Development and Study of an Electrostatic Precipitator for Small Scale Wood Combustion

Andrei Bologa
Karlsruhe Institute of Technology, Germany
andrei.bologa@kit.edu

Hanns-Rudolf Paur
Karlsruhe Institute of Technology, Germany
hanns-rudolf.paur@kit.edu

Klaus Woletz
Karlsruhe Institute of Technology, Germany
klaus.woletz@kit.edu

1 Summary / Abstract:

Wood is often combusted in small scale units for domestic heating. Although the total particle emission levels in Germany have declined steadily over the years, small scale wood combustion is an increasing source of indoor and outdoor air pollution. A novel space charge electrostatic precipitator (ESP) was developed for control of fine particle emissions control from wood combustion stoves and boilers. The ESP ionizer consists of a high voltage isolator, a screen electrode and star-form corona discharge electrode. The charged particles are precipitated in the collector which includes a grounded brush. In the article the results concerning the influence of combustion conditions in the wood-log stoves, gas temperature and flow rate, particle number and mass concentration and values of applied voltage and corona current on the ESP collection efficiency are discussed. For steady flame combustion, the mean mass collection efficiency of the ESP is η_M=87±3% for 13% O_2. The fractional collection efficiency of the electrostatic precipitator is η_N>90%.

2 Introduction

Wood-logs and wood-pellets are often burnt in stoves and boilers for domestic heating [1-3]. Although the total particle emission levels decline steadily over the years, the small scale wood combustion is an increasing source of indoor and outdoor air pollution [4,5]. As high emissions of fine particles and hydrocarbons are associated with increased mortality and cardiovascular diseases, there is an increasing need for development of effective exhaust gas cleaning equipment. Electrostatic precipitators, which have high collection efficiency and low pressure drop, are the most common choice [2,6,7].
In the conventional ESPs particles are charged and subsequently separated from the exhaust gas under the influence of electric field which is formed between the high voltage (HV) electrode and grounded electrode [8]. The ionizing and precipitation sections of the ESP are joined into one module. The high voltage electrodes are normally wires or rods with sharp points which are maintained between the plates or inside of the tubular-form grounded electrodes. To ensure high collection efficiency the conventional electrostatic precipitators are operated at low gas velocities. The typical gas velocity is ~2 m/s. This results in the large size of the ESPs.
The space-charge ESPs operate on the principle of mutual repulsion of charged particles and their precipitation in the external field free collector [9]. The design of a space-charge ESP requires a high potential only for particle charging in the ionizing section and replaces the precipitation section with simple grounded collector passages. The design of a space-charge ESP can be simplified in comparison with the conventional precipitator.
The ESPs for exhaust gas cleaning from small wood combustion can be installed direct at the exit of a combustion facility; in the duct, which connects the combustion unit and chimney; and inside or at the exit of a chimney. The advantages and disadvantages of different technical solutions are discussed in the [6].
The 1st objective of the current study is the development of a novel space-charge ESP for small scale wood combustion. In this process the authors took as the main orienteer the existing norms for particle emission for the small-scale wood combustion and the strategy of their reduction in future [10].
The backgrounds of the development are: (i) ESP might ensure stable operation and high collection efficiency for fine particles, (ii) ESP would be equipped with automatic cleaning system; (iii) ESP would be retrofitted to existing combustion facilities and would have low operation costs.
The 2nd objective is the discussion of the results of the study of the influence of combustion conditions and particle number and mass concentration, gas temperature and flow rate, and values of applied voltage and corona current on the collection efficiency of the electrostatic precipitator.

3 ESP development

The novel space-charge electrostatic precipitator is developed in the Karlsruhe Institute of Technology [11,12]. The ESP consists of the ionizing and collector sections installed in thermo-isolated housing (Fig.1,a). The diameter of the tube-form ionizer and collector is 180 mm. The ESP housing has no openings (excluding input and output) through which the exhaust gas can come out.

The ionizing section consists of a HV isolator; a screen electrode; a HV rod, which is axially installed in the screen electrode and a corona discharge sharp-disk electrode, installed at the bottom end of the HV rod (Fig.1,b). Particles are charged in the charging zone formed between the corona discharged electrode (Fig.2,a) and the opposite tube-form grounded electrode of the ionizer. In the ESP particles are charged in a DC corona discharge. Both positive and negative polarity corona discharge can be used for particle charging.

The charged particles are collected in the tube-form grounded collector. A grounded brush (Fig.2,b) is installed inside of the collector tube and it is designed with the possibility of periodical rotation and cleaning. The collector tube is equipped with a thin plate for cleaning of the brush. The brush plays the double role. First, it is used as a collector for charged particles, and second, it is used for cleaning of the tube-form collector (Fig.2,c). The main part of charged particles is collected by the brush. The brush is periodically rotated and the collected aerosol in the form of large flocks falls down into the ESP plenum chamber, which connects the ionizing and collector sections. The collected aerosol is periodically discharged from the plenum chamber.

4 Test set-up

The experimental study was carried out at two different test set-ups. At the 1st set-up, tests were carried out with a wood-logs stove with thermal power output 8 kW. At the 2nd set-up, tests were carried out with a wood-log stove with thermal power output 9 KW and 2 wood-pellets boilers with thermal power output 20 kW and 32 kW [6,7]. The pilot ESP was installed in the gas duct downstream the small-scale combustion units. The exhaust gas flow rates were: ~50 m³/h for the stoves and from 70 m³/h to 100 m³/h for the boilers. The clean was discharged into the atmosphere through a chimney. In the article the attention is paid to the results of the tests with wood-log stoves.

Fig.1,a Pilot ESP

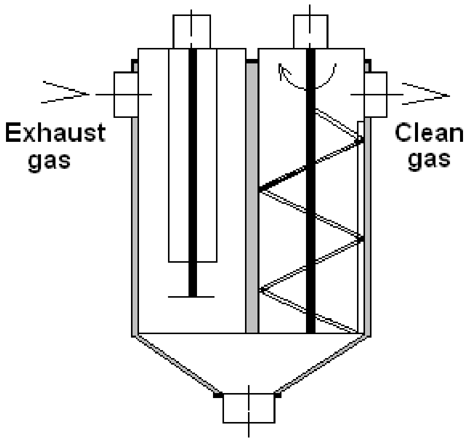

Fig.1, b Schema of the pilot ESP

Fig.1 Novel space-charge electrostatic precipitator

Fig.2,a

Fig.2,b

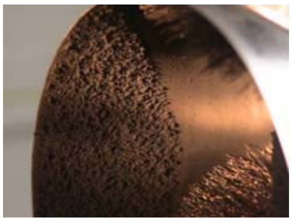

Fig.2,c

Fig.2 Corona dis-charge electrode (a), brush (b) and collector after cleaning (c)

The combustion units were operated according the DIN-4702 norm. The particle mass concentration was measured upstream and downstream the ESP according to the Guidelines VDI-2066. Particle number concentration was measured by Scanning Mobility Particle Sizer (SMPS, Fa. Grimm). During the tests the pressure drop in the ESP was notified and the temperatures of the exhaust gas and clean gas were measured.
The mass collection efficiency of the ESP was calculated as $\eta_M = \frac{C_{Mup} - C_{Mdown}}{C_{Mup}}$, where C_{Mup} and C_{Mdown} were particle mass concentrations upstream and downstream the ESP.
The fractional collection efficiency of the ESP was calculated as $\eta_N = \frac{C_{off} - C_{on}}{C_{off}}$, where C_{off} and C_{on} *were* particle number concentrations in the gas flow downstream the ESP when the electrostatic precipitator was switched-off and switched-on.
The pilot ESP was supported with the automatic control system which ensured switch-on and switch-off of the ESP depending on the exhaust gas temperature.
The combustion unit was connected with the ESP by a gas input duct and the ESP was connected with a chimney by an output duct.
The collector was automatically cleaned by the periodically rotated brush (1 min cleaning cycle per 1 h). A high voltage unit (DC, positive and negative polarity voltage, U_{max}= 20 kV, I_{max}=10 mA, Fa. Heizinger) was used to generate corona discharge in the pilot ESP ionizer.
The wood-logs stoves were operated about 5-6 h per day. Beach wood-logs were stored at room conditions and the dosage of the burnt wood was ~2,5-2,8 kg/hour. A new log was introduces into the stove every half an hour.

5 Results and Discussions

5.1 Influence of corona discharge characteristics on the ESP operation

The ESP current-voltage characteristics (CVC) were measured for positive and negative DC corona discharge and different corona discharge electrode geometries. Two HV electrodes were tested: a bush-form wire electrode and star-form shaped disk electrode. The tests have shown that the disk electrode was more robust than the wire electrode and disk could be easy cleaned or re-placed.
Two types of disk electrodes with thickness 0,5 mm and 2 mm were tested. The thick electrode had twice higher number of corona discharge points (2 points at every needle). This needed higher power input to ensure stable corona discharge. The thick electrode has shown same corona currents at lower power consumption.
The short needle points (height 2-3 mm) were quickly loaded with soot (Fig.B). The high density of corona sharp-points on the disk electrodes also resulted in partial suppressions of the corona discharge. The increase of the number of HV electrodes from 1 to 2 did not enhanced the ESP collection efficiency.

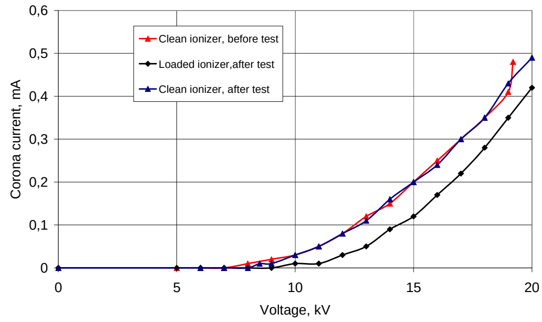

Fig.3 The CVCs of the pilot ESP with clean and loaded ionizer, atmospheric condition

Fig.4 Thick multi-needle disk HV electrode

For pilot electrostatic precipitator it was recommended the use thin disk electrode with long (height 10 mm, Fig.2,a) sharp-needles. The number of needles was 10.
The long-term tests have shown that the loading of the charging zone of the ionizer with aerosol could slightly reduce the ESP corona current (Fig.3). This takes place due to the loading of the sharp-needles with soot and also due to the precipitation of aerosol in the ionizer (Fig.5). The loading of the lateral surface of the HV electrode with particles has no any influence of the corona discharge stability.
The spark-over discharges, which took place in the ionizer during ESP operation, cleaned the sharp points which were covered with aerosol. The loading was also destroyed by a spark-over discharge (Fig.5). This has stabilized the width of the electrode gap necessary for effective particle charging and collection in the electrostatic precipitator.

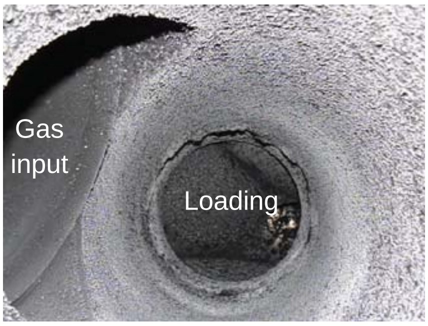

Fig.5 Loading of the ionizer grounded tube

The electrode gap between the corona discharge electrode and grounded ionizer wall was 30 mm. The decrease of the electrode gap resulted in decrease of the ESP operation stability (sensibility of the spark-over voltage to the gas temperature). The use of large electrode gaps resulted in the necessity of strong HV power supply what increased ESP investment and operation costs.

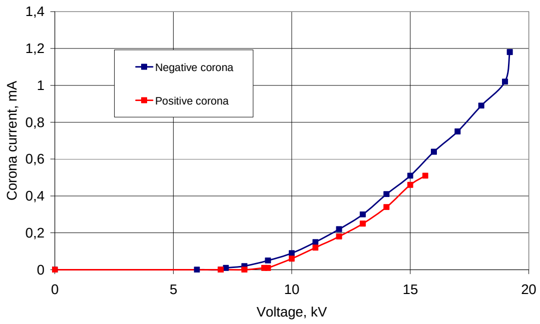

Fig.6 CVC-characteristics of the pilot ESP for different polarity of applied voltage, T≥100°C

The negative corona discharge was mainly used for particle charging in the ESP because at same applied voltage and HV electrode configuration, the negative corona discharge was more stable than the positive one, it had higher operation and spark-over discharge voltages and it was characterized by higher corona currents (Fig.6).

5.2 Influence of gas temperature and flow rate on the ESP collection efficiency

At constant applied voltage and electrode configuration, the increase of gas temperature increased the corona current (Fig.7) and decreased the spark-over voltage. At high temperature conditions, to ensure effective corona discharge currents one needs lower values of applied voltage.
At constant gas temperature, the increase of gas flow rate results in increase of gas velocity in the ESP. The increase of gas velocity in the ionizer from v=0,7 m/s to v=1,2 m/s had no influence on corona discharge characteristics and particle charging efficiency [13]. The same increase of gas velocity in the collector section slightly decreased the mass collection efficiency η_M of the ESP (Fig.8) from η_M=87% for v=0,7 m/s to η_M=65% for v=1,2 m/s.

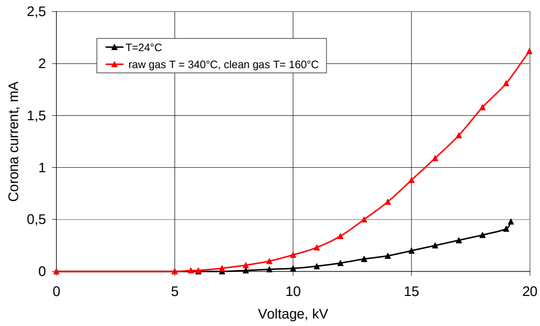

Fig.7 CVCs of the pilot ESP at different gas temperatures

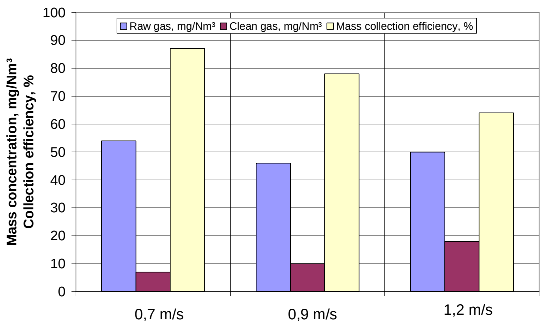

Fig.8 Dependence of the mass collection efficiency on the gas velocity in the ESP

5.3 Influence of combustion conditions on the ESP collection efficiency

In the stove, the wood-log combustion cycle can be divided into three phases: start-up, stable flame combustion and burn-out phase.
At the beginning, the measurements were carried out when the ESP was switched-off.
For a wood-log ca 1,3 kg, the duration of the start-up combustion phase was 5-7 minutes, but generally this time could vary depending on wood quality and humidity and log size and weight. At every charging of a new wood-log, the temperature of the exhaust gas decreased about 100°C. This took place due to the heating of wood and evaporation of the moisture. The gasification of wood surface during the start-up phase resulted in high emission of fine aerosol with particle mean diameter ~150 nm (Fig.9).
The duration of the “steady flame” combustion phase was 15-17 min. During this combustion phase the temperature of the exhaust gas in

the input duct increased up to T=300°-330°C. During the tests, a partial cooling of the gas took place in the input duct and the gas temperature at the ESP input was T=230-250°C. The gas temperature downstream the ESP was T=160-180°C what means, that the gas flow was partly cooled in the ESP. In comparison with start-up phase, the particle number concentration in the gas flow decreased. The mean particle size remained the same (Fig.9).

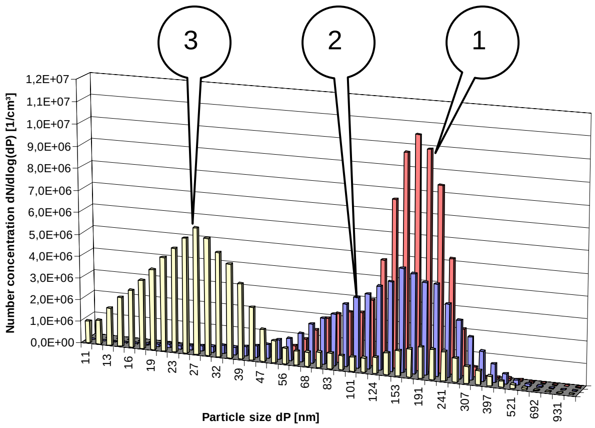

Fig.9 Particle size distribution during different phases of wood-log combustion in a stove: (1) start-up; (2) steady flame; (3) burn-out; dilution factor 1:10

The duration of the burn-out phase was 7-10 minutes. During this phase of combustion, the gas temperature slightly decreased in time. The combustion of charcoal and the rest of wood was characterized by the bi-modal particle size distribution. The larger mode was ~180-200 nm and for the small mode the mean particle size was ~30-40 nm. The charcoal combustion was characterized by mono-modal size distribution with high concentration of ultra-fine particles.

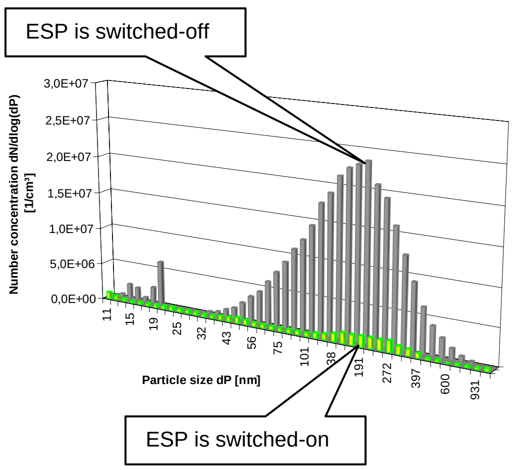

Fig.10 Particle size distribution in the gas flow downstream the electrostatic precipitator, steady-flame phase

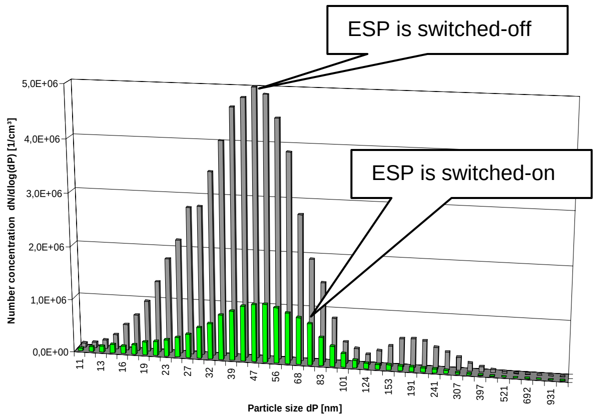

Fig.11 Particle size distribution in the gas flow downstream the electrostatic precipitator, burn-out phase, dilution factor 1:10

The measurements were also carried out when the ESP was switched-on. The results of the SMPS measurements are presented in the Fig.10 and Fig.11.

Particle charging and precipitation in the ESP reduced particle number concentration in the exhaust gas. The ESP mean fractional collection efficiency was η_N>90% for steady flame combustion.

The ESP was operated at U=16-18 kV and corona current I=0,8-1,0 mA during the steady flame combustion phase and I~1,5 mA during the burn-out phase (Fig.12). The increase of the operation current at the same value of applied voltage took place due to reduction of corona suppression in the charging zone by change of the combustion conditions. The strong corona suppression (decrease of corona current to I=0,4-0,5 mA) was observed during the start-up combustion phase, when the particle number concentration was much higher than during the stable-flame conditions.

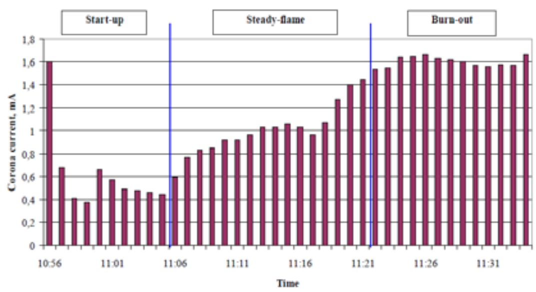

Fig.12 Influence of combustion conditions on the corona current in the ESP

The measurements of particle mass concentration in the gas flow were carried out both for the steady-flame combustion condition and for total combustion cycle. The results of the measurements for the stove with thermal power output 9 kW are presented in the Fig.13.

For the total combustion cycle the particle mean mass concentration in the exhaust was 60-72 mg/Nm³ and for the steady-flame combustion phase it was 30-40 mg/Nm³. The mass concentrations were recalculated for 13% of O_2.

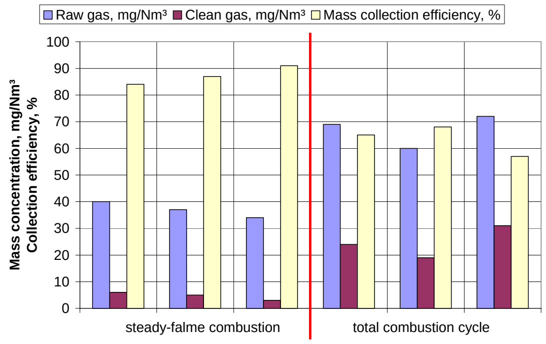

Fig.13 Influence of combustion conditions on the ESP mass collection efficiency

During the steady-flame combustion, the particle mass concentration in the clean gas downstream the ESP was 3-5 mg/Nm³ and corresponding mean mass collection efficiency was η_M=87±3%. In spite of the fact, that the strong corona suppressions took place during the start-up phase, the mean mass collection efficiency of the ESP for the total combustion cycle was η_M=62±5%. The ESP was operated at voltage U~16-18 kV and mean current I~1 mA. The power consumption of the pilot ESP was ~35 Wh. The ESP was equipped with automatic collector cleaning system what ensured stable long-term operation.

Concluding the discussion, it is possible to say that a novel space-charge ESP effectively reduces the fine-particle mass concentration in the exhaust gas from the small scale wood-logs combustion stoves below the exiting norms for particle emissions [10].

The developed electrostatic precipitator was also tested for exhaust gas cleaning from wood-pellets boilers and biomass combustion of mixed pellets (50% wood + 50% straw), straw pellets and grains. The results of the tests are presented in [6] and [7].

The study and optimization of the developed ESP would be continued.

6 Acknowledgement

The authors gratefully acknowledge the support and cooperation of the German Biomass Research Centre (DBFZ) and European Institute for Energy Research (EIFER).

7 Literature

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