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In-situ evaluation of a commercial electrostatic precipitator integrated in a small-scale wood chip boiler

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Abstract

Electrostatic precipitators (ESP) are an effective means of reducing particulate matter emissions from biomass combustion. This study presents a comprehensive evaluation of the performance of an ESP integrated in a 240 kW wood chip boiler. The boiler-integrated ESP is commercially available and is evaluated in-situ using two types of wood chips, unlike previous studies, which mainly focuses on prototypes or lab-based constructions. The obtained results indicate a mass-based ESP efficiency of 94-96%, surpassing previously reported values for small-scale boiler-integrated ESPs. Furthermore, the number-based ESP efficiency is 83-92%, which is in line with values reported in literature. Despite the promising performance, the widespread adoption of integrated ESPs in small-scale appliances faces challenges due to the lack of financial, regulatory and energetic incentives. Nevertheless, the application of ESPs in this context remains crucial in addressing local air pollution and reducing the overall environmental impact of small-scale biomass combustion. To facilitate broader implementation, further research and policy initiatives are necessary. This study provides valuable insights into the true effectiveness of a small-scale ESP in mitigating particulate matter emissions.

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Keywords: Electrostatic precipitator, Particulate matter, Biomass combustion, Wood chip boiler, Electrical low pressure impactor

1. Introduction

Bioenergy has gained significant attention in recent years, particularly in the context of small-scale heat production. This growing interest can be attributed to the abundant availability of biomass as a renewable energy source, coupled with the simplicity and well-established nature of biomass combustion technologies (Ahmed et al., 2022). Moreover, bioenergy is unaffected by fluctuating weather conditions, distinguishing it from wind and solar energy sources. In addition, biomass combustion technologies require relatively low quantities of critical minerals (e.g. copper, cobalt, nickel, lithium, chromium, zinc, aluminium, platinum group metals and rare earth elements) compared to other renewable energy generation technologies and applications, such as wind turbines, solar photovoltaics, electric vehicles and batteries (IEA, 2021). As a result of these advantageous characteristics of bioenergy, wood boilers are becoming increasingly popular for small-scale applications, underscoring their critical role in shaping the sustainable energy landscape (Duca et al., 2014; Junginger et al., 2019; Anca-Couce et al., 2021; IEA, 2022).

Notwithstanding these favourable attributes of bioenergy, the combustion of solid biomass releases various pollutants into the atmosphere, including particulate matter (PM), which have significant implications for both climate and air quality (Tomlin, 2021). Operating automated combustion systems under near-complete combustion conditions can largely prevent the release of organic PM emissions from wood combustion, while inorganic PM emissions are to a large extent inherent to the fuel and can therefore only be effectively reduced through the implementation of secondary measures (Schmidl et al., 2011; Ozgen, 2022). These secondary measures to mitigate PM emissions from biomass combustion include technologies such as cyclones, baghouse filters, flue gas condensers and electrostatic precipitators (ESP). Cyclones separate particles from the flue gas based on inertia and have a high collection efficiency for coarse particles but a limited efficiency for smaller particles (Hasler and Nussbaumer, 1999; Nussbaumer, 2007; Ghafghazi et al., 2011). Baghouse filters utilise fabric filters to reduce PM emissions and achieve an overall particle collection efficiency that typically exceeds 99%, both in terms of mass and number of particles, although this efficiency may decrease for particles smaller than 0.05 µm (Mertens et al., 2020; Cornette et al., 2020, 2021). With flue gas condensers, the energy specific PM emissions are reduced through two processes: increased energy yield from the fuel and particle deposition within the condenser itself, which combined lead to an overall PM reduction of up to 70% (Cornette et al., 2021). ESP systems collect particles through electrostatic attraction between particles and the device, achieving an overall collection efficiency exceeding 95% in terms of particle mass and usually slightly lower in terms of particle number, with a potential decrease in efficiency for particles smaller than 1 µm (Strand et al., 2002; Sippula et al., 2009; Ghafghazi et al., 2011; Mertens et al., 2020).

PM mitigation technologies often exhibit a penetration window in their particle collection efficiency, wherein the mechanisms responsible for capturing particles are less effective, resulting in a range of particle sizes with lower capture efficiency (Hinds, 1999; Li et al., 2009; Cornette et al., 2021). The penetration window for an ESP is in the range of 0.1 - 1.0 µm, where neither inertial nor diffusion processes are highly efficient for particle collection, and due to the particle charging being size-dependent with diffusion charging increasing as particle size decreases and field charging increasing as particle size increases (Zhuang et al., 2000; Strand et al., 2002; Lind et al., 2003; Lillieblad et al., 2004; Jaworek et al., 2007; Nussbaumer, 2007; Li et al., 2009; Sippula et al., 2009; Bin et al., 2017). In addition to the particle collection and charging being sub-optimal in this penetration window, an increased particle agglomeration in the ESP may lead to a higher concentration of particles in this particle size range (Strand et al., 2002).

While flue gas cleaning technologies have been widely implemented in medium- and large-scale biomass boilers, their adoption in small-scale boilers has been relatively limited, thereby posing a persistent challenge in mitigating local air pollution. Cyclones have a low investment cost and flue gas condensers are cost-effective but both technologies have a limited particle collection efficiency (Bianchini et al., 2016; Cornette et al., 2021). On the other hand, baghouse filters offer a high collection efficiency but have a relatively high maintenance cost making them economically viable primarily for industrial applications (Lind et al., 2003; Bianchini et al., 2016). ESPs strike as a suitable technology for PM mitigation from small-scale bioenergy due to their high particle collection efficiency (e.g. higher than that of cyclones and condensers) and relatively low maintenance cost (Lind et al., 2003; Bianchini et al., 2016). It should however be acknowledged that

ESPs may have a noteworthy operational cost.

Small-scale ESPs can be categorised into chimney-top ESP, boiler-attached ESP and boiler-integrated ESP (Jaworek et al., 2021). Among these, the boiler-integrated ESP shows great potential to be the primary solution to reduce PM emissions from small-scale biomass combustion due to its numerous benefits. The integrated ESP is installed within the same housing as the boiler thus separating the user from the high voltage supply, the temperature in the ESP can be higher and easily controlled and the boiler with integrated ESP occupies less space and is more cost-effective than a simple boiler with an external ESP (Jaworek et al., 2021). Despite its considerable prospects for the transition towards more sustainable small-scale bioenergy systems, the boiler-integrated ESP has received less attention compared to the boiler-attached and chimney-top ESP (Jaworek et al., 2021). Specifically, numerous studies have investigated commercially available boiler-attached and chimney-top ESPs (Bologa et al., 2010; Hartmann et al., 2010; Obernberger and Mandl, 2011; Carroll and Finnan, 2017; Struschka et al., 2017; Brunner et al., 2018; König et al., 2021), while the literature on boiler-integrated ESPs remains limited and is primarily focused on prototypes and in laboratory conditions (Matthes et al., 2016; Berhardt et al., 2017; Kelz et al., 2019; Molchanov et al., 2020; Schittl et al., 2021). However, to properly assess the effectiveness of boiler-integrated ESPs, and their benefits for local air pollution, it is essential to conduct in-situ evaluations of commercial appliances. In this study, we aim to address this research gap by conducting an in-situ evaluation of the performance of a commercial ESP integrated in a small-scale boiler fuelled with two types of wood chips. The particle collection efficiency of the ESP is assessed both in terms of total particle mass concentration and in terms of particle number size distribution. By investigating the effectiveness of this ESP in reducing PM emissions, we seek to contribute to a better understanding of the actual impact of ESPs in small-scale biomass combustion systems, ultimately paving the way for more informed decision-making and promoting the adoption of sustainable bioenergy.

2. Material and methods

2.1. Combustion appliance and fuel

The studied combustion appliance is a 240 kW wood chip boiler (eHACK, ETA, Austria), which is used for a small district heating network in a socially engaged farm named *Nos Pilifs*, located in Brussels, Belgium. The green waste obtained from the pruning activities of the farm are processed on-site into wood chips. These wood chips are subsequently used in the wood chip boiler to generate heat that is used locally on the farm, and thus, realising a circular economy. The wood chips are transported from the fuel storage to the boiler by two conveyor screws that are separated by a rotary valve in order to prevent burn-back and uncontrolled air intake (see figure 1). The heat exchanger gas channels of the boiler are equipped with turbulators to increase turbulence and to promote heat transfer from the flue gas to the water. These turbulators feature an automatic shaking mechanism to remove deposits. Downstream of the heat exchanger is an electrostatic precipitator where particles are electrically charged causing them to deposit on the walls of the precipitator. Furthermore, flue gas recirculation is employed as downstream of the ESP a fraction of the flue gas is mixed with fresh air and reintroduced into the combustion chamber as primary air.

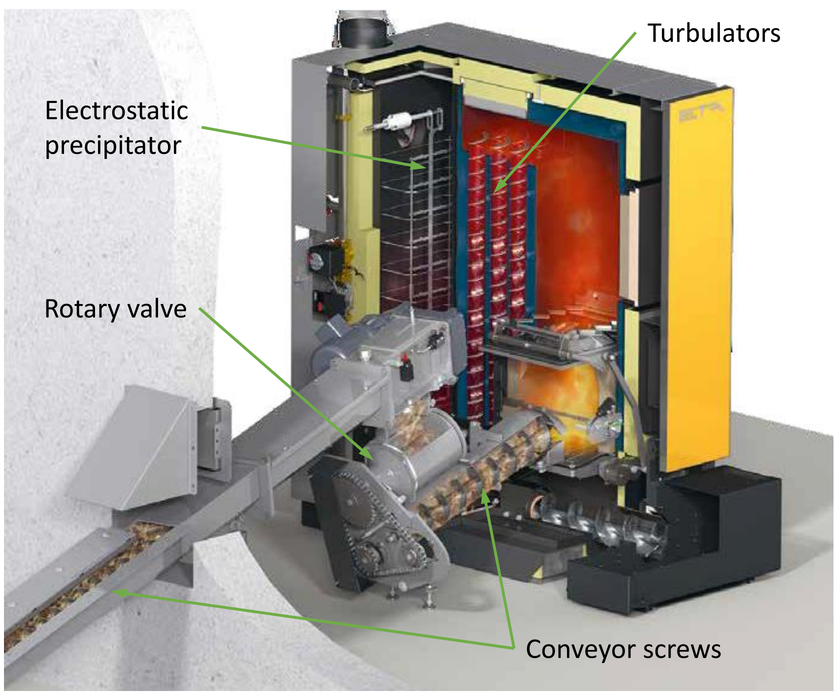

Figure 1: Illustration of the 240 kW wood chip boiler. Figure is a modification of ETA (2020). The boiler is equipped with an integrated electrostatic precipitator (ESP) to collect particles from the flue gas.

The boiler was fuelled with two types of wood chips, namely the wood chips that were processed on-site at the Nos Pilifs farm (denoted as NP wood chips) and commercially available wood chips (denoted as CO wood chips). Both the NP and CO wood chips are a mixture of soft- and hardwood, and had a similar granularity (see figure 2). The moisture content of three samples from each fuel was determined and averaged 12.3 and 15.0 mass% (as received) for respectively NP and CO.

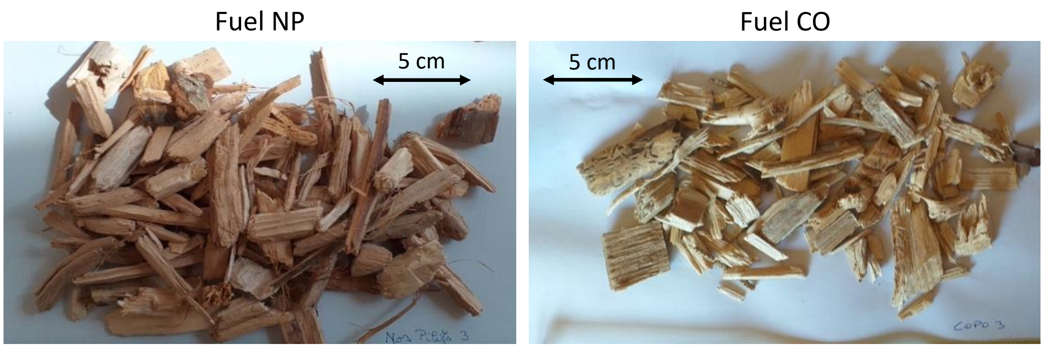

Figure 2: Granularity of the two types of wood chips.

2.2. ESP

An illustration of the ESP integrated in the wood chip boiler is presented in figure 3a. The ESP is tubular with a single discharge electrode. The precipitator channel has a rectangular cross-section (approximately 70 cm by 30 cm), and the gas flow is directed upwards. A high voltage unit (about 27 kV with a current of about 2 mA) is connected to the discharge electrode. The particles in the flue gas are charged by this corona discharge and the same electric field is used to precipitate the particles on the inner walls of the precipitator (Hinds, 1999). Along the inner wall is a grid-shaped sliding rake that can move up and down to remove the particles from the wall. This mechanical cleaning mechanism is activated automatically during the de-ashing of the boiler and was not the focus of the measurements.

The configuration of the discharge electrode is illustrated in figure 3b and comprises a main flat rod, approximately 1 m in length, oriented along the longitudinal axis of the channel. Along the main rod, there are pairs of arms extending horizontally. These arms have a round cross-section and each arm features four conical spikes, which are perpendicular to the arms and have alternating directions.

According the manufacturer's specifications (ETA, 2020), the ESP has a particle collection efficiency of 80-85%, although it is not specified whether this efficiency is based on particle mass or particle number concentration.

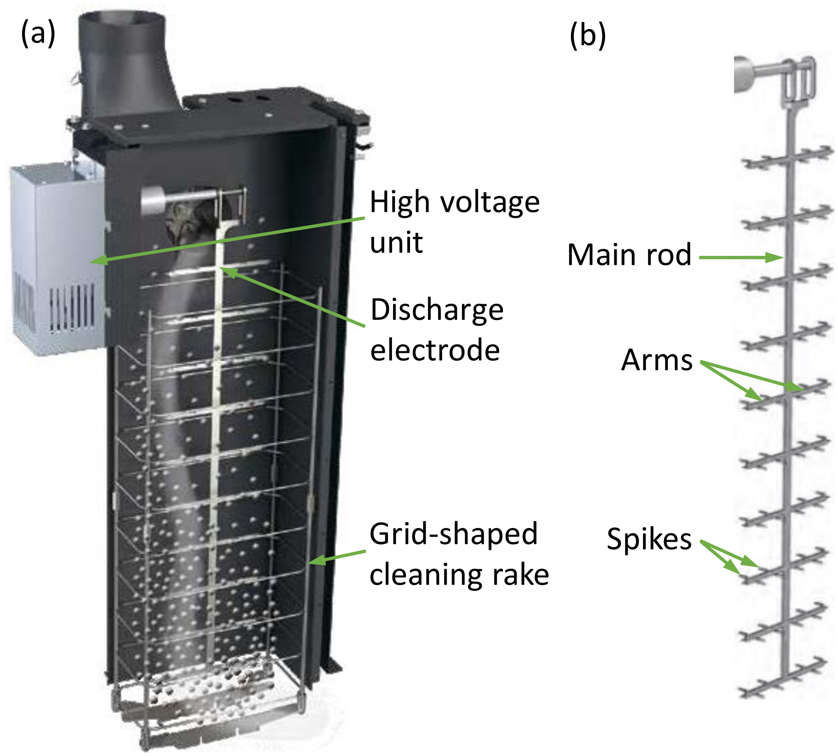

Figure 3: Illustration of the electrostatic precipitator (ESP) implemented in the 240 kW wood chip boiler. (a) Precipitator channel with discharge electrode, cleaning rake and high voltage unit (modification of ETA (2020)). (b) Configuration of the discharge electrode, comprising of a main flat rod along the longitudinal axis and horizontal arms with conical spikes perpendicular to the arms (modification of ETA (2017)).

2.3. Sampling setup

Flue gas samples were obtained from the exhaust channel downstream of the ESP using three sampling probes in order to simultaneously measure gaseous emissions, particle mass concentrations and particle number size distributions (see figure 4).

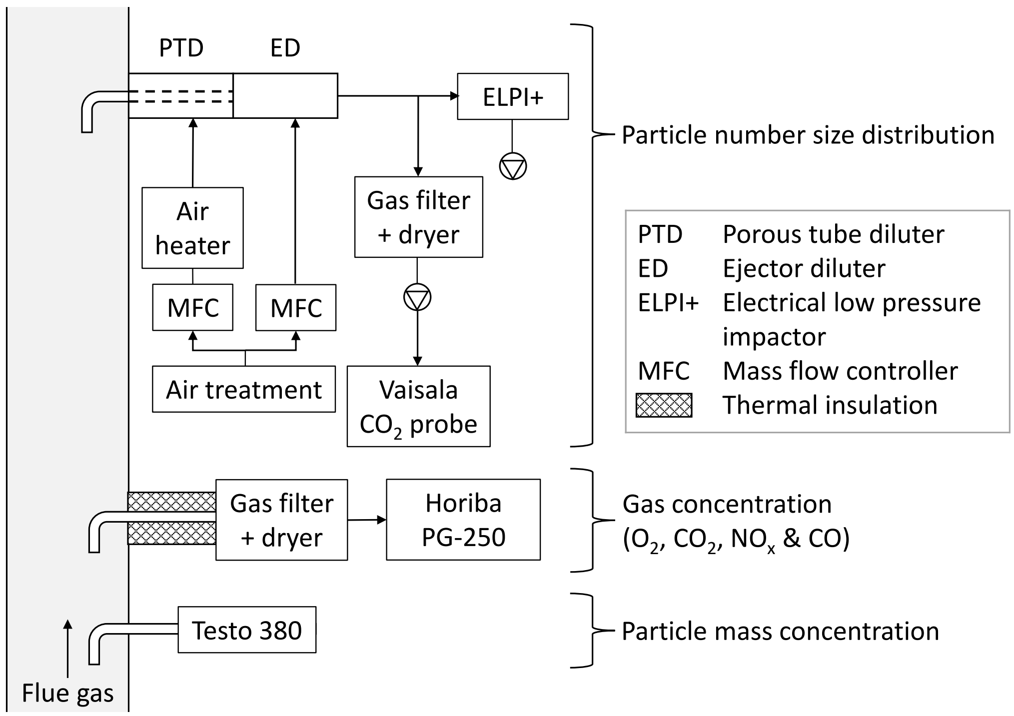

Figure 4: Schematic illustration of the experimental setup to sample gaseous and particulate matter emissions.

2.3.1. *Gaseous emissions*

The dry concentrations of O_2, CO_2, NO_x and CO were measured with a Horiba PG-250 portable gas analyser. Upstream of the gas analyser was a particulate filter and gas dryer to make the sample particle- and moist-free. The sampling line between the sampling probe and the gas dryer was thermally insulated to avoid condensation prior the drying of the sample.

2.3.2. *Particle mass concentration*

The total particle mass concentration was measured with a Testo 380, which is operated according to VDI 4206-2. The flue gas sample was diluted with a rotating disk diluter that is integrated into the Testo sampling probe. The sampling probe can be heated up to 120°C and the dilution ratio is about 100. The Testo 380 also measured the O_2 concentration and flue gas temperature.

2.3.3. *Particle number size distribution*

The particle number size distribution (PNSD) of particles with an aerodynamic diameter between 6 nm and 10 µm was characterised with a Dekati electrical low pressure impactor (ELPI+). The operating principle of ELPI+ is based on the electric charging of the particles using a corona charger, after which the particles are classified in a cascade of inertial impactors that can detect the particle's electrical charge. The sample is first introduced at 10 l/min into the corona charger, which is a needle type unipolar diffusion charger, where the particles are electrically charged by the discharge of a positive high voltage of 3.5 kV with a current of 1 µA (Järvinen et al., 2014). The sample then flows through the ion trap where the remaining ions from the corona discharge are removed from the sample by a potential difference of 20 V (Järvinen et al., 2014). Then, the sample flows through a 10 µm pre-separator stage and to a cascade of 13 inertial impactors. Particles with too large inertia will impact in an impactor stage and induce an electrical current. Particles too small to be collected by impaction will be collected by filtration mechanisms in the filter stage (i.e. stage 1) downstream of the inertial impactors. The electrical currents induced in the stages are detected by a multichannel electrometer and can be converted into the PNSD by means of a data inversion algorithm (Cornette and Bram, 2023). The particle density of wood combustion particles, which is required for determining their electrical properties, is assumed to be 2.0 g/cm^3 (Hueglin et al., 1997; Coudray et al., 2009; Garra et al., 2016). The ELPI+ impactor stages were equipped with greased aluminium substrates to reduce particle bounce compared to non-greased substrates (Cornette et al., 2023a).

A two-stage dilution system is used to condition and transport the flue gas sample from the chimney to ELPI+. This system consists of a porous tube diluter (PTD) to perform the primary dilution with heated (100°C) air followed by an ejector diluter (ED) to perform the secondary dilution with ambient air. The volumetric flow rates of dilution air to the PTD and ED were respectively 15 and 45 l/min. The dilution ratio was on average 36.1 and is calculated with the CO_2 concentrations before dilution (measured with Horiba PG-250) and after dilution (measured with a Vaisala GMP343 CO_2 probe). A more detailed description of the dilution system and its performance can be found elsewhere (Dyakov et al., 2021; Cornette et al., 2023b).

2.4. Experiment design

The in-situ boiler operated at constant nominal power to evaluate the performance of the small-scale ESP with the two wood chip fuels. The experiment design is illustrated in figure 5, where the ESP mode alternated between on and off once or twice per hour. Particle mass concentration (measured with Testo 380) and PNSD (measured with ELPI+) were recorded for each fuel and both ESP modes. The gas concentrations were continuously measured but are segmented into the same intervals as those of ELPI+.

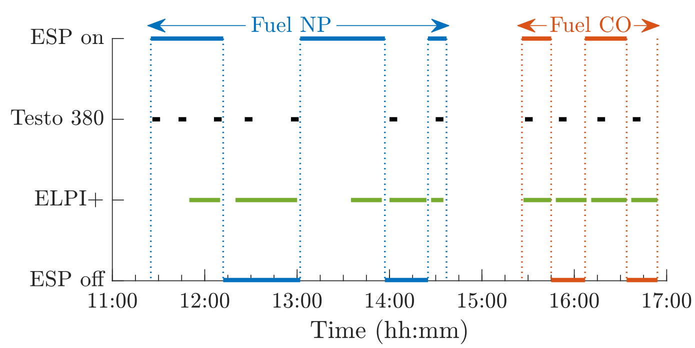

Figure 5: Experiment design to evaluate the performance of the in-situ small-scale ESP with two wood chip fuels. Testo 380 measures particle mass concentration and ELPI+ measures particle number size distribution.

3. Results and discussion

3.1. Gaseous emissions

The average gaseous emissions with the two fuels during both ESP modes are presented in table 1. The gas concentrations are expressed per dry volume of flue gas adjusted to a 13 vol% O_2 concentration (as measured with Horiba PG-250). Table 1 also includes the flue gas temperature (T_{fg}) and the excess air ratio (λ), which is calculated as the ratio of the stoichiometric maximum CO_2 concentration (estimated at 20.2 vol% for both fuels) to the measured CO_2 concentration (not O_2 adjusted). Table 1 confirms that the flue gas conditions (flue gas composition, T_{fg} and λ) were the same for both operating modes. The variation in CO emissions is considered to be intrinsic to the combustion of wood chips rather than attributable to the ESP (Carroll and Finnan, 2017). The differences between the two fuels are also rather limited. The only notable difference is that NO_x is 15% higher with fuel NP compared to fuel CO.

Table 1: Average gaseous emissions, flue gas temperature (T_{fg}) and excess air ratio (λ). The gas concentrations are expressed per dry volume of flue gas adjusted to a 13 vol% O_2 concentration.

quantity	unit	fuel NP		fuel CO	
		ESP off	ESP on	ESP off	ESP on
O_2	vol%	9.1	9.0	9.3	9.2
O_2 †	vol%	8.7	8.5	8.9	8.7
CO_2	vol%	7.7	7.7	7.5	7.6
CO	ppm	25	32	25	10
NO_x	ppm	90	90	78	79
T_{fg}	°C	128.3	124.8	129.7	127.0
λ		1.76	1.74	1.83	1.81

† Measured with Testo 380, the other gas concentrations were measured with Horiba PG-250.

3.2. Particle number size distribution

The PNSD of the 240 kW wood chip boiler with and without ESP are presented in figure 6 for the two different fuels. The distributions are adjusted for the used dilution ratio and are corrected to a reference O_2 concentration of 13 vol%. Both with and without ESP the PNSD is dominated by an accumulation particle mode but the peak of the mode is about 7 times lower when the ESP is active. When the ESP is off, both fuels emit about the same PNSD although it may be suggested that the accumulation mode with the NP wood chips is slightly shifted towards larger particle sizes. With fuel NP and the ESP off, there is one test with a high number concentration for the smallest particle size. This is considered a measurement artefact since a single large particle that is incorrectly measured in an ELPI+ stage can be misinterpreted as numerous small particles (Cornette and Bram, 2023). When the ESP is on, the peak of the accumulation mode with fuel CO is lower than with fuel NP.

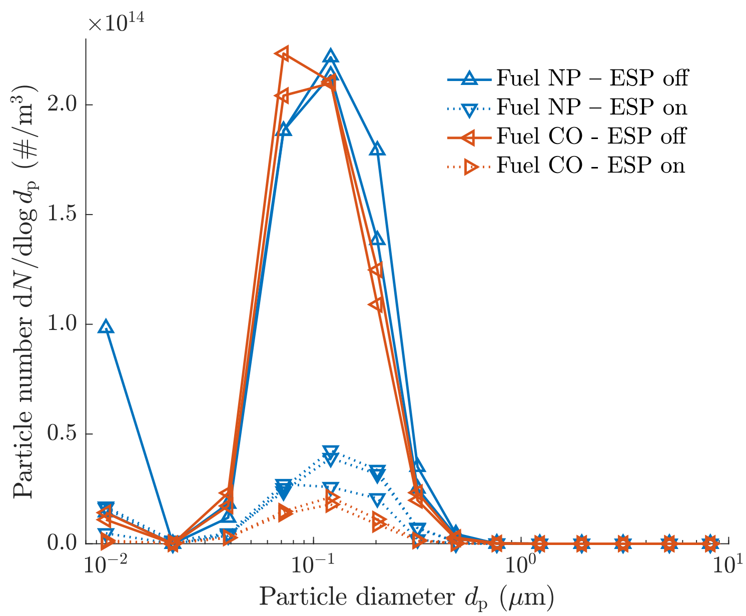

Figure 6: Particle number size distributions from the 240 kW wood chip boiler with and without electrostatic precipitator (ESP). The distributions are adjusted for the used dilution ratio and are corrected to a reference O_2 concentration of 13 vol%. The peak of the accumulation mode is about 7 times lower when the ESP is active.

3.3. ESP polarity

It is noteworthy that both the ELPI+ and the ESP employ a corona discharge to charge the particles. Specifically, the ELPI+ features a needle-type electrode, while the ESP incorporates an electrode with a configuration illustrated in figure 3b. The main difference, however, is that with the ESP the electric field is maintained over the entire length of the precipitator in order to capture the particles, while with the ELPI+ the corona discharge is very momentarily as the needle is less than 1 cm long. In addition, the corona charger of the ELPI+ is followed by an ion trap in order to neutralise the remaining ions in the gas (Järvinen et al., 2014). It is reasonable to raise concerns about the potential impact of particle charging in the ESP on the charging process of particles in the ELPI+. The ELPI+ provides positive charge onto the particles (Järvinen et al., 2014). If the particles entering the ELPI+ are initially negatively charged, the ELPI+ charger is able to first neutralise and then charge the aerosol normally (Järvinen et al., 2014; Moisio, 1999). If the particles going into the ELPI+ are initially positively charged, the output of the ELPI+ charger may be affected, especially for smaller particles where the charging efficiency is low and consequently a higher particle concentration may be measured by the ELPI+ (Järvinen et al., 2014; Moisio, 1999). Nevertheless, it can be assumed that the majority of the particles exiting the ESP and entering the ELPI+ are not highly charged as they would otherwise have been captured by the electric field within the ESP.

With both fuels and both ESP modes, no coarse particles (i.e. particle diameter $d_\mathrm{p} > 1$ µm) were detected. In fact, the currents measurements in these ELPI+ stages were negative. Note that these negative currents are not induced by the charging of the particles in the ESP as the negative values were also observed when the ESP was inactive. Although the ELPI+ was properly zeroed as it met the required criteria regarding measurement stability, the negative currents are presumably the result of a slight offset in the coarse stages during the zeroing of the ELPI+. It can be assumed that the number of coarse particles is low compared to the accumulation mode. The negative currents in the coarse stages can however be used to determine the polarity of the ESP. The measured coarse stage currents with the ESP switched off are lower than with the ESP switched on (i.e. the negative current is further from zero with ESP off). Assuming that the polarity of the ESP is opposite to the ELPI+, activating the ESP would decrease the current due to the opposite charging in the ESP and would also decrease the current because less particles are entering the ELPI+ as particles are captured in the ESP. Thus, the combined effect when assuming an opposite polarity between the ESP and ELPI+ is a lower current when the ESP is on. This is however not in accordance with the observed negative currents, namely, the currents are lower when the ESP is off. Consequently, it can be deduced that the ESP and the ELPI+ have the same polarity, namely positive. This positive polarity could be expected as a negative corona produces about an order of magnitude more ozone than a positive corona (Chen and Davidson, 2003). Hence, from an air quality perspective, a highly ozone-producing negative corona is a poor candidate for a small-scale flue gas cleaning technology. Nevertheless, industrial ESPs commonly use a negative corona because they can be operated at higher voltages and thereby achieve higher collection efficiencies (Hinds, 1999).

3.4. ESP particle collection efficiency

The average ESP particle number collection efficiencies (η_N) per particle size are presented in figure 7 for both fuels. For comparison, the figure also presents several values of η_N with biomass boilers reported in literature: two small-scale boiler-integrated ESPs (i.e. [a, b]), three small-scale boiler-attached ESPs (i.e. [c, d, e]) and two medium-scale boiler-attached ESPs (i.e. [f, g]). Further technical details from these referenced studies are provided in table 2. The efficiency curves of the investigated commercial boiler-integrated ESP have a similar shape for both fuels but is higher with fuel CO. Considering only the particles of the accumulation mode (i.e. d_p from 0.039 to 0.76 µm; ELPI+ stage 3 to 9), the ESP particle collection efficiency is 91.5% with fuel CO and 83.5% with fuel NP. The efficiency is not defined for the coarse particles, as there were no coarse particles measured, and likewise for particles of size 0.021 µm (ELPI+ stage 2).

The efficiencies of the investigated ESP obtained with both fuels are in general within the range of values for η_N of biomass boilers reported in literature (see figure 7). The literature values highlight the variations in particle collection efficiencies for different particle sizes. Furthermore, noticeable variations are evident in both the location of the penetration window and the magnitude of the efficiency drop. With the investigated ESP, the presence of a clear penetration window is not apparent although it should be noted that there is a local minimum of 90% at particle size 0.1 µm with fuel CO and a local minimum of 82% at 0.2 µm with fuel NP. Furthermore, it is observed that η_N may decrease for particles both smaller and larger than those of the accumulation mode.

In addition to the PNSD measurements with ELPI+, the total particle mass concentrations were measured with a Testo 380, which offers convenience as it does not require an external dilution system.

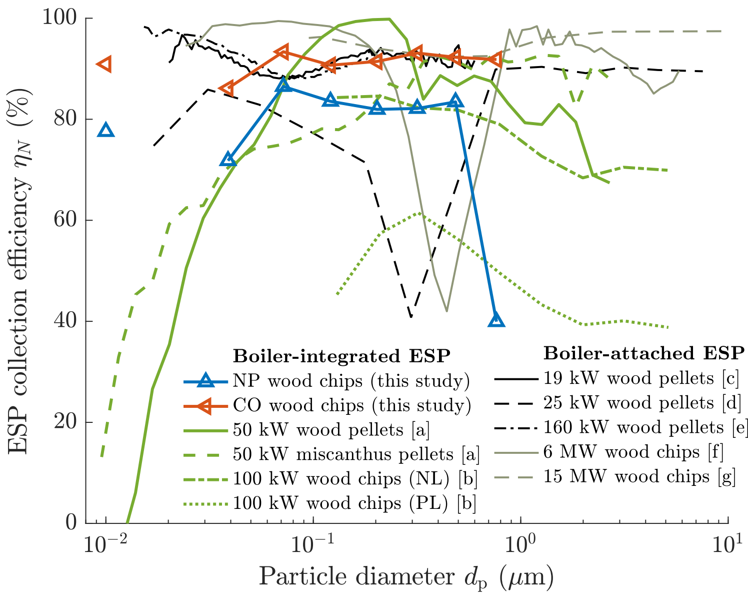

Figure 7: Electrostatic precipitator particle number collection efficiencies (η_N) per particle size of the investigated ESP integrated in the 240 kW wood chip boiler. Additionally, several values of η_N with biomass boilers reported in literature are presented: [a] Matthes et al. (2016); [b] Schittl et al. (2021), NL: nominal boiler load, PL: partial boiler load; [c] Schmatloch and Rauch (2005); [d] Cid et al. (2022); [e] Molchanov et al. (2022); [f] Strand et al. (2002); [g] Sippula et al. (2009). Technical details are presented in table 2. The particles of the accumulation mode are reduced by 91.5% with fuel CO and by 83.5% with fuel NP, which is within the range of values for η_N reported in literature.

Table 2: Technical details from studies on biomass boilers equipped with ESP, as presented in figure 7.

reference	boiler & fuel	ESP specifications	measuring method
[a] Matthes et al. (2016)	50 kW, miscanthus and wood pellets	boiler-integrated, plate-wire (4 channels), 16-20 kV	SMPS and OPC
[b] Schittl et al. (2021)	100 kW, wood chips	boiler-integrated, tubular with double electrode, 37.7 kV, 475 µA (NL); 23.0 kV, 307 µA (PL)	ELPI
[c] Schmatloch and Rauch (2005)	19 kW, wood pellets	boiler-attached, tubular with tapered electrode, 0.3 m long, up to 20 kV	SMPS
[d] Cid et al. (2022)	25 kW, wood pellets	boiler-attached, tubular with 3 mm electrode, 0.8 m long, 8-22 kV	ELPI+
[e] Molchanov et al. (2022)	160 kW, wood pellets	boiler-attached, plate-wire (honeycomb with 0.4 mm wires), 12 kV, 30 mA (NL)	SMPS
[f] Strand et al. (2002)	6 MW, wood chips	boiler-attached, single field, no further technical details available	SMPS and APS
[g] Sippula et al. (2009)	16 MW, wood chips	boiler-attached, 70 kV, 300 mA, filter area of 495 m^2, residence time of 4.6 s	BLPI

SMPS: scanning mobility particle sizer, OPC: optical particle counter, ELPI: electrical low pressure impactor, ELPI+: improved electrical low pressure impactor, APS: aerodynamic particle sizer, BLPI: Berner low pressure impactor, NL: nominal boiler load, PL: partial boiler load.

However, a drawback of the Testo 380 is the lack of additional information regarding particle sizes. Table 3 presents the average total particle mass concentrations (m_{tot}), expressed per dry volume of flue gas adjusted to a 13 vol% O_2 concentration (as measured with Teste 380), alongside the corresponding ESP particle mass collection efficiency (η_m). Additionally, the table provides key parameters characterising the PNSD, namely the total particle number concentration (N_{tot}), the geometric mean particle diameter (GMD) and the geometric standard deviation (σ_{g}) of the particle distribution. Furthermore, the overall particle number collection efficiency (η_N) based on N_{tot} is also included.

Table 3: Average particulate matter emissions and overall ESP collection efficiency. The particle concentrations are expressed per dry volume of flue gas adjusted to a 13 vol% O_2 concentration.

quantity	unit	fuel NP		fuel CO	
		ESP off	ESP on	ESP off	ESP on
m_{tot}	g/m^3	0.105	0.006	0.059	0.003
η_m	%		94.1		95.7
N_{tot}	#/m^3	1.53 10^{14}	2.56 10^{13}	1.41 10^{14}	1.20 10^{13}
η_N	%		83.3		91.5
GMD	µm	0.119	0.118	0.115	0.114
σ_{g}		1.8	1.9	1.7	1.7

m_{tot}: total particle mass concentration, η_m: ESP particle mass collection efficiency, N_{tot}: total particle number concentration, η_N: ESP particle number collection efficiency, GMD: geometric mean particle diameter, σ_{g}: geometric standard deviation of particle distribution.

With the ESP inactive, m_{tot} is higher with fuel NP than with fuel CO, which is presumably because the accumulation mode with fuel NP is more shifted towards larger (and thus heavier) particles (see figure 6). With the ESP active, m_{tot} is also higher with fuel NP, which is due to the higher peak of the accumulation mode. The mass-based ESP efficiency is 94.1% with fuel NP and 95.7% with fuel CO. These efficiencies are notably higher compared to previously reported values of η_m for small-scale boiler-integrated ESPs in prototype and lab-constructed setups: 56-67% (Molchanov et al., 2020), 60-80% (Matthes et al., 2016), 70-89% (Berhardt et al., 2017), 50-

84% (Schittl et al., 2021) and 72-93% (Kelz et al., 2019).

The particle mass concentrations with the ESP switched off (see table 3) are relatively high as the European norm EN 303-5:2012 dictates a particle emission limit value of 0.040 g/m^3 at 10 vol% O_2 (i.e. 0.029 g/m^3 at 13 vol% O_2). According the conformity attest of the boiler, both with and without ESP, the boiler does comply with this emission limit value. The measuring method with the Testo 380, however, does not fully correspond to the measurement procedure stipulated by the norm. In addition, these conformity tests are performed in optimised and controlled conditions whereas the emissions presented here are during real-life conditions.

The particle mass-based collection efficiencies are higher than the particle number-based collection efficiencies. They do however also indicate that the collection efficiency is higher with fuel CO. The ESP is claimed to have a collection efficiency of 80-85% (ETA, 2020), which is a fairly accurate interval although perhaps somewhat conservative as the presented measurements indicate an overall collection efficiency of 83-96%.

3.5. Cost-effectiveness of small-scale ESP

ESPs have proven effective in mitigating PM emissions from biomass boilers, but their adoption in small-scale applications encounters economic challenges. While the investment cost of ESPs is considered reasonable for industrial power plants (Larki et al., 2023), the investment poses a substantial financial burden on a small-scale (Nussbaumer, 2007; Bianchini et al., 2016). For example, the investment cost for an ESP suitable for wood burners with a thermal power below 50 kW typically ranges from €1000 to €3300 (Hartmann et al., 2010; Obernberger and Mandl, 2011; OekoSolve, 2013; Deyle, 2023; Kutzner & Weber, 2023; Heiz24, 2023). In case of the 240 kW boiler investigated in this study, the additional investment required to integrate the ESP is €4250, which can be considered substantial, although this represents a rather modest relative investment increase of 6.2% compared to the same boiler without ESP (Deyle, 2023). ESPs also entail operational costs attributed to their power consumption, albeit these costs are generally considered low (Lind et al., 2003; Nussbaumer, 2007; Larki et al., 2023). For instance, the investigated boiler exhibits a 57% increase in electrical power consumption when the ESP is activated (ETA, 2020). This results in an additional operational cost of 0.10 €/h during ESP activation, which may be considered negligible in comparison to the fuel consumption cost of 11.2 €/h (assuming the current market price of 103 €/GJ for electricity (Brugel,

2023) and 12.4 €/GJ for wood chips (EC, 2023)). Furthermore, while the maintenance cost of an ESP is generally regarded as low, it necessitates qualified personnel as it cannot be carried out by the user (Lind et al., 2003; Bianchini et al., 2016; Jaworek et al., 2021).

Overall, the investment, operational and maintenance costs associated with a small-scale ESP are relatively modest. However, these costs are non-zero, in contrast to the scenario without ESP. Consequently, given that both the ESP-integrated and non-integrated boilers comply with the same emission limit values and produce the same amount of heat, there is no financial, regulatory nor energetic incentive to invest in an integrated ESP. Nevertheless, the boiler investigated in this study is an integral part of a circular economy and therefore the decision to invest in an integrated ESP is motivated by its ability to enhance the sustainability of the bioenergy system.

4. Conclusions

This work focuses on evaluating the performance of an ESP integrated in a 240 kW wood chip boiler. In contrast to the prevailing literature on boiler-integrated ESPs, which mainly revolves around prototypes or lab constructions, this study examines a commercially available boiler-integrated ESP. Moreover, the evaluation of the ESP was conducted in-situ, providing valuable insights into the real-world effectiveness of the particulate matter mitigation technology.

The ESP evaluation encompassed the utilisation of two different types of wood chips in the boiler, and its impact on the emissions was quantified through three distinct measurements: gaseous emissions, particle mass concentration and particle number size distribution. The operation of the ESP exhibited no substantial influence on the measured gas concentrations. Notably, the mass-based ESP efficiency is 94-96%, surpassing previously reported values for small-scale boiler-integrated ESPs in prototype and lab-constructed setups. The number-based ESP efficiency is 83-92% and aligns with the values reported in literature. These findings affirm that the mass-based ESP efficiency is typically higher compared to the number-based efficiency. Furthermore, the results do not show a pronounced penetration window.

Overall, this study clearly demonstrates that employing an ESP effectively reduces PM emissions from small-scale solid biomass combustion, achieving an overall collection efficiency ranging from 83 to 96%. Despite these promising findings, it is important to acknowledge that currently, there is a lack of financial, regulatory and energetic incentives to encourage widespread adoption of integrated ESPs in small-scale appliances. Consequently, the primary driving force for the utilisation of ESPs in this context lies in their ability to mitigate local air pollution and decrease the overall environmental impact of small-scale appliances.

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