

## COMPARATIVE LONG-TERM FIELD AND TEST STAND MEASUREMENTS AT SMALL SCALE ELECTROSTATIC PRECIPITATORS – EXPERIENCES AND MEASUREMENT STRATEGIES

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**ABSTRACT:** PM-emissions from wood fired stoves and boilers are increasingly in the focus while emission limits are tightening in Europe. Small scale electrostatic precipitators (ESPs) can provide some remedy. Recent developments of such retrofit devices are aiming a larger market introduction, but their performance and optimization potential under real life operational conditions is yet largely unknown. A chimney-mounted ESP (by Rufftec AG) and a boiler attached ESP (by Spanner Re<sup>2</sup>) for residential heating applications were therefore tested under controlled test-stand conditions but also in dedicated long-term field measurement campaigns. It became obvious that significant deviations exist between type testing results and real life emissions. The chimney mounted ESP performed at an average efficiency of 63 % in the test stand while mean field test results were only slightly lower at 57 %. However, much more challenging flue gas conditions were mostly applied with the four different combustion units (2 stoves, 2 boilers) compared to the boiler-attached ESP, which was operating with a wood chip boiler and under variable operational conditions (several fuels and loads). A precipitation efficiency as high as 88 % was in average achieved on the test stand with this ESP-type or 83 % during a long-term field observation, respectively. Several observations for functional weaknesses can be used for further optimization, particularly concerning the chimney-top ESP which had a lower mean availability of 68 % over two heating seasons, compared to the boiler-mounted ESP (97 % availability over one month).

**Keywords:** electrostatic precipitator, solid biofuel, combustion, particle emission, reduction, small scale application.

### 1 INTRODUCTION AND OBJECTIVES

Currently, the main contribution to PM emissions in the sector of small-scale residential heating applications is attributed to old combustion systems as well as to small scale biomass boilers using challenging fuels. A significant reduction of these high emissions of critical flue gas compounds is aimed as they are hazardous to health. To achieve this required considerable emission reduction over their remaining lifetime a feasible option is the retrofitting of existing applications with secondary measures such as particle precipitation devices.

However, experience with small scale ESP applications in terms of possible reduction potential, long-term behavior, or real life emissions are currently still low. Due to this lack of experimental data dedicated field measurement campaigns were performed and compared to test stand measurements.

The performances of two types of electrostatic precipitators (ESP) were investigated at various field sites over the duration of several weeks to months. The first ESP (Ruff-Kat by manufacturer RUFTEC) was mounted directly on top of the chimney and could therefore be applied as a retrofit unit to all types of small-scale combustion systems in the capacity range of up to 40 kW. In contrast, the second ESP (SFF100 by manufacturer Spanner Re<sup>2</sup>) was installed directly downstream the residential biomass boiler system. It can be applied to heating units with a capacity of up to 100 kW. The investigation comprised the observation of the ESP's long-term behavior by a remote data acquisition system as well as the execution of dedicated on-site measurements. Additionally, comparative dedicated experiments were performed on the test stand to gain results under challenging conditions.

### 2 MATERIAL AND METHODS

#### 2.1 Discrepancy between test stand and field site measurements

The conditions at the test stand can differ significantly from those found under practical operation in the field. Deviations arise for instance from the fuel quality which is typically higher at the test stand with optimum size and homogeneous size distribution, controlled moisture content and low ash content. Under field conditions the fuel used is often of low cost quality and may have undergone property changes due to long storage periods.

Other variations are found when considering the technology. In the laboratory the appliances used are usually of best stage of maintenance with specifically adjusted control settings and repeatable operation and test conditions. The measuring sections are designed according to the standards given. In contrast, the stage of maintenance in the field might be coincidental with a given risk of malfunctioning. The settings implemented are defined for a wider range of fuel properties, the conditions are less repeatable and the measuring lengths have to be adapted to the prevailing conditions.

When taking into account the operation of the combustion systems they are usually operated by experienced personnel in the test stand. The amount of batches, the fuel loading time, size, and weight as well as the load conditions are highly reproducible and permit constant and optimum operation according to the manufacturer's instructions. However, under field conditions the operators are usually untrained. The fuel loading time, size and weight are selected according to their personal needs. Often occurring load changes and partial load operation are predominant.

#### 2.2 Chimney-mounted ESP

##### 2.2.1 Description of the technology

This single-tube electrostatic precipitator (ESP) is mounted on top of the chimney where it requires no

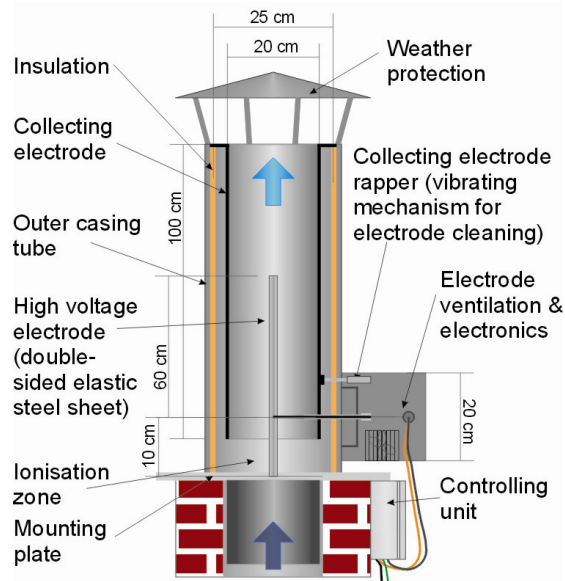
additional space. The precipitator is suitable for all types of small-scale residential wood combustion systems up to 40 kW and can be operated with existing boilers, stoves and cookers as retrofit unit as well as with new installations. With its automatic cleaning system and an automatic controlling unit no additional user effort should be required.

Due to negligible pressure losses any disturbances to users should be avoided and no decrease in the combustion air supply leading to increased emissions should occur.

The principle of the ESP's function is a discharge electrode placed at the lower end of the collecting electrode's tube to which a high voltage is applied. The discharge electrode ionizes the flue gas molecules and thereby charges the particles suspended in the flue gas stream. Due to this electric field the particulate matter (PM) is driven towards the earthed collecting electrode where it precipitates and agglomerates on its surface.

As the periodically operating cleaning system automatically removes dust from the inner tube a long-term operation without any necessity of manual cleaning should be enabled. However, especially old combustion systems discharge high fractions of sometimes sticky organic aerosols and soot and it might be challenging to remove them from the surface of the collecting electrode. A reduced long-term operation can thus be possible [1].

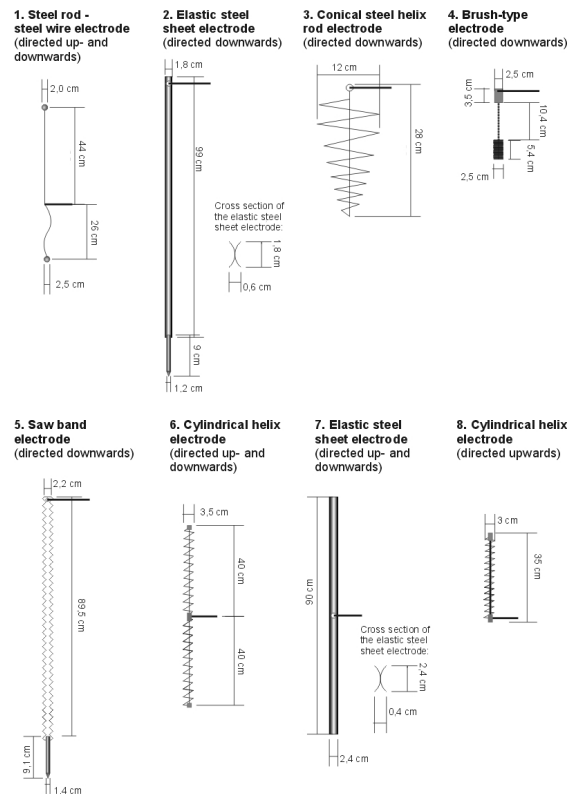
A scheme of the ESP is given in Figure 1.



**Figure 1:** Sketched design of the chimney-mounted ESP by RuffTec

### 2.2.2 Test stand measurements

Within dedicated test stand measurements under laboratory conditions various components were investigated in detail and improved accordingly to implement the most promising parts and therefore to ensure a high efficiency together with a long-term availability of the technology. These adjustments comprised design modifications of the precipitation electrode and of the discharge electrode (Figure 2), the discharge electrode's suspension, the power supply unit, both the controlling unit and the controlling software, the high voltage cable, and further technological adaptations.



**Figure 2:** Design of the ionization electrodes investigated

Additionally, the ESP's performance in test stand measurements was analyzed when connected to different heating installations (including a wood chip boiler, a logwood stove and a wood chip burner). They were fuelled with various partly challenging fuels (beech wood logs, spruce wood chips, poplar wood chips, wet fuel, overloading conditions). Tests were also performed during several combustion phases (ignition mode, main combustion phase, burnout operation). The velocity and the gaseous compounds in the flue gas were analyzed continuously during the experiments. The amount of particles suspended in the flue gas (TSP = total suspended particles) was determined discontinuously but parallel in the raw and in the clean gas. Each test stand measurement was performed according to VDI 2066-1 and contained three repetitions of a single measurement of 30 min duration. The results of the gravimetric dust load and the gas analysis were always related to standard conditions and 13 % oxygen in the flue gas

The heating appliances were operated as specified by the manufacturer. To ensure reliable conditions the measurements were performed as soon as constant behavior was reached in the heated combustion unit and in the flue gas [2].

### 2.2.3 Field tests

To observe the ESP's behavior under environmental conditions and during long-term operation 4 similar ESPs were connected to field site heating appliances. As being of highest relevance for secondary PM abatement measures an old and a modern room heater and an old and a modern logwood boiler were chosen. The combustion systems covered the capacity range of up to approx. 30 kW and were operated with various biomass fuels. Therefore, a wide range of typical installations that

might benefit from this ESP technology were considered. A comparison between these installations is given in Table I.

**Table I:** Overview of field testing sites

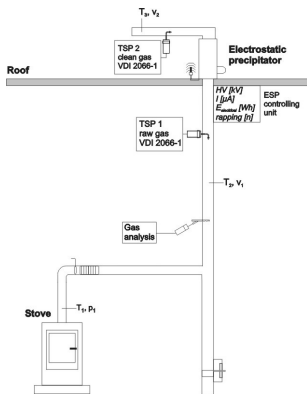
Field testing site	Commissioned in	Capacity	Fuel
Old room heater	1980	5.6 kW	wood logs, wood briquettes
Modern room heater	2010	6 kW	wood logs
Old logwood boiler	2002	29 kW	wood briquettes
Modern logwood boiler	2011	28 kW	wood logs

The ESP's behavior was investigated over a period of two heating seasons. This included the long-term monitoring of significant influencing factors such as the flue gas temperatures at the ESP inlet and outlet, the chimney draught, the environmental conditions and ESP operation parameters such as the applied voltage, the ionization current, the consumed electrical energy, and the cleaning intervals. Therefore, malfunctions and operational disturbances could be detected and eliminated fast and easily.

Within five dedicated measurement campaigns over two heating periods performed at each of the field testing sites the velocity, the temperatures, and the gaseous compounds in the flue gas were determined and the ESP's precipitation efficiency was obtained by measuring the dust load in the raw and the clean gas in parallel. Three repeated isokinetic dust measurements were performed per dedicated testing campaign according to VDI 2066-1 each over 30 min measuring time. To perform clean gas measurements downstream the ESP a special measurement section was required that had to comply with requirements given in the specifications and guidelines (e.g. VDI 2066-1).

A scheme of the measurement setup and a picture of the clean gas measurement section mounted on top of the ESP are presented in Figure 3.

During the dedicated measurement campaigns the combustion systems were operated by the owner in their usual heating manner [2].

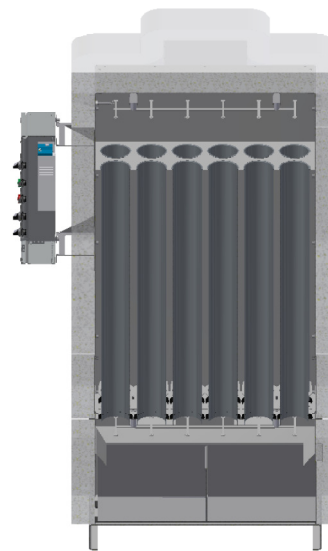


**Figure 3:** Scheme of field measurement setup (left) and picture of the clean gas measurement section (right)

### 2.3 Boiler-attached ESP

#### 2.3.1 Description of the technology

The boiler-attached ESP was a dry operated multi-tube electrostatic precipitator which was designed to be situated in the boiler room to be installed directly downstream the boiler. It was declared suitable for small-scale biomass combustion systems in the capacity range of up to 100 kW. The precipitator consists of 12 vertical tubular collecting electrodes and 12 stainless steel discharge wires aligned along the axis of the tubes and suspended from rods which at the top are supported by an insulator. The raw gas enters at the top of the precipitator and flows down through the collecting tubes. The ESP is equipped with a coupled cleaning system for discharge and collecting electrode which has to be operated manually. A scheme of the ESP is given in Figure 4.



**Figure 4:** Sketched design of the boiler-attached ESP

#### 2.3.2 Test stand measurements

To evaluate the ESP's behavior under challenging conditions measurements were performed at the test stand at a wood chip boiler with 100 kW nominal load (manufacturer: HDG Bavaria). The aspects to be considered comprised the influences of partial versus full load operation as well as different fuel types (spruce and beech wood chips and miscanthus pellets) and qualities (low and high moisture content). During the experiments the ESP's operation behavior was monitored, the flue gas

temperature and velocity, and the gaseous compounds were measured continuously, and the amount of particles suspended in the raw gas and in the clean gas (TSP = total suspended particles) was determined in three repeated parallel measurements each over 30 min sampling time.

The boiler was operated as specified by the manufacturer. To ensure reliable conditions the measurements were performed as soon as constant behavior was reached in the heated combustion installation and in the flue gas. A sketched test stand setup is presented in Figure 5.

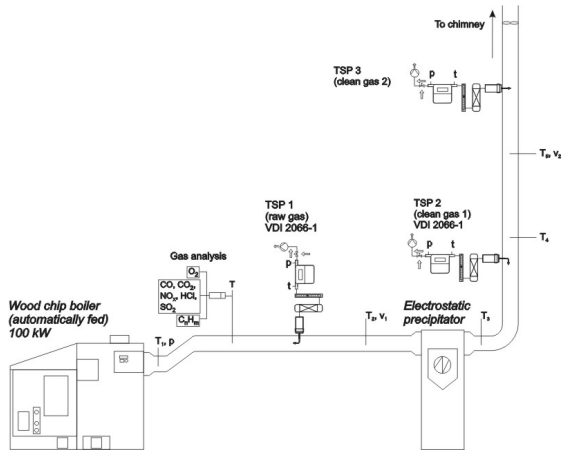


Figure 5: Scheme of test stand measurement setup

2.3.3 Field tests

The field measurements were performed over 12 week’s duration. The aim of these experiments was to gain experience over the long-term operation, the emission behavior and precipitation efficiency achievable in the ESP’s practical operation. Therefore, dedicated measurement campaigns with the analysis of gaseous compounds and TSP measurements parallel in raw and clean gas over 30 min measuring time each with three repetitions were performed.

The field test campaigns were performed using a wood chip boiler with 100 kW nominal load (manufacturer: HDG Bavaria) at the manufacturers test bench. Figure 6 presents a scheme of this setup. The boiler was operated by the manufacturer’s staff in their usual heating manner. The measurement started as soon as reliable conditions were reached both in the heated combustion installation and in the flue gas.

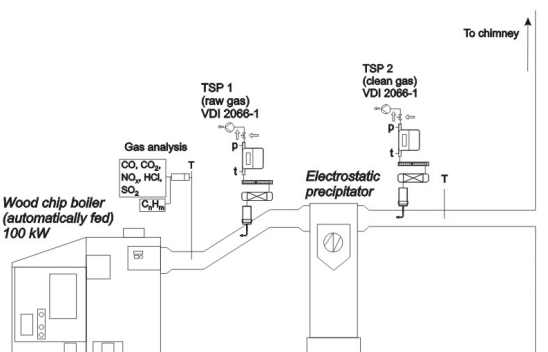


Figure 6: Scheme of field measurement setup

3 RESULTS AND DISCUSSION

3.1 Chimney-mounted ESP

3.1.1 Test stand measurements

Figure 7 presents the ESP’s operational behavior (ionization current, voltage, inlet temperature, cleaning by rapping intervals) continuously recorded over a four week observation period.

The continuously recorded data display a reliable operation behavior of the ESP over a period of several weeks with an availability of the technology of 97 % while the applied voltage remains stable with increased flue gas temperature at the ESP inlet. Nevertheless, these values have to be validated over a longer period of time.

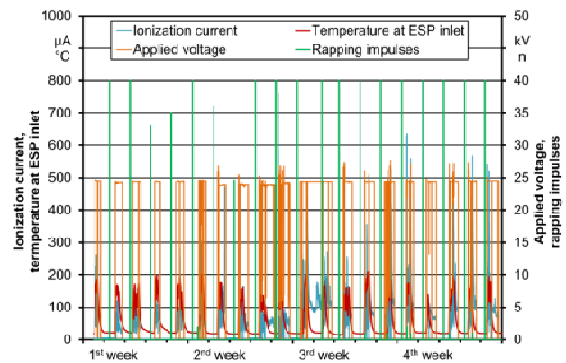


Figure 7: Results of monitoring the chimney-mounted ESP’s operational behavior at test stand (recorded over 4 weeks)

Figure 8 illustrates the average outcome of various test cycles performed at the ESP test bench while the heating installation was operating at constant load. The concentrations of particles suspended in the raw gas at the ESP inlet and in the clean gas at the ESP outlet, together with the achieved precipitation efficiencies are shown in the graph.

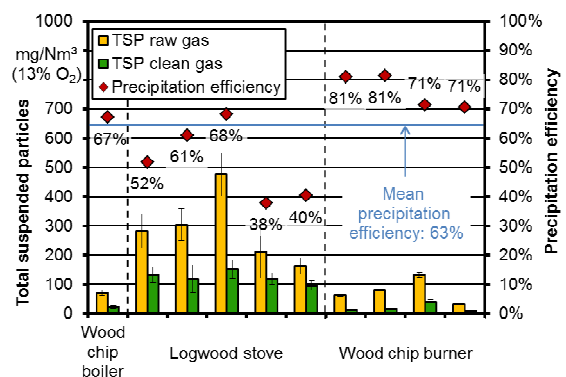


Figure 8: Results from test stand measurements: Raw and clean gas dust emissions and the chimney-mounted ESP’s precipitation efficiency (n = 3) using 3 combustion systems

These dedicated measurements demonstrate promising results obtained for both, high and at low dust concentrations. The mean dust load in the raw gas was 182 mg/Nm<sup>3</sup>, the average clean gas dust load was 72 mg/Nm<sup>3</sup>. An average precipitation efficiency of 63 % was achieved at a mean standard deviation of 6 %.

During the test stand measurements several specific problems were identified. For instance a high dust deposit on the collecting electrode's surface was observed which could not be removed by the vibrating rapper. Furthermore, cracks within the ceramic tube insulation of the ionization electrode had occurred several times during the measurement periods in the field and at the test stand. This had caused spark over behavior. Another malfunctioning observed was an incorrectly measured flue gas temperature which led to a delayed starting operation of the ESP.

3.1.2 Field tests

Continuously recorded operation parameters from the field tests showed that usually the required voltage was applied when the flue gas temperature increased and that it could be kept stable over several days or weeks. As indicated in Figure 9 both, good and poor operation modes were monitored. This is shown by the applied voltage (red line) which mostly increased to a certain preset value (20 kV) with increasing flue gas temperature (orange line), but this was not the case during all days monitored.

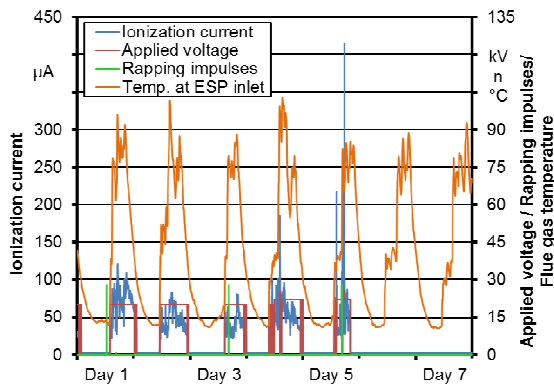


Figure 9: Results of the chimney-mounted ESP's operational behavior with an old stove, recorded at field testing site (example for 1 week recording)

Due to disadvantageous behavior observed several times during the field measurements the technology's mean availability was calculated to 68 %. This availability correlates to the time while the combustion system was in operation as an increased flue gas temperature was detected while the precipitator was out of operation determined by a not applied voltage. The energy demand of 9 to 25 W during operation underlined a low electrical energy consumption.

The achieved results of the TSP measurements performed are outlined in Figure 10.

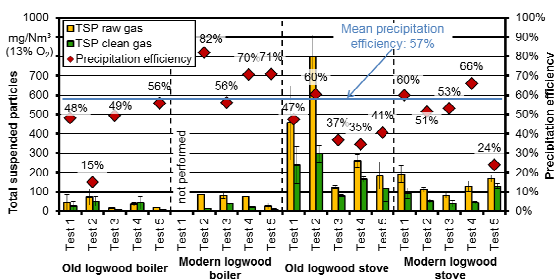


Figure 10: Results from dedicated field measurements: Raw and clean gas dust emissions and the chimney-

mounted ESP's precipitation efficiency (n = 3) over 2 heating periods

The results achieved during the field measurements allowed a clear investigation of real life emissions. In this regard high deviations observed between individual field testing events have to be attributed to the "real life" operation and measurement conditions.

With an amount of particles suspended in the raw gas ranging up to 800 mg/Nm<sup>3</sup> considerably higher dust emissions were reached compared to test stand measurements. A reduction of total suspended particle (TSP) emissions of 57 % on average could be reached, both at high and at low dust loads in the flue gas and with a standard deviation of 10 %.

This observed reduced field test precipitation efficiency of 57 % instead of 63 % and the higher measurement variation compared to lab tests is in line with expectations (see Chapter 2.1).

In the course of the two heating periods several technical failures occurred. They included scorch damage around the high voltage cable which was attributed to a spark over within the cable, cracks in a ceramic isolator part around the ionization electrode, irreproducible and unexpected re-settings of the implemented ESP controlling unit values, and an unstable mounting of the ionization electrode which also caused spark over between the electrodes. It was believed, that these problems can be solved before market introduction.

3.2 Boiler-attached ESP

3.2.1 Test stand measurements

The ESP's operation behavior (ionization current, applied voltage, consumed electricity) was continuously recorded during the test stand measurements. The results achieved are displayed in Figure 11.

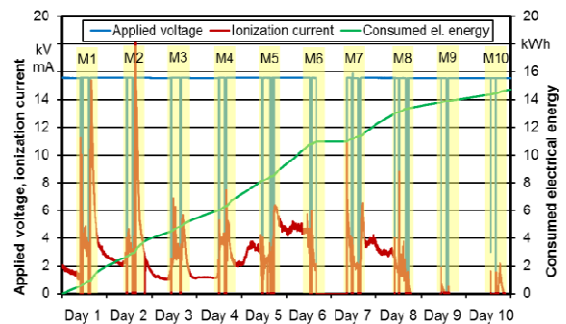
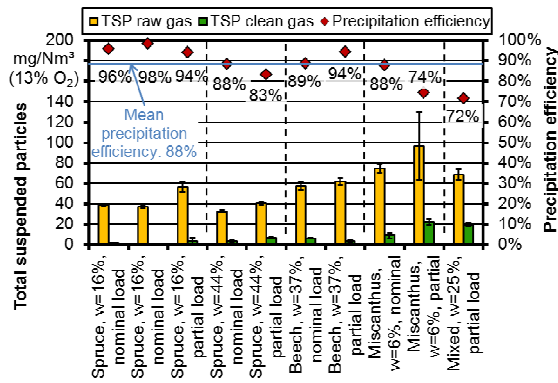


Figure 11: Operational behavior of boiler-attached ESP from monitoring at test stand (recorded over 10 measurements)

A reliable operation of the ESP was observed over the measurement period. Thereby, a high availability of the technology of 97 % was achieved due to reliable components while the applied voltage remains stable when flue gas temperature at the ESP inlet increases. With an energy demand of 13 to 27 W during operation the electrical energy consumed is in a moderate range.

The results of ten test cycles performed at the test stand while the boiler was operating under reliable conditions in its main combustion mode are presented in Figure 12.



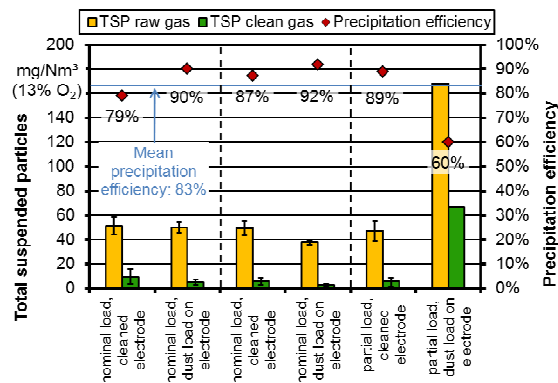
**Figure 12:** Results from test stand measurements: Raw and clean gas dust emissions and the precipitation efficiency (n = 3) of the boiler-attached ESP operating with a wood chip boiler

With a mean raw gas dust load of 57 mg/Nm<sup>3</sup> an already low emission level was prevailing. Due to a mean precipitation efficiency of 88 % mean clean gas emissions of 8 mg/Nm<sup>3</sup> could be achieved.

Increased dust loads can be attributed to challenging conditions like partial load operation, difficult fuels with high moisture content or non-woody fuels. Nevertheless, these unfavorable conditions had an insignificant influence on the clean gas dust emissions. Additionally, low deviations of 2 to 6 mg/Nm<sup>3</sup> resp. 3 % illustrate a high reproducibility with minor uncertainties.

3.2.2 Field tests

The results reached within dedicated field measurements are given in Figure 13.



**Figure 13:** Results from dedicated field measurements using the boiler-attached ESP: Raw and clean gas dust emissions and precipitation efficiency (n = 3)

With a particle concentration of 67 mg/Nm<sup>3</sup> in the flue gas at the ESP inlet the boiler shows an already moderate raw gas dust load. At field measurement conditions the emissions are higher compared to the test stand experiments. As expected, the raw gas emissions are also slightly higher when operating the boiler under partial load instead of nominal load. Nevertheless, these emissions are still inappropriate in view of future emission limit values in Germany of 20 mg/Nm<sup>3</sup>. In contrast, when considering a precipitation efficiency of 83 % a suitable clean gas dust concentration of 16 mg/Nm<sup>3</sup> at the ESP outlet could be achieved. Even

with increased standard deviations in the range of 3 to 5 mg/Nm<sup>3</sup> (i.e. around 7 %) compared to test stand measurements a high repeatability was observed. The high dust load and reduced precipitation efficiency during the 6<sup>th</sup> experiment has to be attributed to a malfunction in the boiler operation leading to disadvantageous conditions and therefore only one single measurement was performed instead of three repetitions.

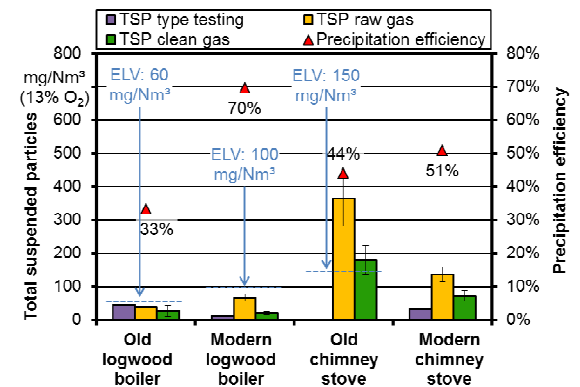
4 CONCLUSIONS

4.1 Chimney-mounted ESP

In line with expectations the dust emissions, the precipitation efficiencies, and the standard deviations measured during the field tests are significantly higher compared to the test stand results.

As indicated in Figure 14, the modern units and the old logwood boiler already operate at an acceptable emission level as it can usually be expected from state of the art technology which meet the current emission limit values (ELV) given by national regulations (e.g. 1.BImSchV in Germany) even without secondary measures. But the modern installations showed considerably higher emissions during the field tests than during the type testing which illustrates the deviations between test stand and real-life practice.

Observed problems during field operation such as an insufficient functioning of the controlling unit and the power supply, spark over behavior, or cracks within the ceramic tube insulator could be solved as a result of the latest hardware and software adjustments.



**Figure 14:** Meeting the current emission limit values (ELV) given in the German emission directive (1. BImSchV) by using a chimney-mounted ESP: Examples from the field test installations (TSP-type testing: Data from official testing protocols are here given for comparison).

For stove and boiler users the here described ESP technology has the advantage that an existing combustion application when not reaching the required PM emission limits can be retrofitted by a chimney-top ESP unit instead of having to replace the combustion unit completely. But to mount an ESP on top of the chimney is a technologically challenging feature. However, the already achieved results with the existing prototypes can be regarded very promising.

Nevertheless, several challenges still have to be solved to achieve reliably high precipitation efficiencies with low deviations over a long lifetime and with a high

availability of the components. Further adaptations and improvements were already considered and will be implemented by the manufacturer [5].

#### 4.2 Boiler-attached ESP

In line with expectations the dust emissions, the precipitation efficiencies, and the standard deviations measured during the field tests are here as well slightly higher compared to the test stand results. But the results also show that significantly fewer malfunctions, interfering factors, and disturbing influences occur when operating the electrostatic precipitator directly downstream of a boiler instead of using a chimney-top unit. This can for example be attributed to the conditions prevailing in the hot flue gas where organic compounds remain still gaseous while they might already condensate on the precipitator surfaces under the mostly cold environmental conditions of a chimney-mounted unit. The stable operation under reliable circumstances allowed precipitation efficiencies in the range of 90 %, both in the field and on the test stand. Hence, the adherence to future emission limit values is guaranteed. Highly disadvantageous effects with reduced precipitation efficiencies were observed when using inappropriate fuels or at unfavorable operational conditions. Therefore, consequently an ESP may not be a universal device to compensate for inappropriate fuels, wrong user behavior or omitted maintenance.

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