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Research paper

2-Year field operation monitoring of electrostatic precipitators for residential wood heating systems

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ABSTRACT

To assess the applicability of electrostatic precipitators (ESP) for particulate matter (PM) emission reduction in old residential wood heating appliances comprehensive field tests with accompanying ESP operation monitoring and dedicated emission measurement campaigns have been performed in the region of Graz (AT). Three OekoTube ESPs were thereby tested during the heating seasons 2014/2015 and 2015/2016 at different sites with rather old respectively high-PM-emission wood burning devices. Before installing the ESPs at the field testing sites they were checked in the lab regarding functionality and precipitation efficiency. The evaluation of the plant monitoring data collected during the field tests revealed high seasonal ESP availabilities between 80.2% and 97.7%. Dedicated test runs with emission measurements at the different testing sites showed high precipitation efficiencies which were well comparable with those gained during preceding lab-tests. Based on these results it can be concluded, that ESP models like the OekoTube are suitable as retrofit units in old appliances and have due to their high availability and particle precipitation efficiency the potential to contribute to a significant reduction of particulate matter emissions from old residential wood burning systems.

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1. Introduction and objectives

According to the European Biomass Association (AEBIOM) more than 50% of the bioheat produced in the EU28 is related to residential heating [1]. Logwood stoves, logwood boilers, pellet boilers and wood chip boilers are thereby the most common heating technologies. However, biomass burning in stoves and outdated boiler systems is increasingly criticized as a major source of particulate matter (PM) emissions. With the introduction of the EU directive 1999/30/EC, which limits among others PM_{10} concentrations in the ambient air, it had to be recognised that in many European regions the related limit value is more frequently exceeded than allowed. As the main sources for PM emissions traffic, industry and domestic heating have been identified. It has furthermore been shown that the contribution of residential biomass combustion to the total PM emissions of the residential heating sector exceeds 80% in some European regions.

Previous research projects dealing with this problem have revealed that especially old wood burning appliances are responsible for the high PM emissions of the residential heating sector [2–4]. An appropriate solution to the problem would be to exchange old appliances by modern low-emission systems. However, since owners of outdated heating systems cannot be forced to shift to newer ones and since also incentives for replacing old boilers did up to now often not show the desired effect, the application of precipitators for PM emission reduction seems to be the economically most feasible short-term approach.

The city of Graz (AT) is located in a typical basin-shaped region with a low exchange of air especially during winter time. This leads to accumulation of PM in the ambient air and consequently to more frequent exceedances of the PM concentrations allowed. A broad application of particle precipitators in old wood burning appliances could therefore, among others, be one appropriate countermeasure against air pollution. Recent work has shown that especially electrostatic precipitators (ESPs) are suitable for PM emission reduction from residential biomass combustion appliances [5]. However, former research projects such as the ERA-NET Bioenergy project FutureBioTec [6] have also revealed that many ESPs presently available are not designed for a long-term operation at the harsh operation conditions prevailing in old logwood boilers and stoves which are characterized by a flue gas with insufficient burnout as well as high soot and organic aerosol emissions. The reason

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therefore is that presently ESPs are mainly developed with the aim to safeguard the keeping of the stringent dust emission limits for pellet and wood chip combustion defined in the 1. BImSchV in Germany (federal emission control act [7]). Consequently, they are designed for much better burnout conditions than prevailing in old appliances. Moreover, no reliable long-term performance data regarding ESP operation are available.

Thus, the overall objectives of the work presented has been to identify an ESP technology suitable for the application with old high-emission wood burning appliances and to test it over two heating seasons within field tests in the region of Graz. These field tests should be accompanied by a comprehensive monitoring and measurement program.

2. State-of-the-art of particle precipitation devices for small-scale biomass combustion systems

In medium and large-scale biomass combustion processes the application of electrostatic precipitators (ESP) or baghouse filters for fine particulate emission control has been state-of-the-art for many years. With steadily decreasing emission limits regarding dust emissions from small-scale biomass combustion systems also the development of filters for such applications has been intensified during the last decade. In 2011 a comprehensive review on PM emission reduction technologies for small-scale wood burning appliances has been published by IEA Bioenergy Task 32, Biomass combustion and co-firing [8]. According to this study, ESPs represent the most promising options while other dust emission reduction technologies (filtering devices, sprayers, condensers and oxidation catalysts) do not reach the anticipated long term performance and emission reduction efficiency. It is worth to mention that generally two different ESP concepts could be identified. One concept is designed for an application as an add-on at the top of the chimney. This concept bears the big advantage that no space inside the building is needed for the ESP which makes it easier to apply as a retrofit unit. On the other side the filter is exposed to the ambient and therefore a robust design is needed. The second concept foresees an application of the filter between the stove or boiler and the chimney. This concept is more space demanding and, in case of stoves, to be assessed as problematic since the ESP must then be mounted in the room where the stove is located (typically the living room).

According to the IEA survey three ESP technologies, the ESPs Zumikon (from Rüegg Cheminée AG, Switzerland), the Airbox ESP (from Spartherm Feuerungstechnik GmbH, Germany) and the ESP Oekotube (from the company OekoSolve, Liechtenstein) have already been in the market in 2011.

At the same time a Danish study [9] evaluated the application of particle precipitation devices in connection with old-technology (high emission) stoves. Five technologies were tested under controlled conditions in the laboratory and subsequently by mounting them on appropriate stoves in private homes. The technologies were the ESPs Zumikon, Airbox and CleanAir ESP (from Applied Plasma Physics AS, Norway) as well as oxidation catalyst technologies from MoreCat GmbH, Germany and ECOXY AS, Norway. The main conclusion of this study was that all the technologies had a reducing effect on the emissions, but their efficiencies were low. The authors concluded that it seems to be much more environmentally sustainable to work for a replacement of old wood stoves and boilers with new low-emission systems.

In a German study [10], multi-pipe electrostatic precipitators for boilers from Spanner RE^2, Germany (type "SFF20" or SFF50″), a chimney-top model from the Norwegian company APP and a Zumikon ESP fitted into flue the gas duct between furnace and chimney were tested over a complete heating season in a field trial. Long-term combustion test stand trials were additionally conducted. Average particle precipitation rates between 12 and 80% were achieved and the authors of the study pointed out that before practical application, some operational problems and malfunction risks of the prototypes have to be solved to make their operation robust enough for a broad market application.

One general finding of all studies performed at this time was that additional R&D was needed to make the different ESP systems more reliable and especially also applicable for old residential wood heating appliances.

In Germany, the Technology and Support Centre in the Centre of Excellence for Renewable Resources (TFZ) and the Deutsches Biomasseforschungszentrum (DBFZ) jointly organize an annual expert meeting regarding dust precipitation devices for small-scale biomass appliances ("Abscheider Fachgespräch") at which an international update on actual filter technologies as well as current developments is provided. In 2015 and 2016 [11,12] these events have shown that especially ESPs are presently under development or already offered on the market by a number of manufacturers. Most of the applications are mounted in between the boiler and the chimney and generally the target application of the filters are modern wood chip, pellet and logwood boilers and not old wood burning appliances characterized by very high emissions of soot and organic particles. Moreover, R&D on some other concepts (filtering precipitators, oxidation catalysts for stoves) is ongoing but these systems are still in the development stage.

3. Approach

3.1. Selection and description of the ESP technology

At first, an appropriate ESP technology, which is capable to operate at the harsh conditions of old biomass burning appliances had to be identified. Test runs with four different ESPs performed within the former Austrian R&D project BM-PM-Filtertest (funded by the Austrian Climate and Energy Fund) have shown that the availability and precipitation efficiency of ESPs may significantly suffer from high concentrations of organic aerosols and soot in the raw gas which lead to problems and failures with ESP operation. In this project, the ESP OekoTube of the company OekoSolve (CH) has been identified as reliable ESP, which can, due to its specific design concept regarding isolator and electrode operate at poor burnout conditions of the biomass boiler resp. stove to which it is connected and achieves very good precipitation efficiencies. Moreover, the OekoTube at this time was the only reliable system, which can easily be applied as retrofit unit, since it is mounted at the top of the chimney. For these reasons, the OekoTube technology was selected for the field tests.

The OekoTube is a typical tube-type electrostatic precipitator. The unit consist of a T-fitting (9 in Fig. 1) and a metal tube which are mounted on top of the chimney (chimney-top application). It uses the inner surface of the chimney or in case of a non-metallic chimney an extended metal tube (as shown in Fig. 1) as precipitation electrode. A 1.6 m long electrode (10) thereby extends downwards in the chimney and is connected with an insulator (5) positioned outside the flue gas stream. The electronic circuit and the control unit (2) are mounted outside and protected with a cover (4) against weathering. The power consumption of the ESP amounts to 20–30 W during operation and the high-voltage power applied is usually in the range of 15–30 kV. The OekoTube is applicable for biomass combustion systems up to 40 kW.

The OekoTube is equipped with a temperature sensor (7 in Fig. 1) which measures the flue gas temperature. Based on the exceedance of a predefined temperature the control system identifies the start-up phase of the heating system and automatically

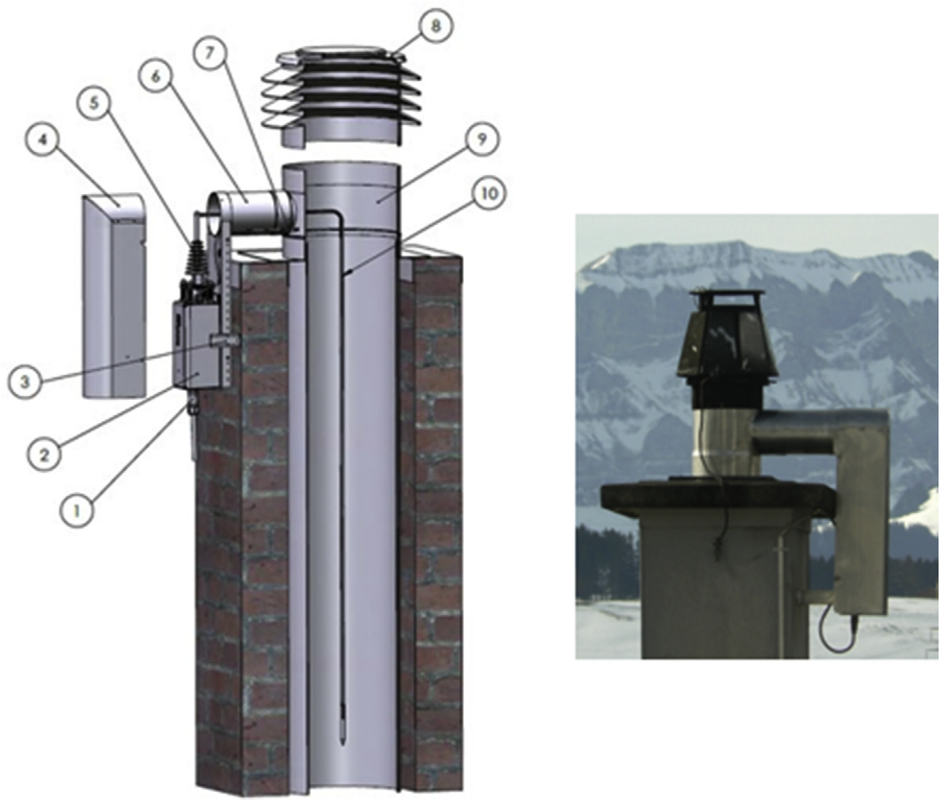

Fig. 1. Scheme (left) and installation example (right) of the ESP OekoTube. Explanations: 1 … power plug; 2 … control unit; 3 … mounting angle; 4 … protective cover; 5 … high voltage insulator; 6 … connecting tube; 7 … temperature sensor; 8 … chimney crest (optional); 9 … T-fitting; 10 … electrode; source: www.oekosolve.ch.

activates the ESP. In turn, when the flue gas temperature drops below a certain predefined limit, the ESP is turned off again. These temperature set-values are configured in the control software before the first ESP start with respect to the expected flue gas temperatures and can be modified also during operation. Also the installation situation of the thermocouple is thereby considered since its readings may be influenced by cold radiation from the metal tube which is exposed to the ambient.

One advantage of the system, especially for integration in existing heating systems, is its positioning at the top of the chimney which demands for no additional space inside the building. As the precipitator has no automated cleaning system, ESP cleaning is carried out by the chimney sweep during his visits. The cleaning interval thereby depends on operating time and type of furnace. However, as a rule of thumb one additional chimney cleaning per year compared to operation without the OekoTube has to be considered.

Within the project presented also one so-called OekoTube inside has been tested. The ESP technology is the same as for the chimney-top model but the OekoTube inside is designed for an installation in between the heating device and the chimney. The only restriction that has to be taken into account is a maximum flue gas temperature of 200 °C during permanent operation.

3.2. Selection of appropriate field testing sites

Identically constructed ESPs have been delivered by OekoSolve and have at first been tested at the testing facilities of BIOS BIOENERGIESYSTEME GmbH to check their principal functionality and to gain benchmark values for the dust precipitation efficiency.

These ESPs should then be applied during a comprehensive field testing campaign in the heating season 2014/2015. For the second field testing campaign (heating season 2015/2016) one ESP has been replaced by an OekoTube inside.

Candidates for the field testing campaign have been screened and the most suitable testing sites have been selected. The aim was to select appliances which are suspected to show high particulate emissions and which are typical for the Graz region. Moreover, easy accessibility of the chimney for field measurements was a relevant requirement. Finally, private buildings with the following heating devices have been chosen:

- Site 1: logwood boiler; year of manufacture: 2010; nominal boiler capacity: 25 kW. During the field test season 1 it was equipped with the OekoTube and during field test season 2 with the OekoTube inside technology. Fig. 2 shows the OekoTube and the OekoTube inside installed at site 1.
- Site 2: logwood boiler, year of manufacture: 1997; nominal boiler capacity: 18 kW (tested during field test year 1). The ESP tested at this plant was moved to site 3 during the second testing season.
- Site 3: logwood stove, year of manufacture: 2009; nominal capacity 8.4 kW.

As an example for these installations the OekoTube mounted at the top of the chimney at site 2 is presented in Fig. 3.

3.3. Performance of field testing and operation monitoring

At these testing sites the ESPs have been continuously operated over the whole heating seasons and relevant ESP operation data have been recorded and evaluated at least once a week. Moreover,

Fig. 2. OekoTube (left) and OekoTube inside (right) mounted at site 1.

Fig. 3. OekoTube mounted at site 2.

two emission measurement (gaseous and particulate emissions) campaigns have been performed per testing site and per heating season.

At the end of the first heating season (2014/2015) the results have been evaluated and possible measures for adaptations respectively optimizations have been communicated to the manufacturer OekoSolve. The modifications have then been implemented for the field testing phase 2 during the heating season 2015/2016.

4. Methodology

4.1. Performance of pre-tests in the lab

In order to check the performance of the three ESPs delivered and to gain reference values regarding their precipitation efficiencies for TSP (total suspended particulate matter = total dust) and PM_1 (particulate matter with a diameter smaller than 1 μm = fine PM), at first the ESPs have been tested in the lab under controlled operation conditions of the boiler applied. Therefore, a state-of-the-art pellet boiler (Windhager BioWIN 210, nominal boiler capacity: 21 kW) has been connected to the ESPs.

In order to simulate the later field operation on top of the chimney, a tube with controlled electric trace heating was installed between the boiler and the ESP, so that a flue gas temperature of about 100 °C has been achieved at ESP inlet. This tube also contained an isothermal sampling section right at ESP inlet, where TSP and PM_1 measurements upstream the ESP have been performed. At ESP outlet a second tube was installed for measurements downstream the ESP and for connection to the chimney. This tube has also been equipped with electric trace heating in order to keep the temperatures constant and to avoid possible influences by the condensation of organic vapours on the measurement results. In Fig. 4 the experimental setup is schematically described.

The boiler was operated with A1-quality wood pellets (according to EN ISO 17225-2) at three different operation modes, which have been adjusted by appropriate manipulation of the process control settings regarding primary air supply, secondary air supply

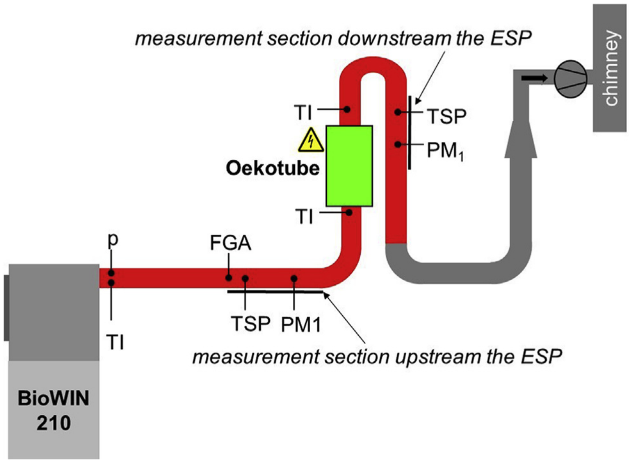

Fig. 4. Scheme of the test stand setup. Explanations: Red colored tubes are equipped with electric trace heating; PM_1 … Berner-type low-pressure impactor measurement; TSP … total dust measurement; FGA … flue gas analysers (O_2, CO, OGC); TI … flue gas temperature measurements; P … chimney draft measurement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and overall excess air ratio.

- Normal operation
- Operation at conditions causing high emissions of organic aerosols to simulate the behaviour of an old logwood boiler
- Operation at sooty conditions to simulate the behaviour of a logwood stove.

The contents of O_2 (paramagnetic sensor), CO, CO_2 (ND-IR sensor) and organic gaseous compounds (FID) in the flue gas were measured and on-line recorded. The particulate emissions have been measured in parallel upstream and downstream the ESP. A total dust measurement equipment according to VDI 2066 and a Berner-type low-pressure impactor (BLPI) to determine the PM_1 emissions where therefore applied. From these parallel measurements the total dust and the PM_1 precipitation efficiencies were calculated. Moreover, relevant ESP and boiler operation data have been recorded on-line and evaluated.

4.2. Field monitoring

To facilitate a continuous observation of the ESP performance during the field tests, relevant operation data were logged by data acquisition systems installed at each site in 5 s intervals. Each day the data were automatically submitted via GSM to the office of BIOS BIOENERGIESYSTEME GmbH. The data received were evaluated at least once a week in order to detect possible system failures and to decide if appropriate countermeasures have to be taken. The data recorded and evaluated were:

- Operating state of the ESP [ON/OFF]
- ESP voltage [kV]
- ESP current [μA]
- Flue gas temperature at ESP outlet [°C]
- Temperature in the ESP control box [°C]
- Error messages regarding the control hardware
- Error messages indicating operation failures

4.3. Dedicated measurement campaigns

At each ESP at least two dedicated testing campaigns have been performed – one at the beginning and one in the second half of the heating season. Thereby the gaseous and particulate emissions downstream the ESP were determined with the same equipment as applied during the lab tests. To enable a correct measurement downstream the ESP, a "measurement section", which is a tube with appropriate sampling ports, was connected on top of the ESP. In Fig. 5 the measurement setup is presented.

As there has been no possibility to measure the PM emissions upstream the ESP, the PM precipitation efficiency was determined with downstream measurements at two successive days; one day with and one day without ESP operation. It has been taken care that the framework conditions during these two days regarding outside temperatures, operation cycles of the biomass combustion systems and duration of the test runs were comparable.

At the logwood boilers (site 1 and 2) consecutive TSP measurements have been performed in order to cover the whole operation cycle of the boiler including the ignition phase, the main combustion phase and the charcoal burnout phase. At least three short-term impactor measurements (duration of some minutes) have been carried out during the distinct combustion phases to determine the PM_1 emissions. At the stove (site 3) one TSP measurement per batch has been performed and at least three impactor measurements were made within one test run day during the main combustion phases of selected batches.

From these data the particle precipitation efficiencies were calculated. However, the main aim of these measurements was to check if relevant changes regarding the precipitation efficiencies in comparison with the lab tests and over the heating seasons occur rather than to get exact data on particle precipitation.

5. Results

5.1. Results of the lab tests performed

The aim of the preliminary lab tests has been to check the ESPs before installing them in the field and to gain data regarding particle precipitation efficiencies under well-controlled lab conditions

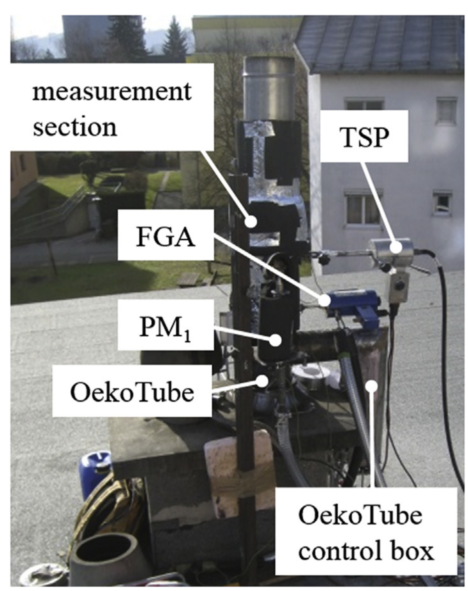

Fig. 5. Measurement setup during the dedicated field measurement campaigns.

which can be compared with results from the field tests.

The ESPs generally could be taken into operation without problems. During the two test weeks performed with each ESP also no relevant failures occurred.

At boiler standard operation conditions, which were characterized by a good gas phase burnout with CO emissions below 60 mg MJ^{-1} (related to the NCV of the fuel) and low PM emissions at ESP inlet (total dust emissions below 10 mg MJ^{-1}) all ESPs showed precipitation efficiencies of 88–93% for total dust and of 88–97% for PM_1. The ESP voltage was slightly below 30 kV and the ESP power between 10 and 16 W. Based on experience from former projects [6] this has been an expected result.

The boiler operation which aimed at a high amount of organic aerosol emissions was characterized by very high CO emissions (around 4000 mg MJ^{-1}) and high oxygen contents the flue gas (up to 18 vol.-% dry basis). Total dust emissions at ESP inlet were in the range between 35 and 50 mg MJ^{-1}. At these conditions precipitation ratios of about 90% could be achieved for total dust and PM_1. The ESP voltage was at about 30 kV and the ESP power between 4 and 10 W. Compared with former experience these values regarding PM precipitation must be assessed as very good.

During the sooty operation the pellet boiler was operated at very low excess air ratios (about 4 vol.-% O_2 in the dry flue gas) resulting in increased CO emissions (up to in average 2000 mg MJ^{-1}) and high total dust emissions of up to 50 mg MJ^{-1}. The ESP voltage was at about 30 kV and the ESP power between 3.4 and 8.0 W. For PM_1 a very good precipitation efficiency of up to 96% could be determined. However, regarding total dust at some measurements the emissions downstream the ESP were even higher than upstream the ESP which can be explained by the high soot emissions. Soot particles form rather loose dendritic agglomerates on the electrodes and the filter walls which can easily be re-entrained with the flue gas and cause emissions of rather big (even some millimeter in diameter) soot flakes. After the flue gas exits the chimney these flakes are immediately precipitated by gravitational forces and do not remain in the ambient air.

Summing up, from the lab tests it could be concluded that the ESPs were functional and showed the expected particle precipitation efficiencies. Moreover, the data acquisition systems have been tested and finally the ESPs were released for the field testing.

5.2. Results of the ESP monitoring at the field testing sites

Field monitoring took place over two heating seasons (2014/2015 and 2015/2016). The data gained have been continuously evaluated in order to regularly check the ESP performance.

As an example in Fig. 6 a typical ESP operation cycle from one day at site 1 is presented. Due to the increase of the flue gas temperature above 35 °C the ESP control identifies the ignition phase of the logwood boiler and turns on the ESP. Immediately, the ESP voltage and power increase. In the following the ESP control tries to maximize the ESP power by increasing the voltage. In the case presented the targeted power of 15 W is reached after 15 s. If the voltage is increased too much, sparkovers can occur. In this case the power is reduced and then increased again and a failure message is sent. The occurrence of such sparkovers is accepted in order to achieve a high average ESP power and therefore a high precipitation efficiency.

The precipitation efficiency of the ESP depends, besides the voltage and power also on the flue gas temperature and the particle load at ESP inlet. From Fig. 6 it can be derived that during the ignition and the main combustion phase (can be identified by the higher flue gas temperatures) voltage and power remain at about the same level of about 25 kV and up to 16 W respectively. The temperature decrease in the second half of the operation cycle indicates the charcoal burnout phase. As soon as the temperature drops below a certain level, the ESP power decreases. This is related to the decrease of the electric conductivity of the flue gas with decreasing temperatures. At a flue gas temperature of 30 °C (set value for this ESP) the ESP control desires the end of the heating cycle and turns off the ESP.

In Fig. 7 the trends regarding the ESP operation parameters during January and February 2015 at site 1 are presented. The logwood boiler at site 1 was typically operated once a day for in average 7 h, usually starting the operation cycle in the late evening to load the buffer storage of the heating system during nighttime. From Fig. 7 it can be revealed that the voltage (black line) always reaches maximum values between 25 and 30 kV which indicates a good precipitation performance.

At site 2 also a logwood boiler was operated and therefore, about the same operation cycles and operation behaviour as for site 1 were observed. However, at this installation very harsh operating conditions prevailed with flue gas temperatures at ESP inlet of more than 300 °C and, as the dedicated test runs have shown, high CO, OGC and PM emissions. This was one reason why at this plant the highest number of sparkovers and the lowest average voltage were detected (see Table 2). Moreover, the high flue gas temperatures after some weeks of operation led to the deformation of the electrode due to thermal tensions and the electrode had therefore to be replaced a by a more robust one with a cross-shaped cross

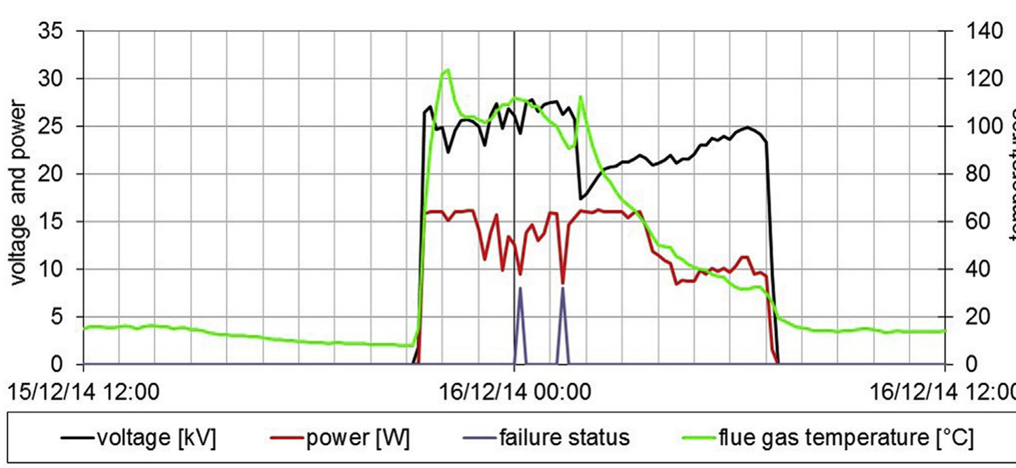

Fig. 6. Typical daily operation cycle of the ESP at field test site 1.

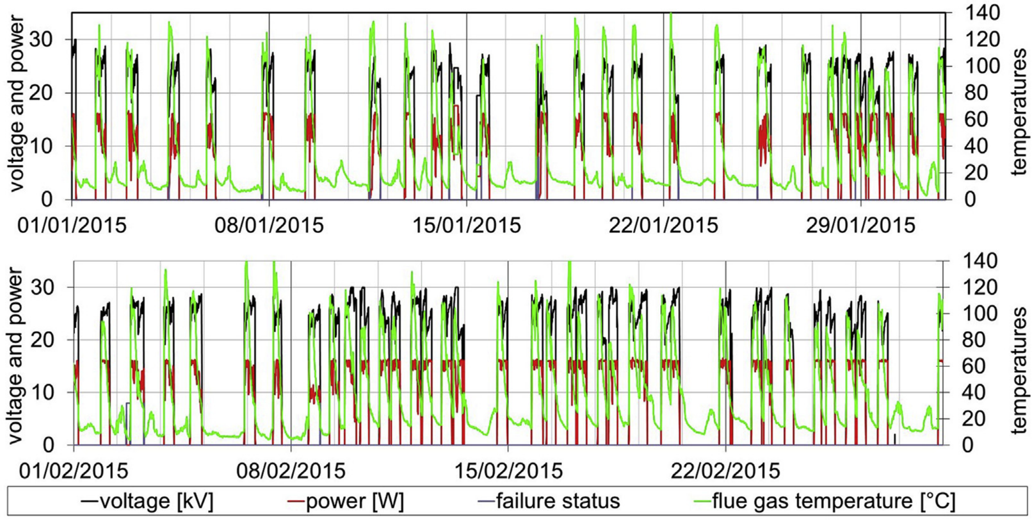

Fig. 7. Operation data of the ESP at field testing site 1 during January and February 2015.

Table 1
Results of the evaluation of the ESP operation data at site 1.

		2014/2015 OekoTube	2015/2016 OekoTube inside
Field test period		12/11/2014–29/03/2015 3288 h	02/11/2015–31/03/2016 3624 h
Maximum possible operating hours	h	915.2	777.7
Number of operation cycles		121	133
Average duration of an operation cycle	h	7.53	5.77
ESP availability	%	97.7	81.2
Average voltage	kV	m: 24.3 *s: 4.3*	m: 21.4 *s: 5.2*
Average power	W	m: 13.5 *s: 3.8*	m: 8.2 *s: 6.5*

Explanations: m … mean value; s … standard deviation.

Table 2
Results of the evaluation of the ESP operation data at site 2 and 3.

		2014/2015 OekoTube site 2	2015/2016 OekoTube site 3
Field test period		01/12/2014–12/04/2015 3168 h	21/10/2015–17/04/2016 4320 h
Maximum possible operating hours	h	573	1360
Number of operation cycles		137	368
Average duration of an operation cycle	h	4.15	3.70
ESP availability	%	81.7	80.2
Average voltage	kV	m: 18.1 S *s: 5.9*	m: 26.1 *s: 8.8*
Average power	W	m: 10.0 *s: 6.6*	m: 6.6 *s: 4.9*

Explanations: m … mean value; s … standard deviation.

section. This was the only failure occurring over the field testing periods with all ESPs which demanded for a revision by the manufacturer.

All data collected during the two heating seasons have finally been evaluated in order to determine the availability of the ESPs as well as the average ESP voltage and power. Therefore, the maximum possible operation hours have been calculated from the periods where the ESP signal indicated operation ("ESP ON"), i.e. the period at which the flue gas temperatures were above the operation threshold values. The availability is calculated by the operation hours of the ESP divided by the maximum possible operating hours. The mean values and standard deviations of the ESP voltage and the ESP power were calculated over all operation cycles (periods between turning on and off the ESP). Moreover, the number of ESP operation cycles and the average duration of an operation cycle has been evaluated. The respective data are presented in Tables 1 and 2.

In Table 1 relevant data collected for the ESP operated at site 1 are summarised. During the first heating season the chimney-top version of the OekoTube has been tested. The detailed evaluation of the data has revealed that at each time when the boiler was taken into operation also the ESP was turned on. Due to a low number of operation failures (sparkovers), which led to short-term shut downs of the ESP, a high availability of 97.7% could be reached. The average voltage (24.3 V) is quite close to the maximum voltage of 30 kV and the average power (13.5 W) is within the range determined during the lab-tests (10–16 W). It has been noticed that dust deposits on the electrode and the walls caused a slight but gradual decline of the voltage and the current, however, after an intermediate cleaning by the chimney sweep at the end of February 2015 the initial values could be reached again.

Due to the stable performance, the acceptable precipitation efficiency achieved, and because of the moderate flue gas temperatures at site 1 it was decided to replace the chimney-top OekoTube by an OekoTube inside for the second monitoring season. The idea was to gain additional experience with this model, which is in terms of precipitation technology identical with the chimney-top version but can be installed inside the building. The advantage are the lower installation costs (no crane is needed and no cable has to be laid to the roof top) provided that there is enough space for mounting the ESP between the boiler and the chimney.

The heating season 2015/2016 was characterized by a rather calm weather and therefore the maximum possible operating hours decreased from 915.2 in the preceding heating season to 777.7 h although ESP operation started earlier. Also the average duration of one operation cycle was lower. Compared with the chimney-top version of the OekoTube the availability of the OekoTube inside was with 81.2% lower but still acceptable. The main reason for the lower availability was that the maximum flue gas temperature of 200 °C was unexpectedly often exceeded which led to failures and short shutdowns. Also with the OekoTube inside one intermediate cleaning in the mid of February 2016 was sufficient to maintain a stable ESP operation throughout the whole heating season.

In Table 2 the results for the ESP installed at site 2 and site 3 are presented. During the first heating season it had been installed at site 2 but problems with the owner regarding access for the dedicated measurement campaigns have led to the decision to change to site 3 during the second heating season.

At site 2 an outdated logwood boiler was operated. Typical features of this boiler were very high flue gas temperatures at boiler outlet leading to temperatures up to more than 300 °C in the ESP and very sooty emissions. Analyses of dust samples taken after cleaning by the chimney sweep have revealed elemental carbon contents of 30–45 wt% (d.b.). Especially the high temperatures caused thermal deformations of the electrode and as a consequence of that massive sparkovers. Therefore, before the electrode was replaced by a more robust one, it sometimes took more than one attempt of the control system to reach stable operation. These effects are also the reasons for the lower availability (81.7%) and the comparably low average voltage that could be reached in comparison with site 1. However, as measured by these framework conditions, the availability achieved can still be assessed as acceptable. As already noticed at site 1 also at site 2 a gradual decrease of the ESP voltage and the ESP current over time occurred and one intermediate cleaning of the ESP by the chimney sweep was needed.

Before the heating season 2015/2016 the ESP has been moved from site 2 to site 3. There, a wood stove is operated as primary heating system, and as the data regarding the duration of an average operation cycle and the number of heating cycles confirm, the system was even more in operation than the logwood boiler in the year before. Logwood stoves typically show relatively high soot emissions and the average voltage (26.1 kV) and the average ESP power (6.6 W) reflect the results of the lab-tests at sooty conditions (30 kV and 3.4–8 W). High amounts of soot deposits on the ESP surfaces caused some problems during continuous operation and therefore the availability of the ESP at site 3 was with 80.2% in the same range as at site 2. Two intermediate cleanings by the chimney sweep were demanded at this site.

5.3. Results of the dedicated field measurement campaigns

At each testing site two dedicated measurement campaigns per heating season have been carried out to check the precipitation efficiencies of the ESPs. Therefore, measurements have been performed at two successive days, one with and one for comparison without ESP operation. It has been taken care that the framework conditions regarding the operation of the wood heating devices have been comparable during both days. The flue gas temperatures, the duration of the operation cycle and the O_2, CO and OGC contents of the flue gas have therefore been evaluated.

As an example for such a measurement campaign a test run performed at site 1 is presented in the following. In Fig. 8 the oxygen contents of the flue gas and the flue gas temperatures for two successive testing days are presented whereby the start of the test runs has been synchronized to gain a better comparability of the results. The average oxygen content of the flue gas over the whole test run amounted to 16.7 vol.-% dry basis (with ESP operation) respectively 17.3 vol.-% dry basis. The average flue gas temperatures at ESP were with 98.6 °C (with ESP operation) and 106.8 °C (without ESP operation) also in about the same range. The CO emissions were with in average 4750 mg m^{-3} during operation with ESP higher than during operation without ESP (3930 mg m^{-3}). The same is true for the OGC emissions (328 resp. 138 mg m^{-3} - all emissions related to dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2). Consequently, during operation of the ESP slightly worse burnout conditions prevailed than during the measurements without ESP operation.

Three consecutive total dust emission measurements have been performed. The total dust emissions varied during operation without ESP between 234.4 mg m^{-3} (during the ignition phase), 45.7 mg m^{-3} (main combustion phase) and 47.8 mg m^{-3} (during the charcoal burnout phase). During ESP operation total dust emissions of 48.0 (ignition phase), 7.2 mg m^{-3} (main combustion phase) and 15.9 mg m^{-3} (charcoal burnout phase) have been measured (all emissions related to dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2). From these single measurements total dust precipitation efficiencies of 80%, 84% and 67% could be calculated for the different combustion phases. Four short term measurements with the Berner-type low-pressure impactor per day revealed PM_1 precipitation efficiencies of 86–87.5% whereby the PM_1 contents in the flue gas amounted from 19.4 to 44.8 mg m^{-3} (without ESP operation) and 2.0–7.4 mg m^{-3} (with ESP operation). When evaluating these data it has to be considered that the total dust measurements covered the whole operation period while the PM_1 measurements are only related to rather short (some minutes) operation phases during which impactor measurements have been performed.

In Table 3 and Table 4 the PM emission data and the precipitation efficiencies achieved at the different testing sites are summarised. The broad variation of the single TSP measurements at the logwood boilers (site 1 and 2) mainly results from the different combustion phases during which the single measurements were performed (ignition phase, main combustion phase, charcoal burnout). It has to be mentioned that during some measurements flaking (re-entrainment of agglomerates of already precipitated soot particles from the precipitator surfaces) occurred. In some cases this caused higher total dust emissions during ESP operation than during operation without ESP. These results have not been considered in Tables 3 and 4.

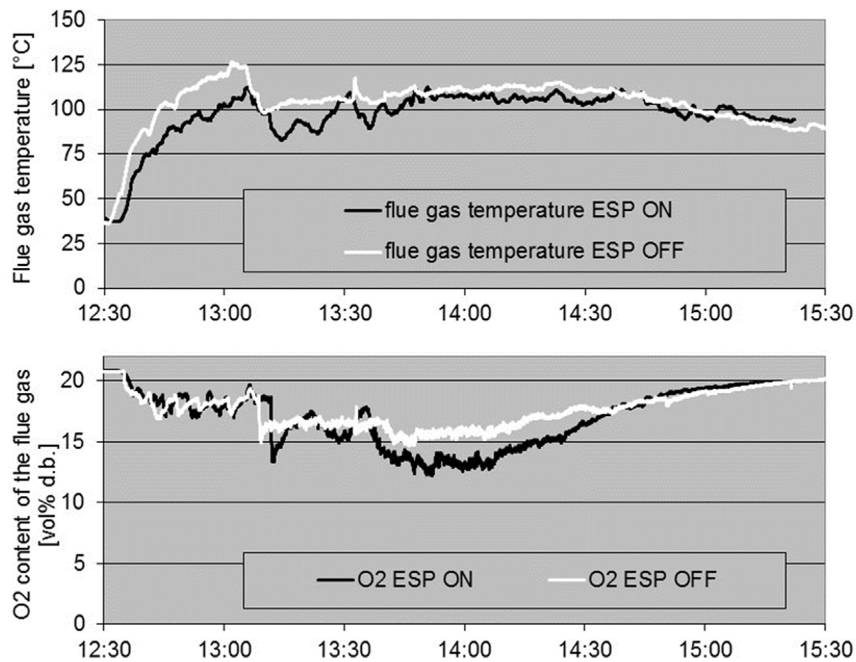

Fig. 8. Comparison of the trends of the O_2 concentrations in the dry flue gas and the flue gas temperatures during test runs at site 1 on two successive days.

Table 3
Results of the dedicated testing campaigns with emission measurements at site 1.

	2014/2015 OekoTube	2015/2016 OekoTube inside
TSP emissions without ESP operation	33–274	15–220
TSP emissions with ESP operation	4–174	2–100
TSP precipitation efficiency	30 - 93%	54–90%
PM_1 precipitation efficiency	55 - 96%	46–98%

Explanations: emissions in mg·m^{-3} related to dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2; TSP … total suspended particulate matter = total dust; PM_1 … particles <1 µm aerodynamic diameter.

Table 4
Results of the dedicated testing campaigns with emission measurements at site 2 and 3.

	2014/2015 OekoTube site 2	2015/2016 OekoTube site 3
TSP emissions without ESP operation	74–736	98–321
TSP emissions with ESP operation	22–154	14–46
TSP precipitation efficiency	35–83%	57–93%
PM_1 precipitation efficiency	44–93%	50–97%

Explanations: emissions in mg·m^{-3} related to dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2; TSP … total suspended particulate matter = total dust; PM_1 … particles <1 µm aerodynamic diameter.

Moreover, the comparability of the combustion conditions during the different combustion phases between the measurement days with and without ESP operation always is limited which also contributes to the scattering of the data regarding particle precipitation efficiency.

The data regarding site 1 show, that the TSP emissions without ESP operation were in the same range for both heating seasons. For both, the chimney-top and the inside version of the OekoTube acceptable precipitation efficiencies were determined (Table 3). The lower values regarding the TSP precipitation efficiency at this boiler are most probably due to re-entrainment of already precipitated soot particles (flaking). The highest precipitation efficiencies (93% rep. 90% for the OekoTube and the Oekotube inside) are well comparable with results gained from the lab tests. The average TSP emissions during operation with filter amounted to 39 mg m^{-3} resp. 22 mg m^{-3} (related to dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2).

The maximum precipitation efficiencies regarding PM_1 show values of up to 96% respectively 98%, which are well comparable with the results of the lab-test performed. However, since impactor measurements are short term measurements (some minutes). Slightly changing combustion conditions at the two testing days which are compared can have a certain impact on the resulting precipitation efficiencies and therefore, the range mentioned in Table 3 has to be evaluated with care.

At site 2 (Table 4) the highest PM emissions upstream the ESP of all testing sites have been determined (up to 736 mg m^{-3}). Moreover, as chemical analyses of selected TSP samples have shown, the contribution of soot to the TSP emissions was very high (elemental carbon content of the TSP of up to 85 wt.-%). The latter explains the low minimum value of the TSP precipitation efficiency, which is assumed to be due to re-entrainment of already precipitated soot particles. In fact soot flakes have been found in the vicinity of the chimney which confirms the occurrence of the flaking effect. The maximum precipitation efficiencies for TSP (83%) and PM_1 (93%) however confirm the expectations from the lab-test. The average TSP emission for ESP operation amounted to 84 mg m^{-3} (related to dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2).

Also at site 3 very good maximum precipitation efficiencies for TSP (93%) and PM1 (97%) have been determined. The average TSP emissions for ESP operation amounted to 28 mg m^{-3} (related to dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2).

Summing up, the dedicated field measurement campaigns have shown that the ESPs worked well and that also in field operation precipitation efficiencies comparable with those gained during lab-tests can be achieved. Moreover, no significant differences between the two measurement campaigns at the beginning of the heating season and in its second half could be found.

6. Summary and conclusions

To assess the applicability of ESPs for particulate matter emission reduction in residential wood heating appliances field tests with accompanying ESP operation monitoring and dedicated emission measurement campaigns have been performed in the region of Graz (AT). Three OekoTube ESPs (two chimney-top and one inside version) where thereby tested over the heating seasons 2014/2015 and 2015/2016 at three different sites, two with logwood boilers and one with a logwood stove.

Before being released for the field tests the ESPs were checked within lab-tests regarding functionality and particle precipitation efficiency.

At the field testing sites the ESPs could be installed and taken into operation without major problems. Also during the operation over the heating seasons no severe problems occurred at site 1 and site 3. Site 2 however distinguished its self by very high flue gas temperatures of up to 300 °C at the ESP which led to a deformation of the electrode. After replacement with a more robust electrode, which was less sensitive regarding thermal tensions, no further problems occurred.

ESP operation periods in the range of 630–1088 h per season were determined. One (site 1) and two (site 2 and 3) additional cleanings by the chimney sweep were needed to maintain the ESP performance over the whole heating season. The cleaning demand could thereby be identified from slightly decreasing ESP voltage and ESP power with increasing operation time.

The evaluation of the plant monitoring data revealed acceptable respectively high ESP availabilities for the chimney-top version of 81.7% and 80.2% (at site 2 and 3) and 97.7% at site 1. The availability of the OekoTube inside was evaluated with 81.2%. These availabilities are all above the target value of 80% which has been defined by the manufacturer OekoSolve for this product.

Dedicated test runs with emission measurements at the different testing sites showed scattering results regarding the precipitation efficiencies. This was due to the fact that they have been calculated from measurement data from two successive days, one with and one without ESP operation. Additionally, flaking (re-entrainment of already precipitated soot agglomerates from the filter surfaces) sometimes occurred. However, the highest precipitation efficiencies determined (>83% for TSP and >93% for PM_1), were well comparable with those gained during the lab-tests. Moreover, the measurements revealed no significant changes of the precipitation efficiencies over the heating season. The total dust emissions could be reduced to in average 39 mg m^{-3} (site 1 – OekoTube), 22 mg m^{-3} (site 1 – OekoTube inside), 84 mg m^{-3} (site 2) and 28 mg m^{-3} (site 3; all data related to the dry flue gas at 273 K, 1013.25 mbar and 13 vol.-% O_2).

From the project also some proposals for further improvements resulted. At boilers and stoves with high flue gas temperatures, electrodes have to be applied which are not sensitive regarding thermal deformations as such deformations lead to increased sparkovers or even to electrode damages. Secondly, the re-entrainment of already precipitated soot particles with the flue gas (so called flaking) should be avoided by the implementation of automated cleaning systems which regularly remove soot agglomerates from the ESP surfaces. This cleaning should be done during shut down phases without reasonable flue gas flow so that the soot flakes can drop to the bottom of the chimney.

Summing up, the results of the project have revealed, that ESP models like the OekoTube have the potential to contribute to a significant reduction of particulate matter emissions from outdated and high-emission residential wood burning systems. More of relevance than the acceptable precipitation efficiencies is thereby the fact, that even at problematic framework conditions such as flue gases with high temperatures, high tar contents and high soot contents during both field test seasons high availabilities were achieved.

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