _DLPI_a	82.1	86.3	x	x
E_Filter	87.4	x	x	x
E_DLPI_b	89.4	89.8	x	x
E_ELPI_a	x	x	96.6	96.6
E _ELPI_b	x	x	96.6	96.6
E _ELPI_c	x	x	96.7	96.7
E35 _ELPI_d	x	x	95.0	95.0
E35 _ELPI_e	x	x	94.9	94.9
E35 _ELPI_f	x	x	94.8	94.8
E35 _ELPI_g	x	x	95.1	95.1
Poor combustion				
P _Filter	88.9	x	x	x
P _DLPI	95.7	98.6	x	x
P _Filter_b	74.2	x	x	x
P _Filter_c	93.7	x	x	x
P_DLPI_b	92.6	97.4	x	x
P _ELPI_a	x	x	98.8	98.8
P _ELPI_b	x	x	98.8	98.8
P _ELPI_c	x	x	98.7	98.7
P_ELPI_d	x	x	97.7	97.7
P_ELPI_e	x	x	97.5	97.5
P_ELPI_f	x	x	98.5	98.5
P_ELPI_g	x	x	98.6	98.6
P_ELPI_h	x	x	98.8	98.8
P_ELPI_i	x	x	98.9	98.9
P_ELPI_j	x	x	98.8	98.8

4.4 PM emissions in relation to regulations

In Figure 6, the concentrations measured of TSP downstream the ESP are plotted against the corresponding concentrations upstream of the ESP. The emission values are also compared to some German emission limits for wood and pellets stoves, and the emission limits for the Blue Angel label. When the TSP concentrations were below 300 mg/m_N^3, the ESP was able to reduce the TSP emission to less than 20 mg/m_N^3 at 10% O_2. This is well below the German emission limit for wood stoves (~29 mg/m_N^3 at 10% O_2 / 40 mg/m_N^3 at 13% O_2). Moreover, up to inlet TSP-values of about 300 mg/m_N^3 the outlet TSP concentrations were even below the tougher blue angel limit for wood stoves. For higher concentrations of TSP (> 300 mg/m_N^3) it is uncertain if the ESP can manage to meet the emission limits in Germany.

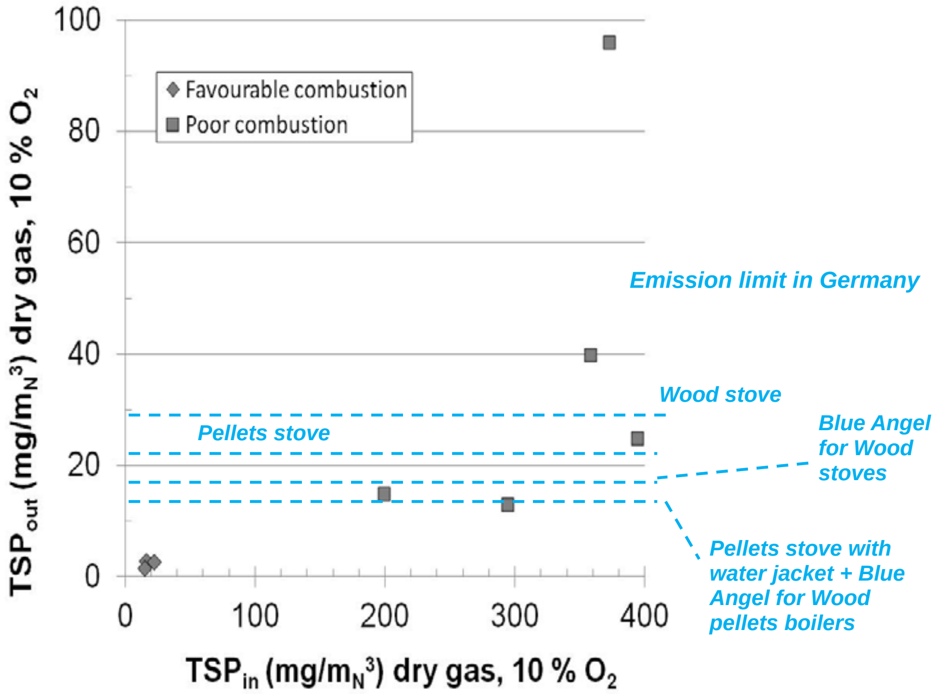

Figure 6: TSP emission downstream of the ESP (TSP_{out}) against TSP upstream of the ESP (TSP_{in}), related to some emission limits.

4.5 Mass size distributions

The mass size distributions of particles at efficient combustion are shown in Figure 7. Upstream of the ESP there was a maximum in the size distribution at about 0.1-0.2 µm and another one indicated at about 10 µm. Downstream of the ESP the concentration of particles are much lower and the maximum of the size distribution was at about 0.4 µm, indicating a less efficient removal of particles around this size.

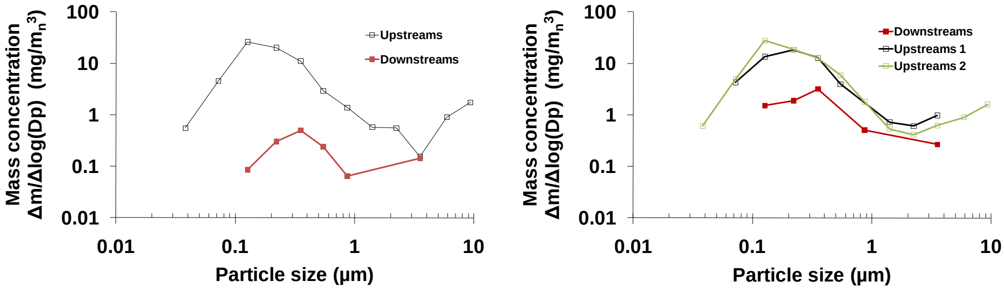

Figure 7: Mass size distributions of particles at efficient combustion. Note that the vertical scale is different compared to Figure 8.

The mass size distributions measured at poor combustion are shown in Figure 8. The results indicate one submicron maximum and another supermicron maximum upstream of the ESP. Downstream of the ESP, two different measurements gave two different results, but both indicate a supermicron maximum and one result also show a submicron maximum around 0.3-0.4 µm.

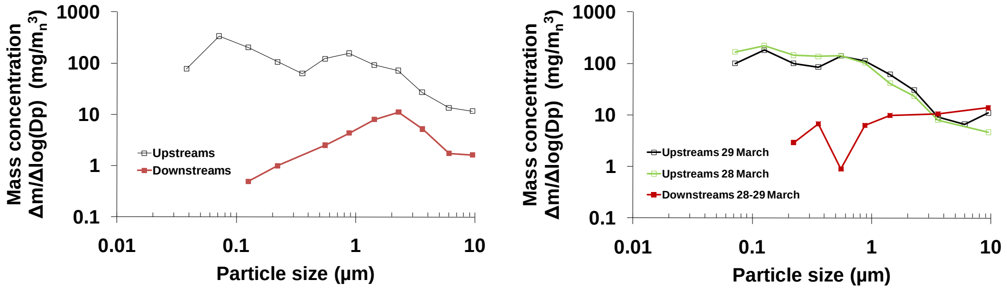

Figure 8: Mass size distributions of particles at poor combustion. Note that the vertical scale is different compared to Figure 7.

4.6 Removal efficiency against OGC

In Figure 9, the removal efficiencies of the ESP are shown against the concentration of OGC in the gas. The removal efficiencies with respect to TSP were about 87 % at efficient combustion and about 93 % at poor combustion. Corresponding values with respect to number concentrations were about 97 % at efficient combustion and almost 99 % at poor combustion. In addition, the results show removal efficiencies of PM_1 similar to those of TSP.

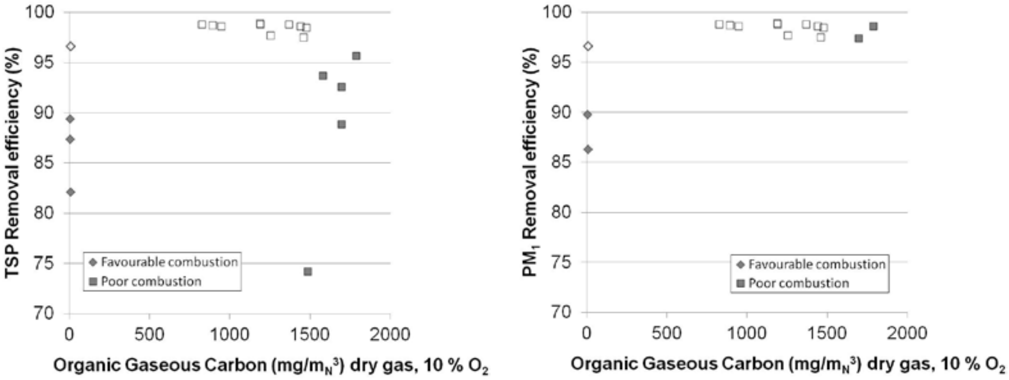

Figure 9: Left: TSP Removal efficiency against OGC going into the ESP. Right: PM_1 Removal efficiency against OGC going into the ESP. Filled symbols indicate gravimetric measurements and empty symbols indicate measurements of number of particles.

4.7 Organic and Elemental carbon

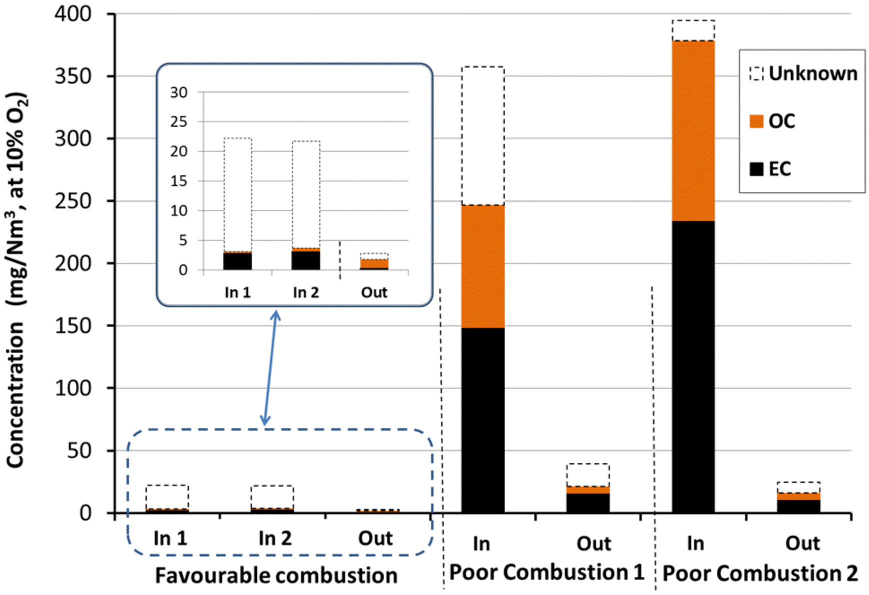

Figure 10: Concentration of particulate EC, OC, and unknown material. Up. = Upstream ESP. Do. = Downstream ESP.

In Figure 10, the masses sampled on filters are presented with the contents of organic carbon (OC) and elemental carbon (EC). At efficient ("Favourable") combustion OC was 1-2 % and EC 13-15 % of the particles upstream of the ESP. Downstream of the ESP, OC constituted about 50 % of particulate mass, implying that the amount of particulate OC in the flue gas had increased over the ESP. This indicates formation of some particulate organic material (POM) in the ESP, possibly as a consequence of the falling gas temperature in the ESP from about 77°C to about 30°C. The temperature drop is caused by introduction of air into the ESP. The drop in temperature can cause condensation of semi volatile organic compounds. The removal efficiency for EC was found to be 89%.

At poor combustion, carbonaceous compounds formed the major fraction of the particles both upstream and downstream of the ESP. In the poor combustion cases of this study, the removal efficiencies of OC at were rather high: 92-96%. Simultaneously, the removal efficiencies of EC were 89% and 95%. The high removal efficiency for particulate organic compounds in poor combustion is likely due to a higher degree of condensation of organic vapors on particles upstream the ESP, caused by lower flue gas temperatures and higher concentrations of organic compounds compared to efficient combustion.

5 Conclusions

The performance of the residential electrostatic R_ESP (Applied Plasma Physics AS) has been investigated. The concentration of TSP upstream of the R_ESP varied in the range of 15-390 mg/m_N^3 dry flue gas, normalized to 10% O_2. Up to concentrations of TSP of about 300 mg/m_N^3 in the flue gas, the ESP was found to be able to reduce the concentrations to less than 20 mg/m_N^3 at 10% O_2. This is well below the German emission limit for wood stoves (~29 mg/m_N^3 at 10% O_2 / 40 mg/m_N^3 at 13% O_2).

The removal efficiencies with respect to mass of particles were about 87% at efficient combustion and about 93% at poor combustion. Corresponding values with respect to number of particles were about 97 % at efficient combustion and almost 99 % at poor combustion. The better efficiency at poor combustion can be explained by the lower flue gas temperature, which led to longer residence time of particles in the ESP. The R_ESP performed well during the two weeks of laboratory tests. Further, high removal efficiencies were measured with respect to OC and EC in the particles.

6 Further work

The long-term performance of the electrostatic precipitator is not included in this work. This is crucial and needs to be further investigated.

7 Acknowledgements

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