Novel Compact Electrostatic Precipitators for Small Scale Biomass Combustion Facilities

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Abstract. Electrostatic precipitation is an effective pollution control technology for reduction of particulate emissions from small-scale biomass combustion facilities. The electrostatic precipitators (ESPs) ensure high mass and fractional collection efficiency at low pressure drop and ESPs have low operation costs. The aim of current work is the development and experimental study of a prototype of a compact ESP for reduction of particle emissions from wood combustion facilities with heat power capacity 4-100 kW. In the designed ESP, particle charging takes place in a corona discharge double-stage electrode system. Particle precipitation takes place under the influence of corona discharge electric field in the ionizing zones and under the influence of electro-hydrodynamic, space charge, thermophoretic and gas-dynamic phenomena in the ash box, installed in the bottom part of ESP casing. The compact ESP assumes manual cleaning of collected fly ash. The results of the study of the influence of gas flow rate, corona discharge power consumption and particle concentration on the ESP mass collection efficiency are discussed. The prototype of a compact ESP ensures mean mass collection efficiency of 76%.

Keywords: Wood combustion. Exhaust gas cleaning. Compact electrostatic precipitator. Collection efficiency.

1 Introduction

Biomass combustion results in undesirable gas and particulate emissions. Fine and ultra-fine particles, which are high in number concentration in the exhaust gases, not only contribute to the environmental pollution, but also provoke serious health problems [1-3].

Various technologies are applied for the exhaust gas cleaning from biomass combustion. The electrostatic precipitation is expected to be the most effective one for reduction of particles emissions from combustion facilities, used for residential heating [4-6]. The advantage of the ESPs is, that they ensure effective collection of fine and ultra-fine particles at low pressure drop. ESPs are characterized with low power consumption, what is important for household application. The known ESPs are designed to be integrated into the combustion facilities, or they could be used as apparatuses, installed in the gas duct between the combustion unit and the chimney [7-9]. To ensure long-term operation stability, the ESPs could be equipped with an automatic system for cleaning of high voltage (HV) and grounded electrodes, and with an automatic system for evacuation of collected fly ash [5]. Unfortunately, the large size, the use of powerful and costly HV equipment, the use of automatic system for cleaning of fly ash, and the necessity of complicated control system result in high investment costs of the most of developed ESPs.

Hence, the design of a compact and cost-effective electrostatic precipitator for small scale biomass combustion facilities, which ensure long-term operation stability and effective reduction of particulate emissions from exhaust gases, is an actual and important task [10, 11]. In the current study, the results of the development and tests of a prototype of compact ESP for small scale biomass combustion facilities with heat capacity up to 100 kW are presented and discussed.

2 Design and operation of a prototype of a compact ESP

The prototype of a compact ESP includes a grounded casing with gas input and output (Fig. 1). The gas input is on the lateral wall of the casing. The gas output could be on the lateral wall (Fig. 1,a) or at the upper plate of the casing (Fig. 1,b). The ESP is equipped with a removable ash box, installed in the bottom part of the casing. A partition wall in placed inside the casing (Fig. 1,c), dividing the inner space of the ESP into gas input and output sections, respectively. A HV insulator is installed on the upper plate of the casing, being protected with a cap. A HV rod passes through the HV insulator. It is connected with its upper edge with an output of a HV power supply unit. The bottom edge of the HV rod is connected to a HV support with barbed HV electrodes. The HV support is installed inside the ash box, avoiding any spark-over discharges during ESP operation. The 1st HV electrode is installed in the gas input section, and the 2nd HV electrode is maintained in the ESP gas output section (Fig.1,c). The electrode gap is formed between the barbed HV electrodes, and the upper part of the lateral wall of the ash box, and the bottom part of the partition wall.

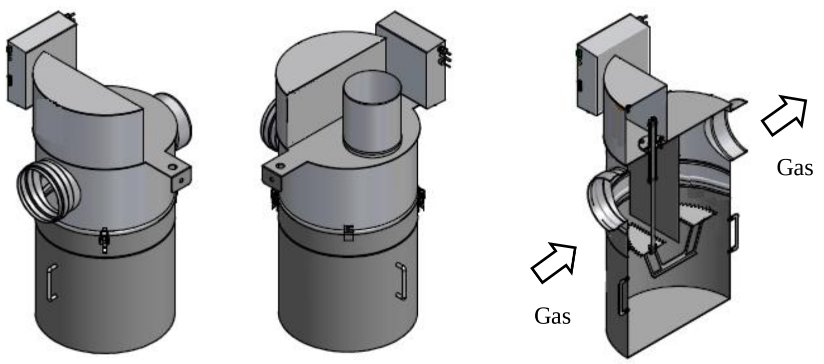

Fig. 1.a Fig. 1,b Fig. 1.c

Fig. 1. Compact electrostatic precipitator: (a) gas output at casing lateral wall, (b) gas output at casing upper plate; (c) ESP constellation

Several ESPs could be installed in series or in parallel. If the ESPs are installed in series, this allows the enhancement of particle collection efficiency from the exhaust gases at constant gas flow rate. If the ESPs are installed in parallel, the set of small scale ESPs could be applied for exhaust gas cleaning from a combustion facility with heat capacity over 100 kW.

The HV power supply unit of the ESP is equipped with a temperature sensor, which is installed at the lateral wall of the gas input tube. The signal from the sensor is used to switch on/off the generation of high voltage in dependence of ESP casing temperature. A DC negative polarity corona discharge is used for electrostatic charging of particles in the ESP.

During the ESP operation, particle loaded gas flows through the gas duct into the ESP via the gas input. The gas changes its flow direction inside the ESP gas input section, and moves downstream through the 1st electrode system. In the ash box, the gas once again changes its flow direction, and moves upstream through the 2nd electrode system, and then through the ESP gas output. The sensor measures the temperature of the ESP casing. When the casing temperature increases over the defined value, the HV is switched on, and the voltage is increased in a step-form up to the maximum value. The corona discharge, being formed in the 1st and in the 2nd electrode systems, is used for electrostatic charging of particles. In the 1st electrode system, charged particles are precipitated on the lateral surface of the ash box and on the partition wall under the influence of gas-dynamic and electro-hydrodynamic phenomena. Being moved with gas flow, charged particles penetrate into the ash box, where they are precipitated due to electrostatic attraction between the charged particles and ground surface of the ash box; due to gas-dynamic, thermos-phoretic and space charge phenomena. The thermos-phoretic precipitation takes place due to temperature difference between the gas flow and ash box wall, especially in the bottom part of the ash box. Among the electrostatic precipitation, the electrostatic agglomeration of particles takes place inside the ESP. The particle loaded gas flows through the 2nd electrode system, where particles are further charged and precipitated preferably due to electro-hydrodynamic phenomena. The precipitation of charged particles and agglomerates take place in the gas output section of the ESP casing under the influence of the space charge phenomena. The gas flow with reduced particle concentration moves outside the ESP through the gas output.

3 Results of experimental study of the prototype ESP

During the experimental study, the pilot ESP (Fig. 2,a) was installed at the test facility (Fig. 2,b) which was equipped with a wood-chips boiler with heat power capacity of 100 kW. The cylinder form pilot ESP had a height of 800 mm. The heigh of the casing was 330 mm. The diameter of gas input and output tubes was 150 mm. The heigh of ash box was 300 mm with diameter of 360 mm. The weight of the ESP was 14 kg without collected fly ash. ESP casing and ash box, being manufactured from the stainless steel, were grounded. The pilot ESP was not thermo-insulated. The ESP design assumed manual cleaning of the ash box and electrode systems. The pilot ESP was designed to be operated at gas flow rate up to 227 kg/h, what corresponded to gas volume flow rate about 300 m^3/h at gas temperature T=200°C.

Fig. 2,a

Fig. 2,b

Fig. 2. Pilot electrostatic precipitator (a) at test facility (b)

The width of the electrode gap between the barbed electrodes and the lateral wall of the ash box in the 1st and the 2nd electrode systems was 35 mm. A DC negative polarity corona discharge was applied for particle charging. The maximum voltage of HV power supply unit was U_{max}=22,1 kV and maximum corona current was I_{max}=2,1 mA. The maximum power consumption of HV power supply unit was P_{max}=60 W. The HV unit was equipped with a microchip, which ensured automatic switch on/off of HV generation at T=70 °C. The measurements of particle mass concentration in the gas upstream and downstream the ESP were carried out simultaneously, using two analysers type SM 500 (Fa. Wöhler).

The experiments were directed to the study of the influence of boiler and ESP parameters on the precipitator opeational stability and particle collection efficiency. During the boiler operation, the measurements were carried out for various gas flow rates. The exhaust gas temperature varied between 180-210°C, depending on wood chips quality and boiler operation parameters. The maximum gas volume flow rate downstream the boiler was 310 m³/h. The ESP was tested at exhaust gas flow rates of 90-100 m³/h; 135-145 m³/h and 205-220 m³/h, respectively.

The pressure drop in the prototype ESP was mesured for various gas flow rates (Fig.3). The experimental data were approximated with a 2nd grade polinomial function (Fig. 3, “x” is gas mass flow, “y” is pressure drop).

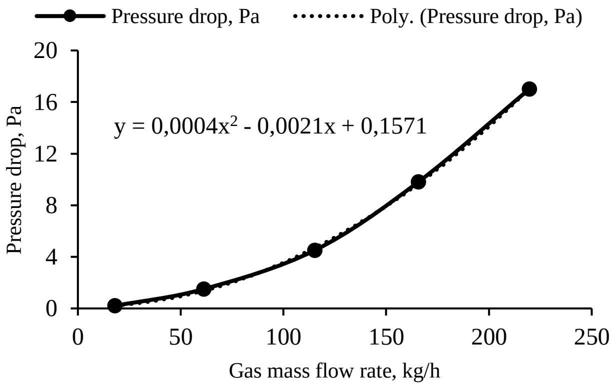

Fig. 3. Pressure drop in the pilot electrostatic precipitator

The gravimetric measurements upstream and downstream the ESP were carried out for variable values of corona discharge power consumption. The results are presented in the Fig. 4-6. The mass collection efficiency η was calcuated as

$$\eta = \frac{C_{up} - C_{down}}{C_{up}}, \quad (1)$$

where C_{up} and C_{down} were particle mass concentration upstream and downstream the ESP. At constant applied voltage U=22,1 kV, with grow of gas flow rate, a slight decrease of corona current from I=0,7±0,05 mA to I=0,53±0,03 mA was observed. The ESP collection efficiency decreased with increase of gas flow rate (Fig. 7).

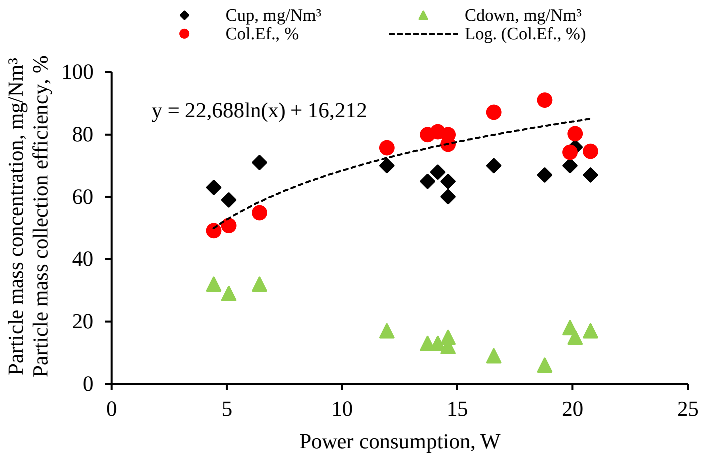

Fig. 4. Particle mass concentration in the gas flow upstream and downstream the ESP, and particle mass collection efficinecy, gas flow rate 90-100 m³/h

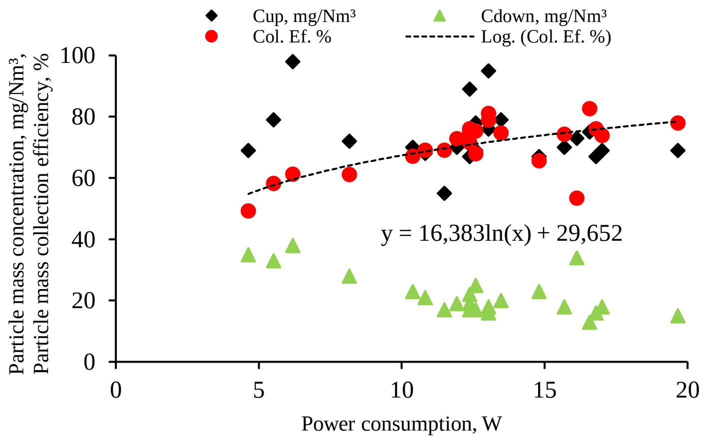

Fig. 5. Particle mass concentration in the gas flow upstream and downstream the ESP, and particle mass collection efficinecy, gas flow rate 135-145 m³/h

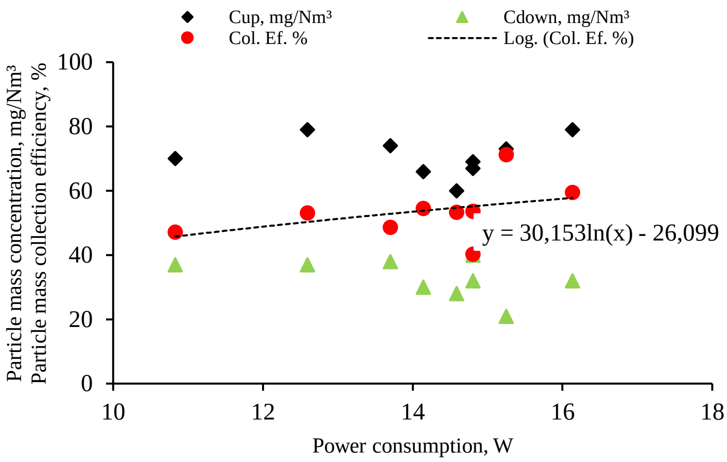

Fig. 6. Particle mass concentration in the gas flow upstream and downstream the ESP, and particle mass collection efficinecy, gas flow rate 205-220 m³/h

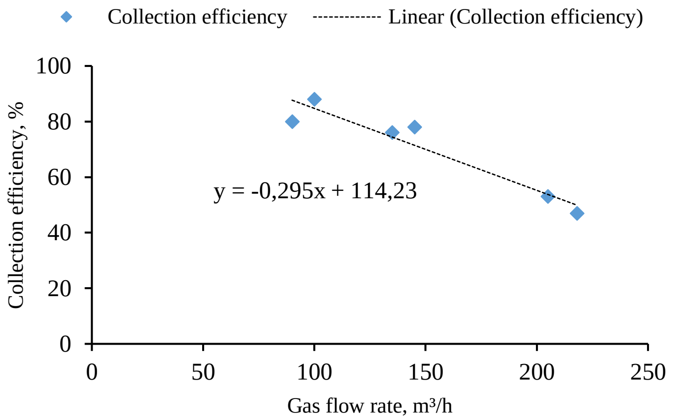

Fig. 7. Particle mass colllction efficiency in dependence on exhaust gas flow rate

The increase of gas velocity in the ESP resulted in decrease in particle residence time in corona discharge field, and in decrease in the efficiency of particle charging. The reduction of the efficiency of particle charging resulted in decreasing of charged particle precipitation in the ash box under the influence of electrostatic attraction forces and space charge phenomena.

The operation stability of the ESP was studied during the test campaign. Particle mean mass concentration in the exhaust gas upstream the ESP was 73±5 mg/Nm³ and downstream the ESP it was 17±2 mg/Nm³. With 40% tolerance of measurement equipment, the mean particle mass concentration in the gas flow downstream the ESP was defined to be 11±2 mg/Nm³. The mean mass collection efficiency of the prototype ESP was 75% (Fig. 8).

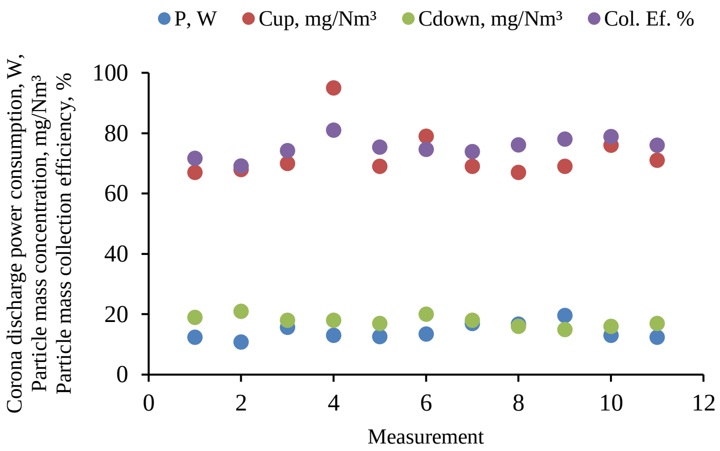

Fig. 8. Operational stability of the prototype ESP, exhaust gas temperature 150±10°C, mean power consumption of corona discharge 15±5W

4 Observations and discussion

Wood combustion could be devidied into three phases. The 1st phase, so called "pre-coombustion", takes place at the beginning of the process and is characterized with increase in exhaust gas temperature. If the temperature inside the ESP is lower than dew point, the condensation takes place inside the precipitator casing. At these conditions, the loading of HV insulator with the condensate takes place, what results in leakage currents alongside the insulator lateral surface. To avoid the leakage currents, in the prototype ESP the HV is switched on when the temperature of the casing is higher than the dew point one. The control is realized via the temperature sensor, connected to the HV power supply unit.

The 2nd phase, so called "stable combustion", is characterized by rather constant exhaust gas flow, gas temperature and particle mass and number concentrations. During the ESP operation, due to electrostatic charging of particles, the corona suppression takes place. At the same value of applied voltage, the corona suppression is characterised with the decrease of corona current in comparison with the clean air conditions. From the other hand, the operation in a hot gas results in increase in corona discharge current in comparison with air flow at room temperature conditions. The effect of increasing of corona current in a hot gas can "compensate" the current decreasing due to corona suppression. Hence, for the stable operation, the control of applied voltage in the ESP plays a decisive role. In the designed ESP, to enhance the efficiency of particle charging, the HV power supply unit regulates the applied voltage. The microchip control algorithm takes into consideration not only the effect of gas temperature and corona suppression, but also number of the spark-over discharges, which appeare in electrode system.

The 3rd phase, so called "post-combustion", takes place when no fuel is delivered into the combustion facility, but the combustion chamber is still full with glowing charcoal. This phase is characterized with a slow decrease of gas temperature.

During the glowing phase, the concentration of ultra-fine particles in the exhaust gas remains high, but the corona suppression descreases and corona current increases, what provokes spark-over discharges. Therefore, during the post-combustion, the HV unit automatically decreases the operational voltage and reduces the number of spark-over discharges. When the temperature of the ESP casing decreases below the defined value, the microchip switches off the high voltage and the HV power supply unit remains in stand-by.

Ash is one of the byproducts, generated during wood combustion. In the current study, no chemical analysis of the collected fly ash was done, but the results of the previous study, discussed in [12], have shown that during the wood-chips "pre-combustion", the concentration of carbon in the ash increased in comparison with another combustion phases. The density of fly ash, collected in an ESP, was 3-4 times lower than the density of the boiler bottom ash. The concentration of most of metals in the ash, collected in boiler heat exchanger and in the ESP, was higher than in the boiler bottom ash. In the fly ash, the concentration of K and Zn was 2-4 and 20-30 times higher, than in the bottom ash, respectively.

Usually, in the ESP a HV insulator is manufactured from a dielectric material, preferably Teflon or ceramics. In the prototype ESP, a quartz glass is used, what ensures the mechanical and thermic stability of the HV insulator at temperature up to 1000°C. The quartz glass HV insulator is installed above the gas input, what minimizes the direct loading of the insulator with particles from the direct gas flow.

In the designed prototype ESP, the loading of the lateral surface of barbed electrodes with dry fly ash does not disturb the corona discharge characteristics. The condensation inside the ESP casing results in a wetting of fly ash, collected on the lateral surface of barbed electrodes, what provokes partial loading of sharp points of corona discharge electrodes with "fly ash caps". During the operation with hot gases, the solidification of "fly ash caps" takes place. The observations show, that with increase of applied voltage, the spark-over discharges from the loaded corona point partly break up the solidified "fly ash caps", and this "self-cleaning" effect regenerates corona discharge. The observations also show, that the loading of the lateral surface of the grounded ash box and partition wall with fly ash could provoke back corona discharge. If the frequency of spark-over discharge due to back corona passes over the defined level, the applied voltage is step wise decreased. The HV unit continues to control the number of spark-overs, and if their frequency decreases, the applied voltage is step wise increased to its next operational level.

5 Compact ESPs for variable gas flow rates

The results of the study were used for the development of the industrial ESPs for the reduction of particulate emission from wood combustion facility with heat capacity 4-100 kW. The attention was given to the ESP operational safety at variable conditions and to the electromagnetic compatibility of the ESPs. The ESP mechanical stability and tightness were tested and proved. The parameters of the designed ESPs are presented in the Table 1. The example of the maintenance of an ESP downstream a wood combustion boiler is shown in the Fig. 9. The tests of the compact ESPs have confirmed mean mass collection efficiency of 76%.

Table 1. Technical parameters of the ESPs for small scale biomass combustion facilities.

Parameter	Electrostatic precipitator		
	ESP-1	ESP-2	ESP-3
Boiler heat capacity, kW	≤ 20	≤ 60	≤ 100
Height, cm	721	725	823
Diameter, cm	203	303	363
Ash box volume, l	8	20	30
Weight (without collected ash), kg	10	12	15
Exhaust gas temperature, °C	≤ 400	≤ 400	≤ 400
Max. gas mass flow rate, g/s	0,0125	0,037	0,063
Max. pressure drop, Pa	≤7	≤ 10	≤ 17
Corona discharge voltage, kV	≤22	≤22	≤22
Max. corona current, mA	≤1,4	≤1,7	≤2,0

Fig. 10. Compact electrostatic precipitator downstream a wood combustion boiler

6 Conclusions

In the current work the results of the study of a compact electrostatic precipitator for reduction of particualte emissions from from small scale wood combustion facilities with heat capacity up 4-100 kW are discussed. In the ESP the surface of the grounded ash box is used as an opposite electrode, what simplifies the design of the ESP. In the ESP, particles are electrostatically charged and agglomerated in the corona discharge field and due to space charge phenomena inside the ash box. The precipitation of particles takes place under the influence of electro-hydrodynamic, gas-dynamic, space charge and thermo-phoretic phenomena, and due to electrostatic attraction forces between charged particles and grounded surface inside the ESP. The use of smart HV power supply unit allows the regulation of applied voltage in dependence of operation conditions. The study of the ESP confirmed that the developed compact electrostatic precipitator ensured effective reduction of particulate emissions from exhaust gases. The mean mass collection efficiency of the ESPs was proved to be 76%.

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