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Growth analysis of the particle layer in a small-scale ESP with biomass combustion

Natalia Cid *, Sergio Chapela, Miguel Ángel Gómez, David Patiño

CINTECX, Grupo de Tecnología Energética (GTE), Universidade de Vigo, Lagoas-Marcosende s/n, Vigo, 36310, Spain

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ABSTRACT

This study presents experimental results of the particle layer growth with the operation of a small-scale ESP as a flue gas cleaning method from domestic biomass combustion. The retention efficiency of the ESP is maintained above 90% for 40 h of operation, which is in agreement with its natural regeneration by partial collapses of the dust layer. The measurements of profile and thickness of the dust layer endorse the aforementioned collapses as discontinuous re-entrainment events that are also identified as abrupt peaks on the particle concentration at the outlet of the ESP and drops on the current values.

1. Introduction

There is a growing need of reducing particulate matter (PM) from the biomass combustion emissions that arises from the detrimental effect of particles in air quality and the increasing use of this renewable alternative to conventional resources. There are numerous adverse health effects attributed to indoor and outdoor exposure to biomass combustion products [1,2]. Therefore, there is a global interest in minimising particle emissions from small-scale combustion units to improve the air quality in the areas where these devices are or will be installed, taking into account the forecasted increase in the use of this resource [3].

Electrostatic precipitators (ESPs) have been considered a promising solution to reduce particle emissions from biomass combustion, which generates a variety of PM [4–6]. Due to the nature of the particles, a removal device with high efficiency in a wide range of sizes is required to clean the flue gas before it reaches the atmosphere. Electrostatic precipitation is the technology that presents higher global retention efficiency (over 90%) compared to other technologies which are often used for the same application, such as bag filters or cyclones [7]. Nevertheless, the retention efficiency for ultrafine particles is lower than coarse particles [8], which is mainly due to the dragging forces of the gas and the weak electrical forces caused by the low charge that is able to acquire this particular fraction of particle sizes.

Electrostatic precipitation is a mature technology that has been used for decades in industry as large scale abatement devices [9–11], but its small-scale application is still at emerging level [12]. The research community has shown interest in the matter with contributions such as different designs [13,14], experimental analysis of performance parameters [15–19], theoretical studies [20], and modelling [21].

The ESP working principle is based on corona generation between two electrodes, the discharge electrode that is connected to a high voltage power supply and the collection electrode that is grounded. The particles are charged and deviated from the flow path to be deposited on the collection electrode, where a dust layer is built up. The composition of the fuel and the combustion conditions define the properties of the PM, and depending on these together with the electrical parameters inside the ESP, the dust layer shows different behaviours that affect the performance of the precipitator, such as back corona or re-entrainment [22,23]. In any case, the retention efficiency is decreased with the accumulation of particles on the collection electrode [24] as well as on the discharge electrode [25]. Periodic cleaning prevents problems of stability in the operation of the ESP and eventual increases of emissions [26,27].

Previous works have reported results of the amount of fouled material on a surface from combustion flue gas, but with scarce detail of the shape of the deposition [28–30] or by means of expensive equipment to measure small fouled areas [31]. To the authors' knowledge, no measurements of particle layer growth inside a small-scale ESP with biomass combustion have been done with a detailed profile of the deposition on the collection electrode. This data would be useful for modelling validation, since the influence of the dust layer on the performance of an ESP should be taken into account and the characteristics of the deposition during real operation need to be provided. In this study, the thickness growth and profile of the deposition of particles on the collection

* Corresponding author.
E-mail address: nataliacr@uvigo.es (N. Cid).

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electrode of a small-scale ESP working with a domestic biomass boiler has been measured every 10 h for a total duration of 40 h of accumulation and the retention efficiency has been determined every 2 h.

2. Materials and methods

The 40-h test has been carried out in an experimental arrangement that was already used and described in Ref. [18]. A simplified diagram of the facility is included in Fig. 1. The particle source is a domestic shell boiler with a pellet burner, which thermal power output is fixed at 25 kW. The selected fuel for these experimental tests is commercial wood pellets, whose analysis is displayed in Table 1. The moisture content, volatile matter and ashes were determined according to EN ISO 18134:2022, EN ISO 18123:2015, and EN ISO 18122:2022, respectively, and the fixed carbon was calculated by difference. The contents of C, N, H, and S were evaluated according to EN ISO 16948:2015 and EN ISO 16994:2016, and oxygen was calculated by difference.

The downstream chimney is divided in two parallel alternative paths for the gas. On one side there is a regular chimney and on the other side there is a small-scale removable ESP. This removable piece is a 1000 mm stainless-steel double-walled chimney (AISI 316) with an inner diameter of 155 mm, which is a commonly used commercial chimney for domestic combustion devices. The discharge electrode is a 4 mm steel rod, with a smooth surface and a uniform cross section. The active length of the rod is 800 mm (discharge electrode length), and it is centred in the tube of the chimney and connected to high-voltage direct current (HVDC). The voltage of the power supply (SPELLMAN) was fixed at −20 kV, which is enough to provide an initial retention efficiency above 94%. An acquisition unit provides the values of voltage and current inside the ESP in real time, so the electrical performance of the device can be evaluated and the power consumption can be determined.

The particle number concentration (PNC) is measured with an electrical low pressure impactor (ELPI+, DEKATI) with a dilution system at the inlet to prevent from exceeding the limits of the analyser and to measure the actual PM exposure at room temperature. The dilution ratio is calculated from the difference in the oxygen concentration at the inlet of the sampling line and at the outlet of the particle analyser, since the flue gas is diluted with clean air. A SERVOPRO gas analyser and a TESTO 350 XL are used simultaneously for these measurements.

There are two isokinetic sampling points in the experimental arrangement, one at the outlet of the boiler and the second one at the outlet of the ESP. The PNC is measured at the outlet of the ESP and consecutively at the outlet of the boiler (inlet of the ESP) to calculate the retention efficiency of the unit as follows:

$$\eta = 1 - PNC_{out}/PNC_{in}$$

where PNC_{out} and PNC_{in} are the mean values of particle number concentrations over 100 s at the outlet and inlet of the ESP, respectively.

Table 1
Analysis of the wood pellet.

Proximate analysis		Ultimate analysis	
	wt. % (wet basis)		wt. % (dry basis)
Moisture	5,2	C	47,2
	wt. % (dry basis)	N	0,1
Volatile Matter	75,5	H	6,3
Fixed carbon	24,1	S	< 0,03 (under detection limit)
Ash	0,4	O	46,0

Small errors might be induced because of the intrinsic fluctuations of emissions from biomass combustion, since the PNC is not measured simultaneously at the inlet and outlet of the precipitator. The values are considered to be representative based on previous results and on the elapsed time per measurement at both the inlet and outlet of the ESP, which is less than 5 min in total.

The thickness and profile of the particle layer accumulated on the collection electrode are determined following the procedure described in Ref. [32]. A high-performance distance sensor WENGLOR and a position sensor ASM POSIWIRE are included in a system that was designed and adjusted to the geometry of this particular ESP collection electrode, but it can be redesigned to be used in different applications. Four full axial profiles of the collection surface are measured at positions separated by 90° (A, B, C, and D) to provide information about the shape of the particle layer along and around the tube. The active length of the discharge electrode is 800 mm, which starts at the bottom of the chimney section as it is depicted in Fig. 1. The collection electrode has a window to allow the connection of the L-shaped discharge electrode to the HV power supply, which reduces the measurable length of the surface to 700 mm. The covers of the fouling measurement system further reduce the analysed length, since they fit inside the tube. To avoid misleading results from possible modifications of the particle layer in the areas close to the limits of the measurement due to the assembly and disassembly process, the total displayed length is 550 mm. Therefore, during ESP operation, the active length of the discharge electrode begins below the total displayed length of the fouling measurements and it ends above them, as it can be seen in Fig. 1 (the red shadow represents the length of the chimney that is not measured). This ensures a uniform distribution of the corona current density along the 550 mm of the displayed length of the particle layer measurements. The deposition of particles and, therefore, the thickness and profile of the particle layer on the measurable area of the collection electrode are caused by the normal operation of the ESP. Otherwise, an uneven distribution of the corona would cause a biased profile of the deposition of particles inside the ESP.

The results presented in this study were obtained from 8 tests of 5 h each, which give a total of 40 h of particle accumulation on the

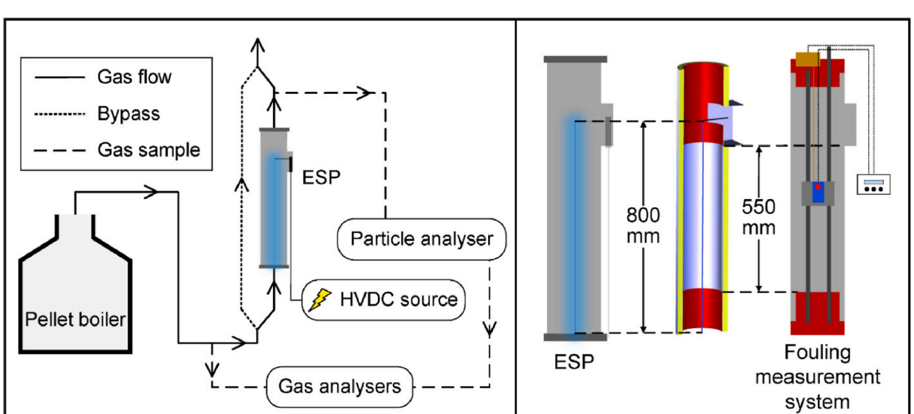

Fig. 1. Diagram of the facility (left) and detail of the ESP (right): length of the active discharge electrode and measurable length of the collection electrode.

collection electrode of the ESP. The thickness and profile of the particle layer are determined every 10 h of operation of the ESP. The PNC is measured every 2 h to analyse the evolution of the ESP performance.

3. Results

This work presents measurements of the thickness and profile of the particle layer deposited on the collection electrode of a small-scale ESP for 40 h of operation. The retention efficiency of the ESP is periodically measured together with the evolution of the dust layer during the test to evaluate the effect of the operating time. These results led to further analysis of the recorded data that confirms presumable collapses of the particle layer.

3.1. Evolution of the particle layer

The thickness growth and profile changes of the deposition of particles on the collection electrode of the ESP are shown in Figs. 2 and 3. The dust layer was measured every 10 h for the total duration of 40 h of accumulation in four different positions separated by 90° (A, B, C, and D) around the circumference of the inner tube of the ESP.

The thickness of the layer grows in general with the increasing operating time of the ESP. As it is observed, there are exceptions to this pattern when comparing the results after 30 and 40 h of accumulation, which correspond to the higher thickness of the particle layer. Fig. 2 shows how the profile of the particle layer after 30 h of operation was modified with the use of the ESP instead of swelling further. This is presumably due to the partial collapses of the layer. Fig. 3 also reflects this collapses with a lower average thickness of the particle layer after 40 h of operation compared to 30 h (position C). This figure includes the associated error of the measurements (left). It should be noted that the top view of the particle layer on Fig. 3 (right) shows a magnified inner diameter of 1.9 mm which maximum is on the centre of the circumference. This representation eases the visual analysis of the results, but it does not represent the dimensions of the actual ESP, since its inner diameter is 150 mm. On the graph, the particle layer grows up to 1.06 mm at position B after 40 h of operation. The values for the four positions (A, B, C, and D) are the average thickness of the particle layer and the values between them around the circle are interpolated since the thickness was measured on the four fixed positions of the collection electrode.

In Fig. 2, the inlet of the ESP is below the bottom of the measurable length (550 mm), therefore, the gas flows from 550 to 0 mm, i.e., from the bottom to the top of the figure. A considerable accumulation of particles was measured as a layer on the surface of the collection electrode, reaching values above 1 mm of thickness in certain areas after 30 h of ESP operation. The profiles of the particle layer for the four positions are not flat, which means that the deposition of the particles is not regular over the length of the tube. From the results included in Fig. 2, it can be seen that particles tend to accumulate at the bottom of the measurable part of the ESP, which is near the inlet of the flue gas. This accumulation is especially noticeable during the first hours of operation. The highest concentration of airborne particles inside the volume of the precipitator is at the inlet and it decreases as the gas flows through the electric field region, since particles are collected. Although, the reliability of the results presented here might be deficient to confirm this assumption and hence further testing is necessary.

A detail of the particle layer that is formed inside the ESP is shown in Fig. 4. The dendritic structure of the layer increases the probability of partial collapses and re-entrainment of particles once the thickness exceeds a certain value due to the low cohesive and electrical forces associated with packing. The particles collected inside an ESP can be re-entrained by the fluid velocity that exceeds the particle adhesion forces or by electrostatic induction within the particle layer [23].

3.2. ESP performance

The PNC is measured at the inlet and outlet of the ESP with the ELPI + every 2 h during the test. The evolution of the retention efficiency is depicted in Fig. 5 as averaged values of the measurements performed during each short test, i.e., a 5-h period. As it can be seen, the evolution of the retention efficiency after 40 h of operation of the ESP is unnoticeable. These results disagree with the expected reduction in retention efficiency as the accumulation of particles on the electrodes grows. Previous studies have reported the detrimental effect of the operating time on the performance of a small-scale ESP without an automatic cleaning system [6,19,33,34]. The removal of the particle layer from the surface of the electrodes would restore the initial condition of the ESP, but in this particular case the study is focused on the accumulation of particles and cleaning is unneeded. Based on experience and the results from other authors, 40 h of operation for this small-size ESP, an initial retention efficiency above 94%, and an average PNC at the inlet of 4.61E07 #/cm^3 would negatively affect the retention efficiency.

The hypothesis previously presented would explain a stable retention

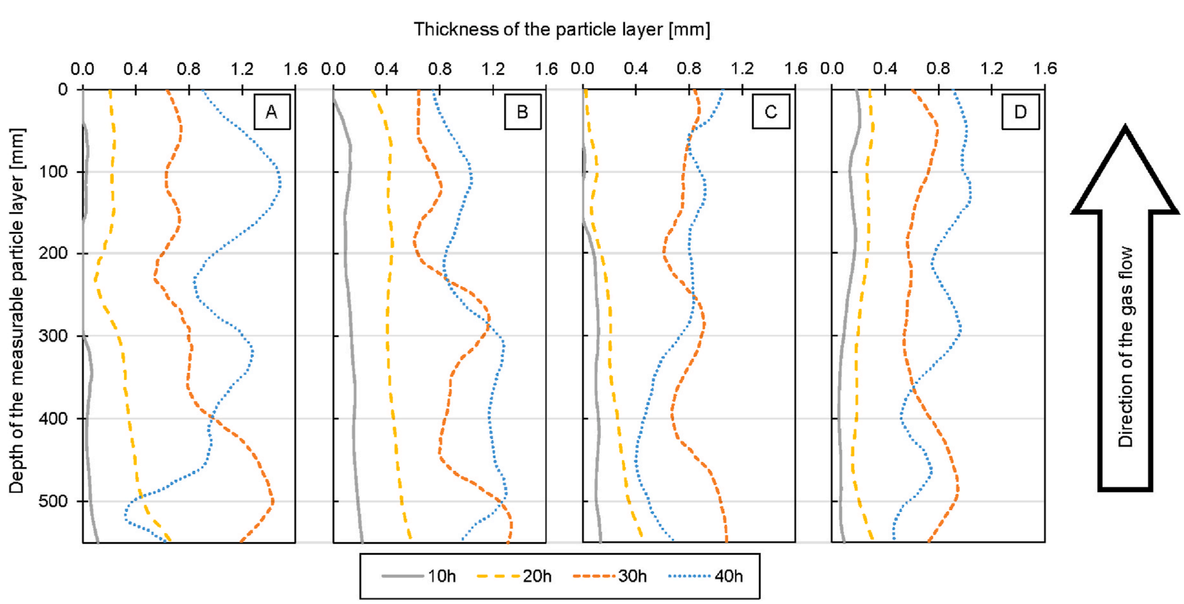

Fig. 2. Particle layer evolution on the collection electrode.

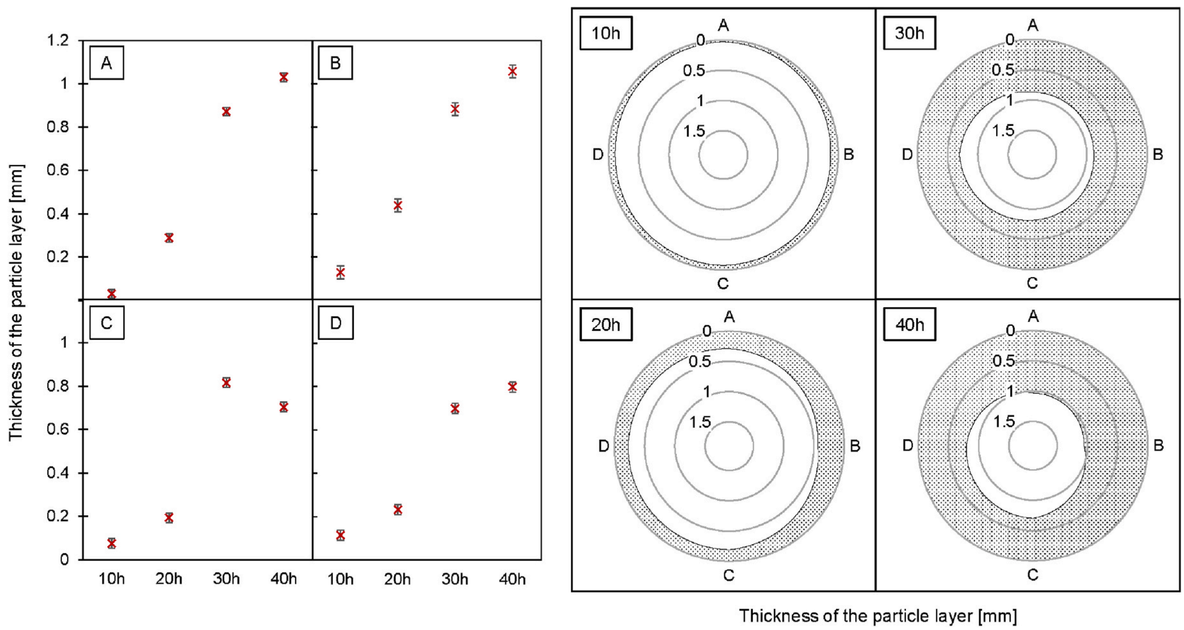

Fig. 3. Evolution of the average thickness of the particle layer: positions A, B, C, and D inside the ESP (left), magnified top view of the graphical representation (right).

Fig. 4. Detail of the particle layer: laser light from the distance sensor (left), and macroscopic structure (right).

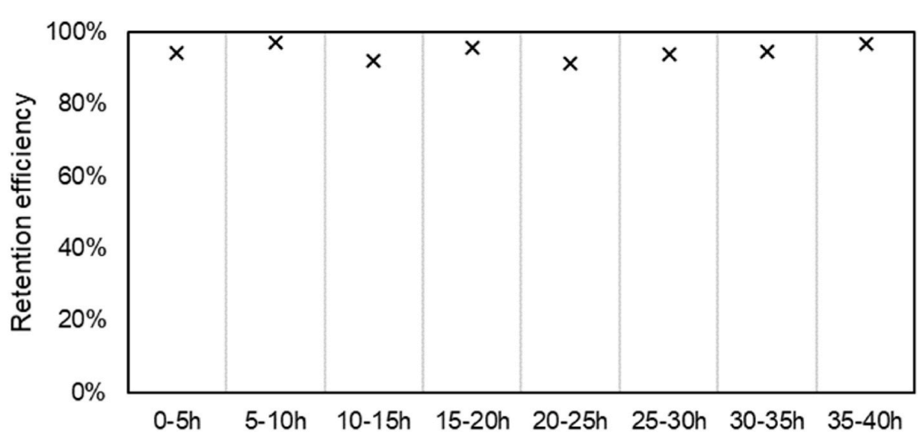

Fig. 5. Average retention efficiency of the ESP.

efficiency of the ESP, since the partial collapses of the particle layer would cause the automatic regeneration of the precipitator and therefore, the conditions would be maintained. Although, the thickness growth that has been reported in the previous section seems to have no influence on the retention efficiency.

Regarding the performance of the ESP, it was already commented that coarse particles are easier to remove from the flue gas due to the effectiveness of the charging mechanisms and the forces that drive the particles towards the collection electrode. To evince this fact, Fig. 6 depicts the geometric mean diameter (GMD) at the inlet and outlet of the ESP, which was calculated from the PNC measurements.

The GMD at the outlet of the ESP is generally smaller than the calculated value at the inlet of the ESP. The total number of airborne particles are reduced inside the ESP, but coarse particles are more effectively removed from the flue gas. As a result, the ratio of fine and ultrafine particles is higher at the outlet of the ESP compared to the inlet. Fig. 6 shows a disagreement at 20–25h of operation of the ESP, where the GMD is almost identical at the outlet and inlet of the ESP. Since these are average GMD values calculated from measurements every 2 h of operation, the presumable partial collapses of the particle layer inside the ESP may have influenced the results.

3.3. Re-entrainment of particles

Based on the previous results and the presumable collapses of the particle layer, further data analysis was carried out. The voltage and current inside the ESP are continuously recorded by the acquisition unit during the 40-h test. The PNC is measured in real time with ELPI + every 2 h at the outlet of the ESP and the measurement at this sampling point lasts 2 min. Some of the PNC measurements revealed sharp peaks in all the particle sizes simultaneously, which do not seem to be outliers, since the magnitude of these peaks is in accordance with the rest of the values obtained. These PNC peaks are in agreement with drops in the value of the current measured inside the ESP, while the voltage is maintained, as it can be seen in the examples of the data included in Fig. 7. These results endorse the hypothesis previously presented. There are partial collapses of the particle layer occasionally, which are noticeable in the PNC measurements as abrupt increases due to re-entrainment. The current drop is caused by the attachment of ions to the high number of particles momentarily flowing through the ESP. The partial collapses of the particle layer are thought to almost naturally regenerate the precipitator. Therefore, there would not be a decay of the retention efficiency with operation since the accumulation of particles on the collection electrode is limited and automatically regulated. However, the actual reduction on the emission of particles from combustion caused by the ESP might be overestimated due to this periodic increases, which can only be measured at the right time of the collapses. This fact should be taken into account when designing and presenting a cleaning system for the ESP.

4. Conclusions

A small-scale ESP was experimentally tested for 40 h with a domestic biomass boiler to analyse the deposition of particles on the collection electrode and its influence on the performance of the unit. A cleaning system is unneeded during the test to allow the accumulation of particles on the inner surface of the precipitator.

The particle layer growth on the collection electrode with the operating time of the ESP has been successfully measured, providing the thickness and profile after every 10 h of accumulation. The thickness of the particle layer tends to increase in the area near the inlet of the ESP. The changes on the shape of the dust layer after 30 h of operation of the ESP revealed presumable partial collapses in areas where the thickness of the layer is around 1 mm. The occasional collapses of the particle layer would regenerate the ESP automatically, which is in agreement with the stable retention efficiency during the test. The re-entrainment of particles is reported as abrupt increases in the PNC at the outlet of the ESP and simultaneous current drops due to the higher particle concentration. Therefore, the actual particle emissions of the system are higher than expected, since the timely PNC measurements might leave out the exact moment of the partial collapses. This influence in the operation of the ESP should be taken into account when designing a cleaning system.

The small-scale ESP highly reduces the emission of particles generated by the pellet boiler during the test (retention efficiency above 90%), and it also modifies the GMD at the outlet of the ESP. A smaller GMD indicates a higher collection of coarse particles compared to the smallest fraction. In addition to the conclusions of this analysis, the experimental data provided in this work is expected to be useful for modelling validation.

Further experimental tests are needed to analyse the influence of the composition of biomass and combustion conditions on the deposition of particles inside a small-scale ESP. These would provide information about how different fuels and selection of parameters affect the accumulation and the collapses of the particle layer. In this line, a re-design of the fouling measurement system would also allow the growth analysis of a higher number of profiles on the inner surface of the collection electrode. This modification would provide more detailed measurements of the presumable collapses of the particle layer.

CRediT authorship contribution statement

Natalia Cid: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sergio Chapela:** Conceptualization, Formal

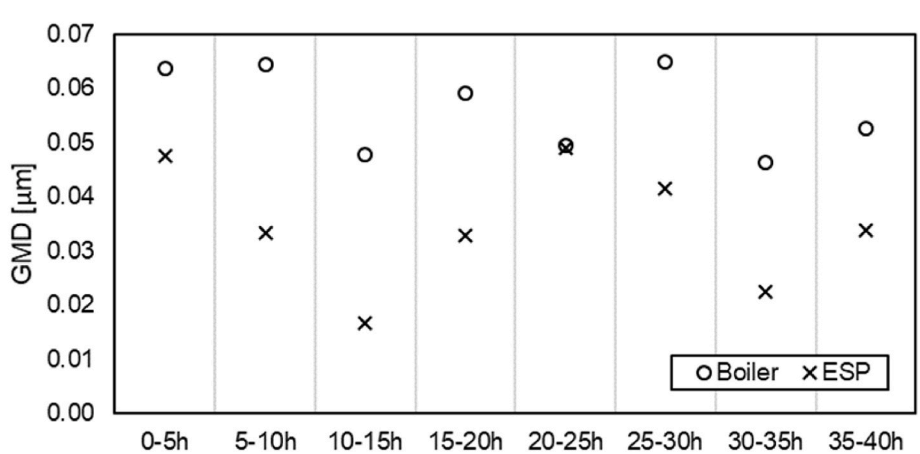

Fig. 6. Average GMD at the inlet and outlet of the ESP.

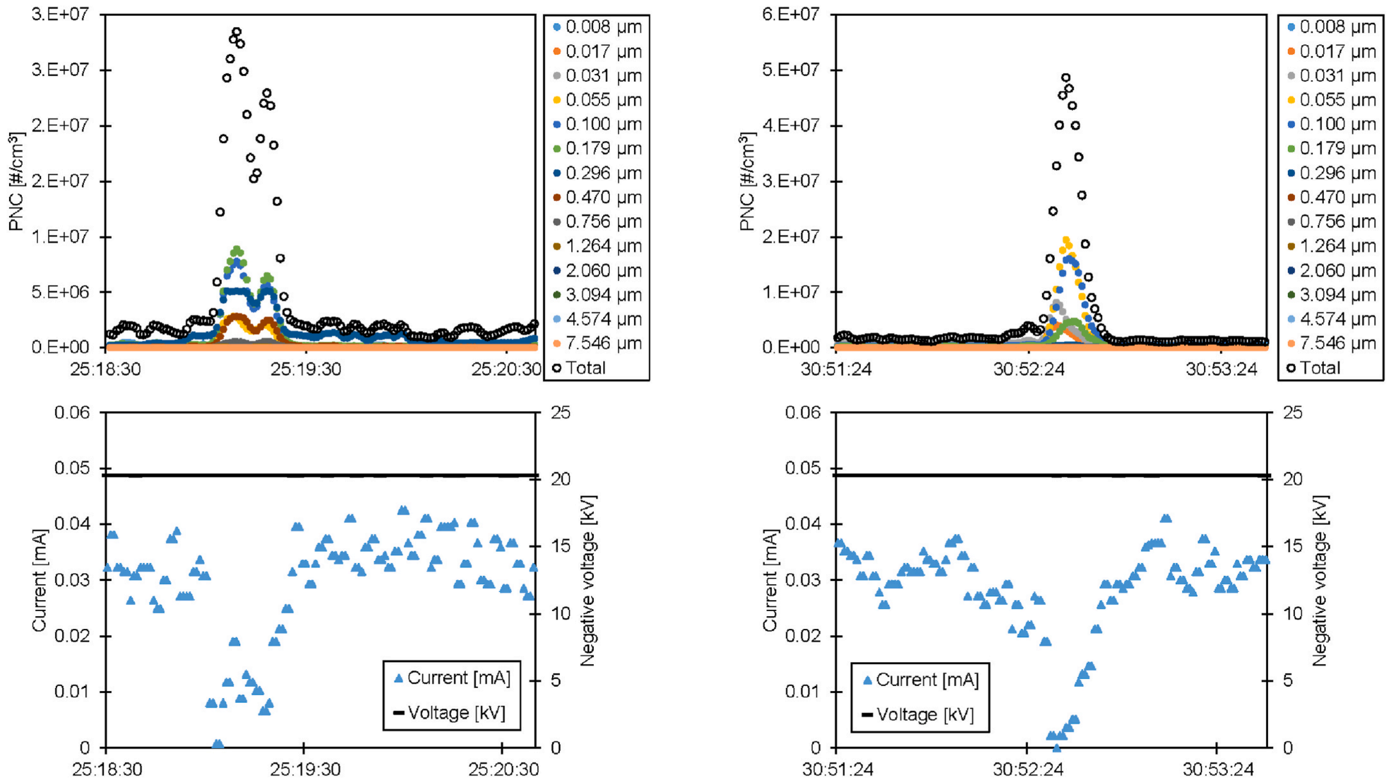

Fig. 7. PNC abrupt increases and current drops due to partial collapses of the particle layer after 25h (left) and 30h (right) of operation of the ESP.

analysis, Writing – original draft. **Miguel Ángel Gómez:** Conceptualization, Project administration, Validation, Writing – original draft, Writing – review & editing. **David Patiño:** Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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