Research paper

Monitoring the availability of electrostatic precipitators (ESP) in automated biomass combustion plants

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ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
26 February 2016
Accepted 27 February 2016
Available online 9 March 2016

Keywords:
Particle separation
Electrostatic precipitator (ESP)
Monitoring
Availability
Uptime
Downtime

ABSTRACT

To achieve emission limit values on particulate matter emissions of less than 20 mg m⁻³ at 11% O₂ volume fraction for 1 MW to 5 MW, automated biomass combustion plants are often equipped with electrostatic precipitators (ESPs). To ensure low emissions, a high availability of the precipitators, i.e., a high ratio between the uptime of the ESP and the uptime of the boiler, has to be guaranteed including operation at part load and during start-up. In the present work, an investigation on seven heating plants with tube-type and plate-type ESP in the size range of 450 kW to 3.5 MW was conducted. The signals on load, temperatures, fans, lambda sensors, voltage and currency were measured during two years. From these data, the availability is determined based on specific definitions for the operation modes of the ESP and the boiler. To evaluate threshold values for the ESP operation and to validate the method, gravimetric measurements on the particulate matter emissions in different operation modes were performed.

The investigation reveals that ESPs in today’s biomass plants can achieve availabilities of greater than 90%. Further, malfunctions and maintenance issues that are not immediately repaired are identified as main source for low availabilities, while availabilities of greater than 95% are considered achievable for new plants. To ensure optimum ESP operation with low particle emissions under real-life conditions, a reliable monitoring of the availability based on the presented method is recommended for automated biomass combustion plants.

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1. Introduction

1.1. Background and motivation

The use of wood and other biogenic fuels can contribute to the substitution of fossil energy carriers and has therefore steadily increased over the past years. On the other hand, however, wood combustion causes pollutant emissions of nitric oxides (NOₓ), volatile organic compounds (VOC) and particulate matter (PM). PM in ambient air is responsible for adverse health effects and has been identified as main indicator of the health relevance of air pollution [1,2]. In particular, long-term exposure to combustion-related fine particles increase the risk of cardiopulmonary and lung cancer mortality [3].

Commonly used indicators for the air quality are the inhalable particles with an aerodynamic diameter smaller than 10 μm described as PM₁₀, the respirable fraction referred to as ‘fine particles’ smaller than 2.5 μm described as PM₂.₅, and ‘coarse PM’ defined as difference between PM₁₀ and PM₂.₅ [4]. Further PM₁ are also distinguished and ‘ultrafine particles (UFP)’ smaller than 100 nm are considered as most relevant, since the mobility in the body and the specific active surface increase with decreasing particle size.

Depending on the fuel type and the combustion regime, different primary particles from biomass combustion can be distinguished [5]: soot (nearly elemental carbon EC), which is formed due to local lack of oxygen, condensable organic compounds (COC, also called ‘tar’), which result from primary and secondary pyrolysis products, and mineral compounds such as salts, which result from ash constituents [6]. With respect to particle size, a bimodal size distribution is often found resulting from coarse fly-ash particles on the one hand and ultrafine particles formed by nucleation and condensation processes in the
combustion [7].

Since the combustion of solid fuels causes PM in the ambient air including organic substances [8], a potential trade-off between climate protection and air pollution prevention may arise. In order to mitigate this problem, the particle emission limits from biomass combustion were decreased in multiple European countries and even further measures were announced by some governments. A winter period during which the emission limits for particulate matter were exceeded for more than three weeks brought the Swiss winter period during which the emission limits for particulate combustion were decreased in multiple European countries and to mitigate this problem, the particle emission limits from biomass climate protection and air pollution prevention may arise. In order including organic substances [8], a potential trade-off between gas components, i.e. moisture and potentially organic compounds.

In addition, the definition of the ESP uptime, which is accounted for to determine the availability, is indicated, while two different cases are introduced for the definition of the combustion uptime as described in chapter 2.

1.2. Objectives

The objective of the present evaluation consists in determining the characteristics of electrostatic precipitators in practical operation in automated biomass combustion plants, in deriving measures for good operational conditions, and in developing a monitoring method for the system operation.

1.3. Approach

Seven plants were monitored for two years and periodical particle measurements were performed to characterise the precipitation performance. Signals on load, temperatures, fans, lambda sensors, as well as voltage and currency were recorded from the boiler control system and the ESP control system. The data was recorded in a frequency of 1 Hz to calculate and save average values in a frequency of 0.5 min⁻¹ for the detailed data evaluation. The plants covered the size range from 450 kW to 3.5 MW and consisted of biomass boilers from three different manufacturers and ESPs from for different suppliers [12]. For the particle precipitation, tube-type and plate-type ESPs as described in Fig. 2 were investigated.

2. Monitoring method

2.1. Definition of the precipitator availability

To characterise the operation of the ESP, the precipitator availability \( A_P \) is defined as ratio between the precipitator uptime and the combustion unit uptime (also 'combustion uptime' or 'boiler uptime') during the inspection period \( t \). The precipitator uptime also corresponds to the difference between the combustion uptime and the precipitator downtime described by the following definitions:

\[
A_P = \frac{t_P}{t_C} = \frac{t_C - t_{P(down)}}{t_C} = 1 - \frac{t_{P(down)}}{t_C} \tag{1}
\]

where

\( t_P = \) Precipitator uptime in the inspection period \( t_C = \) Combustion unit uptime in the inspection period \( t_{P(down)} = \) Precipitator downtime during the inspection period.

The availability is equalling 1 minus the unavailability \( U_A_P \):

\[
U_A_P = \frac{t_{P(down)}}{t_C} \tag{2}
\]

and therefore:

\[
A_P = 1 - U_A_P \tag{3}
\]

\( A_P \) is commonly described in hours per hours as a dimensionless factor and often indicated in %. Hence, the following conditions needs to be fulfilled:

\[
t_P \leq t_C \leq t \tag{4}
\]

\[
0 \leq A_P \leq 1 \tag{5}
\]

where
t = Inspection period (e.g. 1 a = 8760 h or 1 d = 24 h).

In case of an independent determination of the combustion uptime and the precipitator uptime (which is often used as an easily applicable method by two hour meters for the boiler and the precipitator), situations resulting in \( t_P > t_C \) (and thus \( A_P > 1 \)) can occur. This is physically incorrect and illustrates, that a simultaneous recording of both, the boiler operation and the precipitator operation and a logical linkage between both signals is necessary.

To characterise the contribution of the combustion plant to the total air pollution, an inspection period of one year (typically described by 8760 h) is commonly used thus describing the year-to-year availability. However, shorter periods such as the day-to-day availability (described by 24 h) are also of interest, since a low day-to-day availability may cause unacceptable local and momentary air pollution.

2.2. Definition of the combustion uptime

For the characterisation of biomass combustion plants, the determination of the uptime and downtime of the combustion and the precipitator is related to uncertainties and needs further clarification. The combustion device exhibits a high thermal inertia resulting in a relevant time-delay of the heat output and the release of flue gases, both after start-up and after shutdown of the boiler. Thus, the release of flue gases is not directly coupled to the fuel input only, but additionally influenced by the air flow through the boiler. The air flow on his part is primarily controlled by the forced draught fans for the combustion air (typically divided into primary and secondary air) and additionally influenced by the flue gas fan. Due to the thermal inertia and the independent control of fuel input as well as primary air, secondary air and flue gas fan, a meaningful determination of the combustion uptime is essential to enable a comparison of different combustion plants. Therefore, a detailed definition of the uptime is needed. Upon recording of the combustion operation, two cases are differentiated.

2.2.1. Case 1

For plants with a short follow-up time for the flue gas fan (here defined as being less than 15 min) after the shutdown of the primary air supply, the combustion unit uptime is determined by method 1 as follows:

\[
t_C(1) = \text{time during which the primary air fan determining the combustion performance is running}
\]

(6)

Since it does not take shutdown periods with deactivated primary air fan into account, its applicability needs to be limited on plants with short follow-up time of the flue gas fan. If this condition is fulfilled and the combustion uptime is significantly longer than the combustion downtime (which applies in the case of a good operation mode), method 1 provides a meaningful assessment of the availability as shown by a detailed evaluation of data from seven plants, which were monitored during two years.

2.2.2. Case 2

For plants with long follow-up time for the flue gas fan of more than 15 min, method 1 can cause an unacceptable over-estimation of the availability, since the ESP ontime can be counted during periods at very high oxygen content in the flue gas and thus without relevant heat production. In this case, the availability is determined and proven not only with method 1 but additionally by method 2 as follows:

\[
t_C(2) = \text{time during which the flue gas fan is running and the oxygen content in the flue gas is below a limiting value of e.g. 18% or 19% volume fraction}
\]

(7)

This method enables the appropriate recording of the dust loading over the overall uptime (including the boiler operation with deactivated primary air fan and relevant flue gas production).
However it also exhibits two disadvantages. Firstly, a reliable oxygen measurement needs to be available which is not always safely guaranteed with the lambda sensors used for the boiler control systems. Secondly, those plants are not correctly and often too optimistically evaluated whose oxygen level stays below the limiting value for a long time period during the shutdown phase with deactivated primary air supply but activated flue gas fan. The reason therefore is found in the fact that this phase is misleadingly counted as combustion uptime even though the useful heat output practically equals zero. If the ESP is running during this follow-up period, the availability is hence artificially increased. Therefore, the single control by \( t_{C(2)} \) is not sufficient for which reason in case 2 the availability needs to be determined by methods 1 and 2, hence \( t_{C(1)} \) and \( t_{C(2)} \) need to be determined.

### 2.3. Definition of the precipitator uptime

In order to determine the uptime of an electrostatic precipitator, the signals measured for voltage and current may be considered. Today, the voltage is often used to identify disturbances, but its threshold value is generally defined at a quite low level, e.g. 5 kV. This is not sufficient to monitor the availability since the precipitation performance is thereby not ensured. Based on the theoretical behaviour of ESPs, it is recommended to introduce threshold values for both, the voltage and the current. This implies that upon acceptance inspection the reference values of the precipitator need to be determined according to Table 1.

Fig. 3 displays the ESP operation regime with a characteristic current–voltage curve. The admissible operating range of the example can be assumed due to four reference points of gravimetric particle measurements. In addition, the theoretical progress of the particle concentration in the clean gas is calculated by application of the ESP theory as introduced e.g. by White in Ref. [13] representing interim values in Fig. 3. From this information, the theoretically allowable operation regime, in which the emission limit value is expected to be met based on the ESP theory, is derived. The graph illustrates the typical behaviour of an ESP and shows that the current may decrease significantly more than the voltage to comply with the emission limit value.

Table 2 summarises the main causes for malfunctions that arose during the study and need to be differentiated from admissible operating points. Considering the examples in Fig. 4, this is easily possible since the voltage drops significantly, while in Fig. 5 the current drop is less distinct and the definition of a limit between operation and malfunction is more difficult.

The operation regime in Fig. 3, however, shows that the characteristic behaviour of the response curve generally enables a clear differentiation between operation and malfunction for threshold values of 60% and 30% for the voltage and current, respectively. Hence these thresholds are introduced as illustrated in Fig. 6. It is mostly possible to act on the assumption that upon exceeding of these threshold values precipitation is ensured. This hypothesis was confirmed by means of an impact analysis of the threshold values for the seven investigated ESPs.

Another critical factor for the monitoring is the guarantee that the precipitator uptime is only counted during the combustion uptime. It therefore needs to be ensured that the signals of the combustion unit and the precipitator are simultaneously recorded and that the data evaluation considers a respective logical link between these signals. To illustrate this, the example shown in Fig. 1 refers to an ESP operation with a simultaneous stop of the primary air fan and the ESP. This can be identified by the increasing dust emissions after the ESP uptime and it refers to an operation mode which is uncritical to evaluate the availability. However, a follow-up time of the ESP after the shutdown of the primary air fan enables to reduce the dust emissions in the period between the shutdown of the primary air fan and the shutdown of the flue gas fan. This concept is therefore commonly applied and the ESP is then either shutdown after the considered time delay or — if achieved earlier — when the flue gas temperature reaches the threshold value. For such applications, the ESP operation is not allowed to be counted as uptime while the combustion is counted as down (which in Fig. 1 is true for the combustion uptime case 1), as this leads to an incorrect and over-estimated availability enabling theoretical values of greater than 100%.

Besides, possible bypass lines of the ESP need to be monitored and the precipitator operation needs to be evaluated only at closed bypass.

### 3. Experiences in practical operation

#### 3.1. Year-on-year availability

A final evaluation of the seven investigated combustion plants is performed based on the year-on-year availability. The results are based on the definition of case 1 introduced in chapter 2.2.1. Fig. 7 displays the distribution of the relative downtime of the ESPs indicated as precipitator unavailability, and the availability accordingly, classified into the various operating modes. Plant 5 did not exhibit malfunctions and achieves an availability of more than 98% in both evaluated years despite appropriate controlling. Plants 1 and 7, in contrast, exhibited in one respective heating period malfunctions in the dust removal device which was repaired only after several days. In case of a combustion unit uptime of 2400 h per year, the availability is decreased by 1% for a one-day malfunction. Consequently, the downtime due to

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**Table 1**

Reference values determined upon acceptance inspection.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle concentration (standardised)</td>
<td>( c_m )</td>
<td>mg m(^{-3})</td>
</tr>
<tr>
<td>ESP voltage</td>
<td>( U_{ref} )</td>
<td>kV</td>
</tr>
<tr>
<td>ESP current</td>
<td>( I_{ref} )</td>
<td>mA</td>
</tr>
</tbody>
</table>

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**Fig. 3.** Operation regime of an electrostatic precipitator normalised with reference values. The measured current–voltage curve is illustrated by a blue line. The particle emissions were measured at four operation points (at 11% \( O_2 \) volume fraction). The calculated particle concentration (for a precipitation efficiency of 90% and a reference particle level of 10 mg m\(^{-3}\)) is illustrated by iso-lines. In the upper right corner, the reference point is denoted. The green area depicts the admissible operating range due to theory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
malfunctions for several days results in an insufficient availability for plants 1 and 7.

In the case of plant 2, false alarm signals of the ESP repeatedly appeared upon start-up of the combustion unit in the first operating year. During the evaluations, the problem was corrected by updating the software and, hence, a much higher availability was achieved in the second year.

### 3.2. Influences of part-load operation, start-up procedure and ESP temperature

The start-up of the combustion unit can lead to higher emissions of unburnt gases and particulate matter. Therefore, it is essential that the ESP is in operation during these phases. Hence, additional evaluations were performed to investigate the day-to-day availabilities and the influence of part-load and start-ups. This information is of specific interest for both, plant operation and air pollution control strategies, since part-load operation and frequent start-up of the combustion unit can potentially cause downtime of the ESP due to insufficient temperature and/or due to a time delay of the ESP start. Consequently, the results were classified by application of the minimum requirements for the plant operation as defined by the quality management (QM) system for automated biomass combustion plants [14]. For the investigated combustion units, this corresponds to a minimum combustion uptime of 12 h per day and daily average heat load of more than 15%–40%, depending on the system configuration.

A detailed evaluation showed that the number of start-ups influences the availability only in the case of a few plants. In particular, a relevant influence of the number of start-ups occurred in cases where the ESP was operated with a start delay. Otherwise, the compliance with the operating temperature had a much higher influence on the availability thus emphasising the importance of good thermal insulation and optional ESP pre-heating. If the operating temperature is conserved and there is no start delay, the number of start-ups hence influences the availability only marginally. Since the ESP downtime during start-ups is accounted for in the availability, a provision for a minimum availability

<table>
<thead>
<tr>
<th>Malfunction</th>
<th>Cause</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage drop</td>
<td>Blocked dust bunker (bridge formation)</td>
<td>Fig. 4</td>
</tr>
<tr>
<td></td>
<td>Conductive isolators (condensation, contamination)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broken discharge electrode or scraper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Damaged high-voltage supply line or isolator</td>
<td></td>
</tr>
<tr>
<td>Current drop</td>
<td>Contaminated discharge electrode</td>
<td>Fig. 5</td>
</tr>
<tr>
<td></td>
<td>Suppression of the discharge current due to dust loading</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 4](image-url). Examples for voltage drop. Left: Short-circuit due to a blocked dust hopper. Right: Conducting isolators during the start-up phase.

![Fig. 5](image-url). Examples for current drop. Left: Increased contamination of the discharge electrodes. Right: Suppression of the discharge current due to dust loading of the flue gas.

![Fig. 6](image-url). Operation regime of an electrostatic precipitator as described in with threshold values for the voltage and the current introduced in the present investigation.
4. Conclusions

The investigation on seven automated biomass combustion plants shows that the availability defined as uptime of the precipitator divided by the uptime of the combustion unit is in principle a well suited criterion for the monitoring of electrostatic precipitators. In order to determine the availability appropriately, uniform definitions concerning the combustion uptime and the precipitator uptime are however essential. Furthermore, a simultaneous recording of the data of the combustion unit and the ESP as well as of possible bypass lines is required. Since these signals are available in the control devices from where they can be made accessible for the monitoring, the method can be applied at reasonable cost.

The signals needed as minimum information are the status of the primary air fan for the combustion uptime and the voltage and the current of the ESP for the precipitator uptime. The current is an additional signal compared to often applied control concepts based on voltage only. To determine the precipitator uptime, threshold values of 60% for the voltage and 30% of the current compared to the reference values determined during the acceptance inspection are proposed.

The evaluation shows that the information on the primary air supply is a suitable signal for the combustion uptime unless the primary air fan is deactivated and the flue gas fan continues its operation for a relevant delay time of e.g. more than 15 min. If the flue gas fan operates for more than 15 min without primary air supply, it is recommended to additionally record its signal in combination with an oxygen measurement to determine a second availability. In this way, long shutdown phases and the maintenance of the fire bed without primary air are not treated preferentially.

The practical enquiry reveals that malfunctions and maintenance issues that are not immediately repaired are primarily responsible for high un-availabilities. In the case of three of the seven plants, malfunctions decrease the availability in one operating year to below 90%. In all other cases, the availability is greater than 90%. Two and three plants achieve an availability of more than 95% in the first and second year, respectively.

Besides the immediate repair of malfunctions, it is decisive to keep a permanently high precipitator operating temperature or to quickly achieve the starting temperature. The availability is contrarily decreased with time delayed ESP start leading to a significantly reduced availability in the case of a high number of start-ups.

The evaluation confirms the benefit of a plant monitoring on the basis of data from the control systems. Since malfunctions are primarily responsible for high emission values, it is assumed that requesting a proof of availability of 90% for existing plants already has a high impact and will ensure a relevant improvement of the plant operation._availabilities of above 95% contrarily seem achievable for new plants.

Acknowledgements

This investigation was funded by the Swiss Federal Office of Energy (SFOE), which is gratefully acknowledged. The work was supported by the providers of the combustion units, i.e. Mawera GmbH, Müller AG, and Schmid AG energy solutions, and the providers of the electrostatic precipitators, i.e. APF GmbH, BETH Filter GmbH, Meisterfilter AG, and Scheuch GmbH. Experience on plant operation was provided by Ardens GmbH and the plant owners provided access to their combustion units, which is gratefully acknowledged.

Nomenclature

<table>
<thead>
<tr>
<th>Roman letters</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>availability (–)</td>
</tr>
<tr>
<td>Ap</td>
<td>precipitator availability (–)</td>
</tr>
<tr>
<td>I</td>
<td>current (A)</td>
</tr>
</tbody>
</table>
\[ t \] inspection period (h)
\[ t_C \] uptime of the combustion unit during the inspection period (h)
\[ t_P \] uptime of the precipitator during the inspection period (h)
\[ t_P^{(\text{down})} \] downtime of the precipitator during the inspection period (h)
\[ U \] voltage (V)
\[ UA \] unavailability (–)

**Indices**
- \( C \): combustion unit
- \( P \): precipitator
- \( \text{down} \): downtime
- \( (1) \): case 1
- \( (2) \): case 2

**Abbreviations**
- ESP: electrostatic precipitator
- PM: particulate matter
- QM: quality management

**References**


