Development of an online monitoring method for electrostatic precipitators on commercial biomass combustion plants

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Abstract

Combustion plants based on wooden biomass as fuel can contribute to a decarbonization of the energy sector by reducing the need for fossil energy usage, which decreases the net carbon dioxide output in the atmosphere. However, the flue gas of biomass-based combustion plants contains increased amounts of particulate matter, which need to be separated before release into the environment because of legal emission limits. In medium-sized plants, electrostatic precipitators (ESP) are commonly used separators to minimize the particulate matter concentration. Due to new regulations based on the medium combustion plants directive introduced by the EU, continuous surveillance of secondary precipitation technologies like ESP has to be implemented. The method proposed in this paper focuses on the readily available current (I) and voltage (U) data of the high-voltage unit supply of an ESP to calculate the efficiency of the particle separation. Consequently, a continuous proof of function can be delivered without high cost for additional measurement equipment. This article proves the effectiveness of the method in calculating the precipitation effectiveness of the ESP. It is shown that the deviation from the separation efficiency calculated by the method and the measured efficiency is smaller than 7%. Additionally, it is necessary to define a suitable reference signal that indicates whether the combustion plant is running or not. Hence, the availability of the system can be evaluated. This method will help operators to meet legal requirements.

Keywords Bioenergy · Emissions · Combustion · Flue gas cleaning · Electrostatic precipitators · Precipitation monitoring

1 Introduction

Climate change is one of the most imminent threats to the planet [1]. A major contributor to this issue is the burning of fossil fuels leading to increased CO₂ concentrations in the atmosphere [2]. The utilization of biomass for heating applications and power production is part of a solution to overcome this problem [3]. Although advantageous, one major drawback of biomass combustion is the increased particulate matter concentration in the raw flue gas [4, 5]. Electrostatic precipitators (ESP) are used to reduce these particulate matter emissions [6].

In 2015, the EU has concluded a new regulatory framework—the medium combustion plants directive (MCPD)—which defines emission limits for different

pollutants including particulate matter and operation boundary conditions for medium-sized combustion plants [7]. Plants with a total thermal input of more than 1 MW and less than 50 MW are considered medium-sized combustion plants [7].

An operation condition of the MCPD (article 7, § 3 and 4) for plants using secondary abatement equipment in order to meet the emission limit values is that the operator shall keep a record of, or information proving, the effective continuous operation of that equipment.

However, an effective continuous operation is not defined further. The German legislative has issued the new directive 44. BImSchV (for “Bundesimmissionsschutzverordnung”), which implements the MCPD on a national level [8]. Article 3 § 21 thereof stipulates that solid fuel combustion plants have to measure the emitted dust concentration in the flue gas continuously.

A plant with a thermal input of less than 5 MW and without a dust separation device downstream of the furnace does not need a continuous dust measurement, if it passes the defined discontinuous emission concentration measurements every three years. Concerning that, it is unclear, whether a cyclone

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or an integrated precipitator in the firing system is defined as downstream separation device. However, a similar plant with a downstream dust separation device, like an ESP, requires either a continuous dust measurement system approved according EN 15267-3 [9] or the proof of the continuous effective operation of the dust collector with a state of the art system. This could also affect smaller plant and even household heating systems in near future.

Although approved equipment from several suppliers is available to measure, monitor, and record the particulate matter concentration [10, 11], the additional costs would decrease the economic competitiveness of biomass-based combustion plants. This can have a negative impact on biomass usage and can impede a wider use of solid biofuels [12]. This paper proposes a monitoring method, which relies on data already measured in the ESP with low additional cost, meeting the demand for a state of the art monitoring system. Since this research deals predominantly with electrostatic precipitators, a basic understanding of the principle is necessary (Fig. 1).

Stage 1: The high-voltage generator creates an electric field between the spraying and the collecting electrode, which causes a corona discharge leading to free electrons that are accelerated away from the electrode. On their path, they collide with air molecules in the precipitator, which leads to the impact ionization of the molecules. Stage 2: Dust particles traversing through the cloud of ions collect the charged gas molecules. Stage 3: As a result of the electric field, the charged particles drift relatively to the flow towards the collecting electrode, where they adhere and at least partly discharge. This process has already been described in various books and journal papers [6, 13–17].

The voltage (U) and current (I) depict the physical behavior of the precipitator and lead to a continuous monitoring method for the precipitator (see Section 2.2). By monitoring the

current and voltage while measuring the separation efficiency, the availability of the ESP for two medium biomass combustion plants, located in Germany and Austria, has been determined. This method is a related approach to the work of Nussbaumer and Lauber [18]. Yet, the difference is to use the continuous approach without the need for threshold values in voltage and current. Other researchers are usually focusing on improving the precipitation efficiency such as Fraunhofer UMSICHT [19] or focus on the theoretical calculation of the ESP performance as E. C. Potter [20]. The approach will be explained further in the next section.

2 Methods and approach

2.1 Experimental setup

The presented method will be evaluated in a project funded by the “Fachagentur Nachwachsende Rohstoffe e.V.” In this project, a total of six commercial wood-based combustion plants located in Germany and Austria are investigated. All plants are equipped with a grate firing for wood chips. By doing this, it is possible to determine whether the method could be suitable for all plants, despite having characteristic operational behavior. The plants have a rated thermal output from 0.75 to 1.3 MW. Furthermore, it is important that the measurement points are accessible and allow representative probing. In most cases, it was not possible to find measurement points that meet the requirements of the VDI (for “Verein deutscher Ingenieure”) guideline 2066 [21] for gravimetric dust measurements, but the points that came closest to the requirements were selected. For this work, results from only two plants can be discussed, because it is an ongoing investigation. The other results will be included in a later publication. One of the

Fig. 1 Basic function of an electrostatic precipitator (left) and exemplary construction as a double tube precipitator (right)

discussed plants has a thermal output of 0.75 MW (plant 1) and the other 1.3 MW (plant 2). Both plants used wood chips as fuel. The measurement devices used are divided into three categories:

- Online dust sensors
- Gravimetric dust measurement devices to calibrate the sensors
- Gas analytics

The in situ dust monitoring is performed by the so-called Dusthunters of the company Sick AG. These are scattered light sensors using a laser with two available versions, SP100 and SP30. The light signal is transformed into a 4–20 mA output signal. The SP100 version is placed directly after the outlet of the combustion unit, because it can withstand high gas temperatures. However, the SP30 version is sufficient to operate after the precipitation unit [22]. Delphin Technology AG's data logger collects the output signals from both devices [23].

A plane filter measurement device by the company Paul Gothe GmbH is used as reference system to calibrate the sensors [24]. An additional gravimetric measurement device, the FSM system by the company MRU GmbH, is used to generate more data points. This device can be used more efficiently because the filter can be exchanged along with the cage conveniently and weighed on-site [25]. Preliminary tests showed that all concentrations measured with the MRU device are within a range of $\pm 10\%$ similar to the values measured by the Paul Gothe device. This difference is seen as sufficient to assume that the results are comparable. The point measurements of these two devices are used to define the linear calibration curve for the dust sensors. Therefore, it is possible to link the output signal from the sensors to the corresponding dust concentration value.

Another important task is to monitor the composition and material properties of the flue gas via gas analysis. This is necessary in order to determine the residual oxygen content, gas temperature, and velocity, which are crucial to define the dust concentration in the flue gas [21]. In addition, it is possible to determine the concentration of carbon monoxide (CO) and the nitrogen oxides (NO_x). These are important factors to evaluate the quality and status of the firing process and are regulated by law as well [7]. The gas analysis device MGA Prime by the company MRU GmbH performs these measurements. The device uses nondispersive infrared (NDIR) and electrochemical sensors for precise measurements, but it can also withstand the expected flue gas temperature and dust load [26]. The overall measurement setup is shown in Fig. 2:

The measurements from each plant were obtained over several days in three steps:

- I. Installation of the online measurement devices

- II. Calibration of the installed devices at different load conditions (mostly full load and 70% partial load) and operation statuses (steady state, ember preservation)
- III. Analysis and recording the flue gas conditions including U and I logging

Critical information for the calibration such as load, ventilation statuses, and flame temperature was also taken from the control software of the furnace itself.

2.2 Concept

The aim of this project is to find a cost-efficient way to monitor the efficiency of electrostatic precipitators by collecting data that are already available at the site. The operation voltage and current of the ESP are continuously recorded and stored by the plant control software. The precipitation efficiency (η) is defined by the difference between the outlet (c_{out}) and inlet concentration (c_{in}) of particles in the flue gas with respect to the inlet concentration.

$$\eta = \frac{c_{\text{in}} - c_{\text{out}}}{c_{\text{in}}} \quad (1)$$

By using the so-called Deutsch equation (Eq. 2), it is possible to calculate the efficiency of the precipitator on a physical level. The equation describes the physical behavior of the dust particles in the electromagnetic field of the precipitator and was first proposed by Deutsch in 1922 [14]. The theory was then developed further by White in 1963 [15].

$$\eta = 1 - \exp\left(-\frac{w \cdot A_D}{\dot{V}}\right) \quad (2)$$

The drift velocity w is mostly dependent on flow condition of the flue gas, electric field properties, and the charge transported by the particle. The depositing area A_D represents the geometry of the ESP flow channel and the volumetric flow rate $\dot{V}$ represents the amount of flue gas passing through the ESP. The voltage set between the electrodes of the ESP determines the electric field strength. The current flowing between the electrodes is enabled by the particles transporting the electric load. Given the assumption that the mean load per particle is constant, the current represents the amount of particles reaching the collecting electrode, where they are precipitated from the gas flow. Other influences like flow conditions and ESP geometry can be combined to a factor k . When the chemical and physical properties of the flue gas are constant, meaning nominal conditions, the factor k should be constant. Therefore, Eq. 2 can be rewritten as:

$$\eta = 1 - \exp(-k \cdot U \cdot I) \quad (3)$$

Based on this equation, it is possible to calculate the efficiency of the ESP, if it is in nominal operation without

Fig. 2 Used measurement setup

electrical breakdowns. To do so, the precipitator constant needs to be calculated by measuring the actual precipitator efficiency while logging the ESP parameters U and I . Using Eq. 3, the precipitator constant can then be calculated. After that, it is sufficient to use U and I for the monitoring of the ESP, thus eliminating the need for any additional measurement devices. According to Eq. 3, it is then sufficient to check if the present product of voltage and current is higher than the product that would result in the legal limit to see if the regulations are fulfilled. Therefore, in a plot of voltage over current, the legal limit defines a precipitator limit line shown for different efficiency in Fig. 3.

Every state of operation produces a point in this plot and if this is on the top right of the limit line, the precipitator works efficiently and if it is on the bottom left, it does not. Of course, this is only a theoretical approach. In real combustion systems, the chemical and physical properties of the dust particles, as

well as their concentration, can vary widely. This means that the method needs to be evaluated in detail to define the limits of the theory. This approach is similar to the one proposed by T. Nussbaumer and A. Lauber [18], but without specifying threshold values.

Yet, the efficiency of the ESP itself should not be the target value in evaluating the performance of the whole heat generating system because it only describes the emissions when the ESP is on. Highest amounts of emissions pass through when the ESP is not running. This can be the case in a start-up scenario for example. When the furnace is starting operation, the ESP has to heat up first in order to prevent condensation [27]. This means that the ESP start is delayed and the dust particles can pass unfiltered. Additionally, when an error occurs, the ESP is turned off and set on bypass (when possible) also causing high emissions. Therefore, it is important to relate the time when the ESP is running efficiently t_{eff} with the time

Fig. 3 Exemplary theoretical precipitator limit lines for different precipitation efficiencies for constant operation conditions and flue gas conditions

when the furnace is actually running and producing flue gas $t_{\text{Fire on}}$. This relation is called availability A :

$$A = \frac{t_{\text{eff}}}{t_{\text{Fire on}}} \quad (4)$$

This leads to the task of defining when the furnace is on. This signal is essential for evaluating the precipitation process. By now, there is no uniform and universally applicable method to identify this state. One possible way to achieve this is by determining the residual oxygen concentration, the operation state of primary air fan, and the flue gas air fan, a technique proposed by QM Holzheizwerke in Switzerland [18, 28]. The on and off conditions proposed there are summarized in Table 1.

As every method has its limitations, this one is no exception. For instance, plants without a primary air fan cannot be represented fully. Additionally, many plants do not adjust their thermal output to the heat demand of the grid. Instead, they operate at steady power (steady-state operation), overproduce heat, and fill the buffer storage. When the storage is full, the plant shuts down. When the heat grid empties the storage again, the power plant starts again. In between these two operation intervals, the furnace uses an ember preservation state to enable a warm start. In this state, the oxygen concentration in the flue gas can drop drastically and this would cause a false on or off signal. This effect is further described in Section 3.3. Another problem is the availability of raw data. Measuring the operation states of the air fans causes an additional financial effort, which leads to a dependence on the furnace manufacturer. Presently, some furnace manufacturers deliver a “Fire on” signal to the precipitator, but this is not uniform. To eliminate these factors, it is beneficial to extract the “Fire on” signal directly from the flue gas flow and therefore be independent from digital signals of the furnace.

2.3 Analytical approach

As mentioned before, the data logger collects the output signals of the in situ dust sensors. The sampling rate is one value per second, but only minute averages are used and this applies to the gas analytics as well. In addition, the manufacturers of the precipitation units provide the data on the operating current and voltage. These are instantaneous values taken every minute. The different data sources will form a common SQL (structured query language) database in Python. Additional

evaluations were done in Microsoft Excel whenever necessary.

For biomass-fired heating plants, it is state of the art to separate the coarse and even glowing particles in a first step with a cyclone, which is designed in most cases as a multicyclone [29]. The cyclone separates particles with a diameter larger than 3 μm . The ESP is placed downstream from the cyclone to separate the particles smaller than 10 μm . Space-optimized ESP-concepts, where the multicyclone is integrated into the ESP-housing, are common as well.

Therefore, at some plants, there is no suitable measurement point between the cyclone and the ESP to measure the dust concentration accurately, so the dust concentration before the cyclone is measured. This implies that the overall efficiency measured is not the efficiency of the ESP alone and the method based on Eq. 3 needs to be re-checked for this case. Given that, the overall efficiency of the combined precipitator can be calculated by [30]:

$$\eta_{\text{total}} = \eta_{\text{cyclone}} + \eta_{\text{ESP}} - (\eta_{\text{cyclone}} \cdot \eta_{\text{ESP}}) \quad (5)$$

Using Eq. 3 for the efficiency of the ESP in Eq. 5 leads to another expression describing the total efficiency:

$$\eta_{\text{total}} = 1 - \exp\left(-k \cdot U \cdot I + \ln\left(1 - \eta_{\text{cyclone}}\right)\right) \quad (6)$$

This results in a similar structured equation, suggesting that the efficiency of the cyclone could be integrated in the precipitator constant proposed earlier, so that the basic equation is uniform for all plants. In this case, the cyclone will be evaluated with a constant separation efficiency of 60% at nominal conditions, which is the mean efficiency proposed by the manufacturer. Given that, the precipitator constant can be varied so the new curve fits the original curve based on Eq. 3. Assuming a usual k value of 0.05 W^{-1} in Eq. 3, which neglects the cyclone, the efficiency plotted over the product of U and I results in the upper, blue curve in Fig. 4. The lower, orange curve however represents the same relation using the new Eq. 6. The precipitator constant can now be varied to fit the blue curve. The new precipitator constant is then 0.063 W^{-1} . A visual comparison between the two equations is shown in Fig. 4.

The usual overall efficiency measured is in the range of 85 to 98%. In this area, the difference between the two calculation methods is less than 2% in absolute values. This means that the behavior of the cyclone can be integrated in the

Table 1 Fire on and off conditions proposed by QM Holzheizwerke [28]: it is sufficient when one of the state signals indicates on or off

State signal	Switch-on condition	Switch-off condition
1	Primary combustion air fan ON	Primary combustion air fan OFF
2	Flue gas fan ON AND $\text{O}_2 \leq 18 \text{ Vol.-%}$	Flue gas fan OFF OR $\text{O}_2 \geq 19 \text{ Vol.-%}$

Fig. 4 Comparison between the efficiency calculated by Eq. 3 and the overall efficiency calculated by Eq. 6 (dotted line)

precipitator constant to unify the further investigations on every plant. Every result discussed in Section 3 is based on the assumption that the precipitator constant includes the cyclone, when it is integrated mechanically.

3 Results and discussion

3.1 Proposed method

The first step was to calculate the precipitator constant from the measured efficiency and the ESP parameters U and I . In Fig. 5, the measured efficiency is plotted over one operation period of the combustion, meaning start-up, stationary operation, and turn-off. The dotted lines mark when the furnace delivers the signal “Fire on.” Additionally, the measured dust concentrations in the inlet and outlet flow are shown. The concentrations show significant peaks, which result from the cleaning events of the boiler that occur every 60 min. As a result, a dust cloud moves through the exhaust duct and is detected by the sensors implying that in some cases the

efficiency calculated from these signals (Eq. 1) can decrease drastically due to the time delay between signal peaks.

This indicates that it is difficult to derive a constant that represents a steady operation state when external events trigger unspecific peaks. Hence, it is expected that the precipitator constant can only be specified within a certain scope of validity. Table 2 represents the values of the constants calculated. The value itself is characteristic for the plant where such a system is operated. It is the mean value determined over a period of around one hour of steady operation. The deviation is dependent of the number of peak events inside the determination period.

These results indicate that the precipitator constant needs to be evaluated with an uncertainty that will decrease the accuracy of the method as well. This is a limitation of this method. Nevertheless, the aim is to determine the efficient functioning of the filter, and precision and fine-tuning will be focused on later. It is also critical that every change of the combustion unit can lead to a different precipitator constant, meaning that the evaluation has to be updated.

Figure 6 depicts the difference between the measured efficiency and the efficiency calculated by the method. This

Fig. 5 Progression of the inlet c (in) and outlet c (out) dust particle concentration over an operation period (m^3 i.N.: nominal cubic meters at 6% O_2 concentration)

Table 2 Calculated precipitator constants for two plants

Plant	Mean precipitator constant in W^{-1}	Deviation from mean
1	0.0549	13%
2	0.00430	8%

comparison uses the precipitator constant determined in previous measurements to calculate the efficiency for a different operation period for the same plant.

From Fig. 6, it is evident that peak events lead to a decrease in the actual efficiency and this effect cannot be recreated by the method. However, the calculated values match the actual values in steady-state operation. During the plotted operation period of plant 1, the mean relative deviation of the efficiencies is 6.9%. In conclusion, the method is applicable within certain boundaries that need to be evaluated further.

At plant 2, the mean relative deviation can even reach values below 5% in regular operation. This value could only be achieved due to the lack of peak events and errors in one measurement period of 150 min.

This operation can also be displayed in the precipitator limit line approach proposed in Section 2.2. Using 90% as target efficiency, Fig. 7 shows how often the precipitator works efficiently.

The points, representing different states of operation, indicate that there are multiple occasions of malfunction. Additionally, the deviation indicates that there are multiple values that need to be discussed with an uncertainty. Further investigations need to address this issue and improve the accuracy of the method.

3.2 Availability of the precipitator

As mentioned in Section 2.2, the efficiency of the electrostatic precipitator alone should not be the key evaluation criterion. From Eq. 4, it can be described that the availability A of the

ESP takes into account the operation state of the ESP (On/Off) and the exact time of dust emissions from the furnace. Hence, it is possible to evaluate the dust emissions that are not filtered due to a possible failure or downtimes of the precipitator. Table 3 compares the measured values for the availability A for two plants. Because the term effective operation is not defined clearly, two different evaluation methods for t_{eff} in Eq. 4 are used. The values in the second column are in respect to the time when the output concentration of dust was below 20 mg per nominal cubic meter (mg/m^3 i.N.). The values in the third column represent the time when the ESP had a calculated efficiency over 90%. Deviations were neglected here. Both values are with respect to the “Fire on” signal from the furnace.

Usually the availability is below 100%. The ESP has a waiting time until the gas temperature inside the precipitator is above a certain limit to avoid steam condensation effects [27]. This is the reason for the ESP to be turned on with a time delay. This effect decreases the availability in both cases. At plant 1, the inlet dust concentration was very low, so the cyclone could keep the outlet concentration under the $20 \text{ mg}/\text{m}^3$ i.N. at 6% O_2 limit.

It can be described that the availability calculated with the method is considerably lower than the effective availability. This has two main reasons:

- When an error occurs in the ESP, the electric field is switched off automatically and the ESP is on bypass mode. The reason for this can be a flash over between the electrodes, for instance.
- The electric current decreases drastically, so that the calculated efficiency also decreases. This may be attributed to the fact that when the inlet concentration is already low, less dust can be precipitated.

Another possible scenario was already discussed in Section 3.1. When a cleaning event causes a peak in the inlet

Fig. 6 Comparison between the measured efficiency and efficiency calculated by the method over one operation period of plant 1

Fig. 7 Plot showing the pairs of values of voltage and current in relation to the precipitator limit line including the deviation of 6.9% at plant 1

dust concentration, the outlet dust concentration exceeds the limit. Nevertheless, the ESP can still work effectively and the method calculates a separation efficiency over 90%. Addressing these issues will be an important task for further investigations. After that, legislation based on this method can find fair availability regulations.

3.3 “Fire on” signal

The “Fire on” signal is crucial in evaluating when the ESP needs to be turned on and off and defines the availability as well. The “Fire on” signal comes from the process control unit (PCU) of the furnace, if it is available.

Currently, the signal is not standardized and therefore not uniformly designed by all boiler manufacturers. The data transmission from the boiler PCU to the ESP PCU causes additional costs and sometimes considerable technical interface and port problems. Furthermore, it is not transparent under which conditions the signal is formed and turned on. In addition, retrofitting is usually not possible. Therefore, a “Fire on” signal from the boiler PCU is not the preferred method.

Defining a “Fire on” signal that is independent from the furnace is crucial for finding a method that can be licensed under legislation. The best way is to derive the signal directly from the flue gas at the precipitator inlet. Available signals are the temperature (T-Gas), the oxygen (O_2), the carbon monoxide (CO), and the nitrogen oxides (NO_x) concentrations. Initial measurements showed that the CO concentration was highly unstable and varied from values around 10 to 8,000 ppm within minutes under steady-state operation. Therefore, the CO

signal is unsuitable and was not considered further. In Figs. 8 and 9, the progression of the remaining signals is plotted over an on/off operation of the furnace at plants 1 and 2. The x-axis represents the time after the measurement started.

The oxygen concentration seems to be a suitable parameter that can be considered as a switch-on condition. It is visible that after the furnace is shut down, the oxygen concentration decreases in time intervals. This is a result of the furnace trying to maintain the embers on the grate. In certain intervals, a quantity of fuel is conveyed inside the combustion chamber along with a considerable amount of air to support ignition. This short combustion process is measurable in the oxygen concentration. Using the conditions proposed before (Table 1, [28]), this would result in a false “Fire on” signal. Figure 9 shows a drop of oxygen concentration that is similar to the actual steady-state operation. This implies that the oxygen concentration alone cannot be used as a “Fire on” signal trigger. The oxygen signal at the ESP entrance could be realized with a lambda sensor, which is suitable for an oxygen content in the flue gas from 4 to 16%, but this would create additional costs [31].

The flue gas temperature shows similar limitations as the oxygen concentration in the ember preservation mode. It is suitable as a switch-on trigger at 150 °C, but lacks the ability to give a distinguishing feature to steady-state operation. Additionally, these two plants use a bypass valve on the boiler to primarily increase the flue gas temperature. Therefore, the behavior shown here is not characteristic for every furnace.

The signal from the NO_x concentration correlates directly to the flue gas temperature and gives no additional information. Furthermore, this would be more expensive to monitor and was not evaluated further.

The best solution would be a combination of oxygen concentration and flue gas temperature signal to determine the “Fire on” signal. Considering Figs. 8 and 9, suitable threshold values can be 15% oxygen concentration and 150 °C flue gas temperature. Additionally, it is inevitable to regulate the ember

Table 3 Comparison of the measured availability based on the criteria output concentration and efficiency calculated by the method

Plant	A ($c \leq 20 \text{ mg/m}^3 \text{ i.N. at } 6\% O_2$)	A (method)
1	100%	83.7%
2	97.8%	82.1%

Fig. 8 Progression of O_2 , NO_x , and flue gas temperature in temporal relation to the given “Fire on” signal from the furnace at plant 1

maintenance operation, which is by now a legal gray area, as it is defined as “Off” situation of the furnace. At this point of the project, the stated values could only be verified on two plants. Further investigations are necessary to find a generally valid solution.

3.4 Partial load operation

The proposed method focuses on a nominal operation state. When the heat demand is low or the firing plant is over dimensioned, the furnace often operates in partial load. Less biomass is fed to the combustion chamber and the ventilation system uses diminished less air input. At this state, the flue gas volume flow decreases and consequently changes the flow mechanical situation inside the precipitator. This implies that the precipitator constant describing the flow and geometry will change as well and the method is inapplicable. However, measurements show that the partial load operation is far less critical than the full load state because fewer emissions are produced and the reduced flow velocity in the ESP leads to an increased residence

time of the particles within the electric field. This increases the efficiency as well [15]. Figure 10 shows the progression of the efficiency over two operation periods. The first one at 70% partial load as an exemplary state of operation and the second one was operated on full load.

The average values indicate that on a partial load, the efficiency increases, making it far less critical when it comes to emissions. Additional measurement will show if this is also valid for 30% partial load, as it is often the lowest possible continuous part load. The drastic drops in efficiency are caused by cleaning mechanisms that are similar to the peak events described in Section 3.1. Further investigations would focus to find a suitable way to deal with partial load states for the legal implementation of the proposed method.

4 Conclusion

The proposed method is effective in monitoring electrostatic precipitators on commercial biomass combustion plants with

Fig. 9 Progression of O_2 , NO_x , and flue gas temperature in temporal relation to the given “Fire on” signal from the furnace at plant 2

Fig. 10 Comparison of the progression of measured precipitation efficiency for a full load and a 70% partial load operation at plant 1

only few further investment costs for the operator. It can help to meet the legal requirement to prove that the precipitator is capable of effective and continuous operation. Furthermore, it can monitor the availability of ESPs and help to find deviations from normal behavior during operation. This can be helpful for any future developments in this area.

The article demonstrates that one precipitator constant can express the nominal state so that the operation can be determined by the voltage and current of the system. The calculated constants are highly dependent on the combustion and precipitator unit. The calculated efficiency of the model fits well to the measured values with a relative deviation of 6.9%.

Furthermore, it is possible to calculate the availability of the ESP. The calculated availabilities vary from 82.1 to 100% depending on the calculation method. At the current state of the study, the calculated availability is significantly lower than the actual value. This must be considered as well. However, these investigations are only a proposal on how the legal implementation could calculate this value in the future.

This also applies to the calculation of the “Fire on” signal. A combination of the oxygen concentration, with a threshold value of 15% and the flue gas temperature, with a threshold value of 150 °C is applicable as switch-on and switch-off conditions for both evaluated plants. At plant 2 however, the ember preservation states after operation would trigger false “Fire on” signals. Further investigations will show whether this behavior can be avoided or needs to be regulated. Assuming this problem will be solved in the future, the measurements prove that it is possible to find suitable triggers for this signal in the flue gas conditions.

The preliminary results show the 70% partial load state is uncritical when using the method because the efficiency increases. Further measurements will determine whether this is also valid for 30% partial load.

The next step in this project is to test the method on more combustion plants to eliminate the influence of characteristic behaviors of different plants. Additionally, the “Fire on” signal needs to be investigated further to find reliable trigger values. This will result in an overall monitoring method that is uniform and universally applicable.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Abbreviations A, availability [/]; A_D , depositing area of the precipitator [m^2]; BImSchV, German: “Bundesimmissionsschutzverordnung”; c_{in} , inlet dust concentration at nominal conditions [$\text{mg}\cdot\text{m}^{-3}$]; c_{out} , outlet dust concentration at nominal conditions [$\text{mg}\cdot\text{m}^{-3}$]; ESP, electrostatic precipitator; FNR, German: “Fachagentur Nachwachsende Rohstoffe”; η , η_{Total} , precipitation efficiency of the whole system [/]; η_{cyclone} , precipitation efficiency of the cyclone [/]; η_{ESP} , precipitation efficiency of the ESP [/]; I , current [A]; k , precipitator constant [W^{-1}]; MCPD, medium combustion plant directive; PCU, process control unit; SQL, structured query language; t_{eff} , time, when the filter is running efficiently [s]; $t_{\text{Fire on}}$, time, when the furnace is on [s]; U , voltage [V]; V , volume flow rate [$\text{m}^3\cdot\text{s}^{-1}$]; VDI, German: “Verein Deutscher Ingenieure”; w , drift velocity [$\text{m}\cdot\text{s}^{-1}$]

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