ELECTROSTATIC PRECIPITATORS FOR SMALL STRAW BOILERS

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ABSTRACT: Straw combustion generates a high concentration of particle emission. Particulate matter in ambient air is associated with health problems. Therefore, there is a need for a filter technology to clean the flue gas and achieve an effective reduction of dust emission from biomass boilers. The aim of this work has been to develop and optimize electrostatic precipitators for small biomass boilers. Focus has been on a filter connected to a 150 kW manually stoked batch straw boiler. In order to ensure low emissions, a high flexibility of the ESP is required, ie. an accurate regulated ratio between the heating time of the ESP and the boiler operation must be guaranteed inclusive operation at partial load and especially during start-up. Control automation as well as effective mechanical systems for removing dust deposits on discharge electrodes and plate collectors have been developed and tested. For a set-up with the 150 kW manual batch stoked straw boiler results show a filter efficiency of about 95 percent. The PM in the cleaned flue gas is 6-16 mg Nm^{-3}. The technology will contribute to increase the use of biomass and help in reducing in overall CO_2 emissions by substitution of fossil energy with renewable biomass.
Keywords: Combustion, particle emission, biomass, straw, small scale application.

1 INTRODCION

The interest of renewable energy and thus the use of biomass have increased over the last decades. Straw, wood, wood chips and similar biomass can contribute to the substitution of fossil energy. Combustion is the most mature technology for utilization of these biomasses. However, biomass combustion causes pollutant emissions of NO_X, SO_2, CO, volatile organic compounds (VOC) and particulate matter (PM). Particular straw combustion generates a high concentration of particle emission. Particulate matter in ambient air is responsible for adverse health effects and has been identified, as main indicator of the health relevance of air pollution [1]. Therefore, there is a need for a filter technology to clean the flue gas and achieve an effective reduction of dust emission. For straw combustion the particles are so fine that they cannot be excreted by means of standard cyclone systems [2, 3]. Fabric filters may be an option, but are not optimal for small scale batch fired straw boilers due to high pressure loss (energy demand), and risk of fire [4]. However, an effective and low-cost filter solution for small biomass boilers is crucial for the use of these boilers in the future both in Denmark and in the rest of Europe [5, 6].

For large scale biomass combustion applications emissions are minimized by different abatement technologies. This is not the case for small scale applications such a stoves and straw boilers. In most cases the emissions are not controlled, and the combustion may have unwanted consequences [7].

In case of poor or incomplete biomass combustion, particles of solid carbon (soot) may occur in the flue gas [8]. However, under conditions of complete combustion, particle emissions primarily result from the release of inorganic material from the fuel, and such particles consist mainly of K, Cl, S, Na although the principal element is K [4, 9, 10].

In Denmark there is no threshold for PM from small straw boilers. However, from 2022 it is expected that the current derogation for straw expires, and the European Standard EN 303-5 [11] for smaller straw-fired boilers will be fully implemented. The threshold for automatically and manually fed boilers will be 40 mg Nm^{-3} and 60 mg Nm^{-3} of solid PM in the flue gas respectively. These thresholds can only be met by using some kind of flue gas cleaning technology.

Electrostatic precipitator (ESP) technology can be used for cleaning the flue gas. [12, 13, 14, 15, 16]. However, the flue gas from straw combustion contains a very high amount of dust and the particles form dust with a high resistivity. Therefore, in an ESP for straw boilers the most important problem is the back corona. The thickness of the dust layer on the collecting plates must be reduced to a minimum if the filter should have high efficiency. For batch stoked straw boilers a particular challenge arise due to the on-off operation of the boiler including start-up with insufficient temperature in the ESP. Traditionally ESPs are operated at steady state [12, 17].

This project is aimed at ESP for small straw-fired boilers. Beside the challenges concerning back corona, on-of operation and low flue gas temperature during start up, focus is on the control program for the high voltage and current regulation, type of discharge electrodes, collecting plate spacing, mechanism for removing the electrostatically fixed dust layers from both collecting plates and discharge electrodes and overall management at minimum power consumption.

2 MATERIALS AND METHOD

The project is a collaboration between companies and a university. The companies Alcon and Reka produces biomass boilers and Reka moreover have newly started a production of electrostatic precipitators for automatically continues fed biomass boilers. Alcon focus on the production of manual stocked batch straw boilers whereas Reka focus on automatically stoked boilers. Aarhus University, department of engineering, has conducted research in biomass combustion for many years. The research has focused on optimizing the combustion process as well as technological solutions for the purification of the flue gases. Several projects have involved industrial partners. Based on literature and existing knowledge within project partners experimental models have been constructed, tested and optimized in the laboratory.

2.1 Laboratory test facilities

Test and measurements have been conducted in the biomass combustion laboratory at Aarhus University, Figure 1. The laboratory has facilities for developing and test of small biomass boilers. The primary object of the projects and the research that is being carried out at the laboratory is to improve the efficiency of smaller biofuel plants, reduce emission of environmentally damaging substances. Straw is the main biomass, but the work include incineration experiments with other types and different combinations of biomass.

Figure 1: Biomass combustion laboratory at the Foulum campus of Aarhus University

The capacity of the laboratory is dimensioned for boilers up to 1MW. The standard measurement set-up includes: Inlet temperature (Pt-100), outlet temperature (Pt-100), water flow (Inductive flow meter), flue gas temperature (Thermo element), available draught (Micromanometer), O_2 in flue gas (Paramagnetic detector), CO-content in flue gas, 0-1000 ppm (infrared detector), CO_2 detector, NO_x detector, hydrocarbon detector, SO_2 detector, flue gas dust content and flue gas conditioning (heating coil + refrigerant type dryer). Biomass moisture content is calculated by drying a sample at 105°C until constant weight. Ash content is calculated by heating/burning a sample in a muffle oven at 550°C during 3 hours. Boiler capacity and emissions can thus be documented for the actual tested equipment

2.2 Electrostatic precipitator principle

An electrostatic precipitator consists of positive and negative electrodes which are connected to a high voltage supply, Figure 2. The fundamental principle is that PM are passed through the electric field where the particles initially receives an electric charge and then the charged particles (negative charged) are deflected across the field to be collected on the positive charged electrode, Figure 3 [12, 16].

The voltage level is 10-100 kV, depending on the filter size and design. The positive electrodes are traditional formed as large steel plates mounted with a mutual distance of 100-400 mm, thereby forming parallel channels between the plates. A set of discharge electrodes are placed between the positive charged plates, - the collection plates [18, 19]. The flue gas is passed in a horizontal flow in these channels. Another and very simple design of an ESP consists of a cylinder with a thin wire stretched along the axis of the cylinder. In this case, the cylinder wall form the grounded positive collector electrode and the wire form the discharge electrode.

Electrostatic precipitators are operated near the sparking limit; i.e., corona voltage is continuously adjusted to maximize the collection efficiency. Besides optimal energization of an electrostatic precipitator by correct voltage and current, several other factors must be controlled to achieve a good performance. The flue gas velocity profile should be even to fully utilize the capacity of the electrostatic precipitator. Also, the flue gas flow outside the active collection sections should be minimized. Keeping the electrodes clean is also of great importance, especially when eliminating the harmful effects of high-resistivity dust. Dust of high resistivity, over about 10^9 Ωm, will form a tight barrier on the collection plates, causing accumulation of electric charge leading to back-corona discharge [12, 13, 19]. The collected dust is normally removed by rapping forces [18, 20], which are generated by mechanical impacts or by vibration of electrodes,- either mechanical or by sound valves, but this techniques is not sufficient for removing dust in case of flue gas from straw combustion [2, 4].

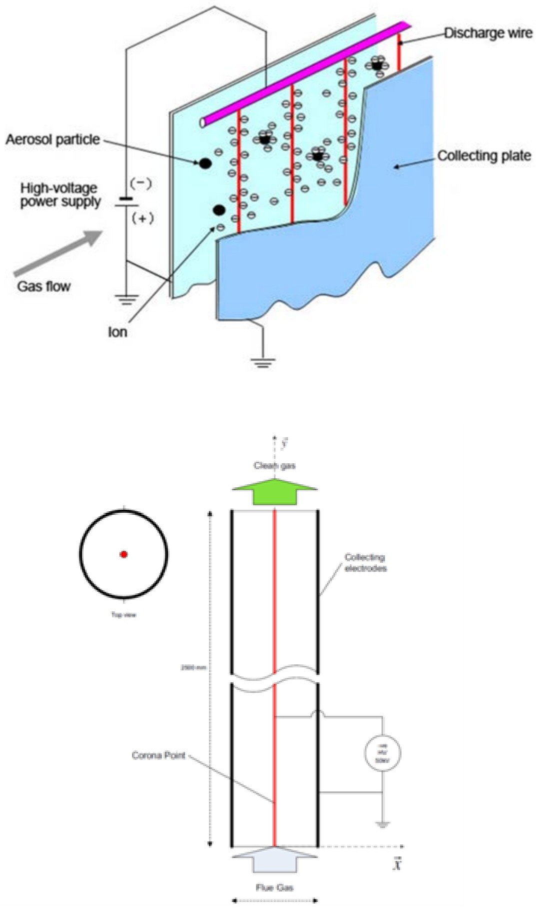

Figure 2: Two types of ESP. Wire-plate type and a tubular ESP (Schematic diagram by Hitachi and [16].

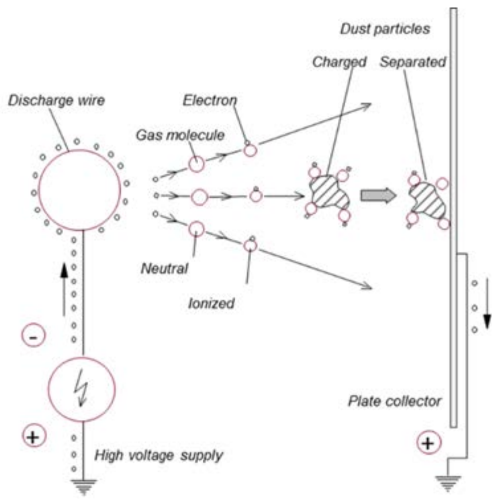

Figure 3: Corona discharge and the precipitation process in a wire-plate filter. Airborne particles are charged by the ions causing them to cluster and be caught in the filter.

The flue gas from straw fired boilers contains both a very high amount of dust and the particles produced are of the type leading to dust with a high resistivity. Therefore, in an ESP for straw boilers a very critical and important problem is the back corona. The layer thickness of the dust on the collecting plates must be reduced to a minimum if the filter should have a good cleaning effect.

2.3 Experimental ESP concept

This work has focused on developing a new ESP set-up with rotating collection plates with a mechanical system for removing the dust layer on the colleting plates [2, 4]. For removing dust deposits from the discharge electrodes and other critical parts of the filter housing, compressed air by chock blasters are used [4]. The basis developed ESP concept is shown in figure 4.

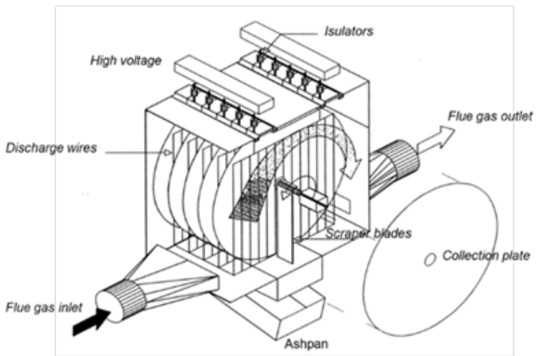

Figure 4: Principle drawing showing the working principle of the developed filters [2].

Based on this basis concept, ESP for different size of filters was built and tested. The number and size of collector plates, as well as distances between plates and distances between discharging wires, were optimized relative to different boiler sizes so that there is a base filter for respectively 4 - 20 kW, 20 - 80 kW and 80 - 200 kW chain output.

This first set of filters were all designed for automatic continuous stoked biomass and straw boilers. Next step has been the development of a filter for a batch fed straw boiler. At that type of boiler there will be lots of start-ups with a cold filter leading to condensation and thereby sparks and shot down of in the filter if no actions for heating is done. To achieve sufficient effect of the filter it must be active throughout the whole combustion period. Different methods and systems for heating up the whole filter or only the critical spots where sparks were seen during cold startup have been developed and tested. Finally an ESP with electric heating elements on the insulators has been developed and tested. These tests were conducted on purification of the flue gas from an Alcon 150 kW batch stocked straw boiler.

2.4 Particulate emission

Total solid particulate emissions were measured using an EN 13284-1 sampling train using isokinetic conditions. A 28 mm quartz wool filter in combination with a 45 mm flat filter were used. The filters were dried and weighed before and after the passing of a known quantity of the combustion air. This figure was then converted to a standard mg Nm^{-3} value at 10 percent oxygen by using conversion factors

3 RESULTS

For an ESP automatic control of current and voltage is crucial. Different voltage supply and control systems has been developed and optimized for the current filter size. Focuses has been on ensuring a robust and inexpensive control system that can handle the special challenges on the flue gas from straw, wood pellet and wood chips in small boilers (4 - 200 kW).

The developed PLC based automatic control program aims high as possible filter voltage without too many sparks. When the sparking limit is reached and a spark occur, the voltage and current are shortly shut down. The control system then automatically increases the voltage and current to the maximum level again. In the control system, a start-up phase is included for starting with a cold filter. For ESP's designed for small wood pellet boilers with capacity of 10-20 kW, a relatively simple control unit has been developed. Here a fixed constant voltage and current is set during operation without continuous regulation.

To overcome the specific problem on batch fed boilers which occur due to the on-off operation, including start-up with insufficient temperature in the ESP, modifications were tested. Heating up of the filter housing through heating of filter surfaces by mounting radiator unit supplied with hot water did not secure sufficient high temperature in the filter prior to start-up. A system with heating elements on the insulators showed good results and seems to be sufficient. A temperature of 85°C on the insulators was achieved after about 90 minutes. Hereafter the boiler could be started and the ESP worked effectively throughout the whole combustion period without shut downs in the start-up phase due to low temperature, condensation and sparks.

3.1 ESP for pellet boiler with heat output 4 – 20 kW

Filters for smaller plants must be adapted to the current operating conditions, including the fact that an energy-efficient wood pellet boiler operates with a relatively low temperature of the flue gas. Two prototype filters have been developed and gave satisfactory operating results. An

ESP with two channel and rotating plate collectors with a diameter of 250 mm, is shown in figure 5.

Figure 5: ESP for smaller wood pellet boiler. The filter is with two channels and rotating plate collectors with a diameter of 250 mm.

In order to get a simple and inexpensive ESP for the small pellet boilers, a very simple automatic control unit has been developed and tested. After the start-up period, the control automatic just secure a pre-set fixed filter voltage.

Results from experiments with a constant voltage of 18 kV are shown in Table 1. The cleaning efficiency decreased slightly compared to the test with a more advanced controller. However, a high cleaning effect was obtained and the PM of the purified flue gas was about 5 mg Nm^{-3}, and thus below the existing limit values. The power supplied to the filter high voltage unit was approx. 10 W.

Table 1: ESP efficiency. Fixed filter voltage of 18 kV. Automatic stoked 10 kW wood pellet boiler.

Operating set-up	Test no.	Flue gas		Mass collection efficiency
Boiler: Reka TPK - wood pellets Boiler capacity: 10 kW		Inlet	Clean gas	
		PM, mg/Nm^3 (10% O_2)	PM, mg/Nm^3 (10% O_2)	%
Flue gas temperature. Before/after the filter: 110/90°C	1	41	3	93.2
	2	43	6	86.6
	3	42	6	85.0
	Avg.	42	5	88.3

3.2 ESP for pellet and chip boiler with heat output 20 - 80 kW

For pellets and wood chip boilers in the performance range of 20 - 80 kW, an ESP filter with 4 channels and rotating plate collectors with a diameter of 600 mm has been developed.

Using the automatic control system where the applied voltage and current are regulated and optimized as near as possible to the sparking limit and thus the highest possible cleaning efficiency good results were obtained. Experiments and measurements have been carried out during the purification of flue gas from wood pellets, straw pellets, wood chips and baled straw combustion. Results from testing with wood pellets and straw pellets used as fuel in a Reka 40 kW boiler are shown in table 2. High cleaning effect was obtained and the PM of the purified flue gas was for wood pellets and straw pellets 2 and 16 mg Nm^{-3} respectively. A mass collection efficiency of 97-98 percent was achieved.

In order to examine the maximum capacity of the filter, it was tested on a 200 kW automatic fed biomass boiler. Experiments were carried out on wood chips and wheat straw. When combustion wood chips, an efficiency of 91 percent was achieved. The PM in the purified flue gas was 33 mg Nm^{-3} and thus below the limit value of 40 mg Nm^{-3} (CEN 2012). However, the results on straw combustion showed a poorer and insufficient cleaning of the flue gas for this ESP and the 200 kW boiler. The PM in the purified flue gas was 151 mg Nm^{-3} and the mass collection efficiency on average 79 percent.

Table 2: ESP for pellets and chip boiler in the range 20 - 80 kW. Results on wood- and straw pellets.

Operating set-up	Test no.	Flue gas		Mass collection efficiency
Boiler: Reka Boiler capacity 40 kW		Inlet	Clean gas	
		PM, mg/Nm^3 (10% O_2)	PM, mg/Nm^3 (10% O_2)	%
Wood pellet Flue gas temperature inlet filter: 125°C	1	49	0.4	99.3
	2	84	4	96.1
	Avg.	67	2	97.7
Straw pellet Flue gas temperature inlet filter: 135°C	1	664	18	97.3
	2	664	13	98.0
	3	676	18	97.3
	Avg.	670	16	97.5

3.3 ESP for manual stoked batch fed straw boiler with heat output 80 - 200 kW.

This ESP has 5 channels and rotating plate collectors with a diameter of 900 and the insulators are mounted with heating elements. The discharge electrodes consisting of suspended thin steel wires. The ESP is shown in figure 6.

As for the ESP developed for 20 – 80 kW biomass boilers, the automatic control system regulated and optimized voltage and current as near as possible to the sparking limit. In the control program a pre-heating period of 90 minutes of the insulators were included. Experiments and measurements have been carried out on purification of flue gas from combustion wheat straw bales in a batch-fired 150 kW Alcon boiler.

Figure 6. ESP for batch fired straw boiler. The filter is with a system for heating-up the insulators prior to start of the combustion and flue gas purification.

Before the experiments and tests of the ESP the manually stoked Alcon boiler was adjusted to ensure optimal combustion processs for this boiler. The main parameter to be controlled is the oxygen concentration in the flue gas. The variation of flows in primary and secondary air is automatically regulated based on oxygen content (lambda probe) and temperature of the flue gas going out of the boiler. The total measured volume of flue gas from the boiler was of about 500 m^3 per hour. Besides the oxygen content and the flue gas temperature the CO content in the flue gas was measurede during the combustion tests. Figure 7 shows the evolution of a trial running in the perioed from 8h 24m until 13h 12m. A trial comprises combustion of a 200 kg wheat straw bale. Moisture content was about 13 percent and ash content about 3 percent in the straw used for the trials.

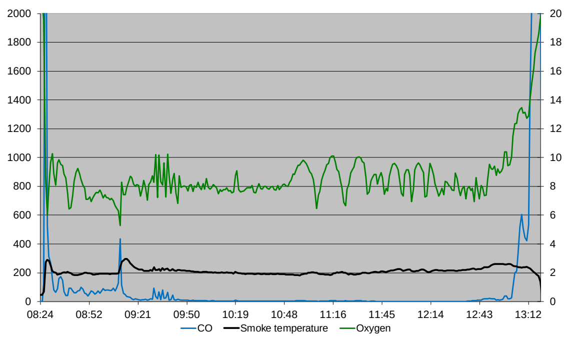

Figure 7. Time evolution of straw combustion in the Alcon boiler. Concentrations of O_2, CO and flue gas temperature. The oxygen percentage is on the axis to the right, CO concentration (ppm) and smoke temperature (°C) on the axis to the left.

Largest emission concentrations arise mainly during ignition / start up and extinguishing of the combustion process. The figure of the evolution of the combustion trial shows a first stage with high CO content and after a few minutes a fast raise of the flue gas temperature and a initial adjustment of the oxygen content to about 8 percent is seen. After the start up fase the combustion process becomes very steady with a low CO content in the flue gas and a flue gas tempertur of about 200°C. Low CO content in the flue gas is an indicator for a correct combustion process. Around 9h 05m a peak in CO and a drop in O_2 is seen. This might be caused by changes in bale structure leading to slight different in patterns of flame distribution. Finally, when almost all the straw in the boiler chamber is burned, optimal combustion can not be obtaind, and a raise in O_2 and CO content is seen.

Overall, a very good combustion process were achived for this Alcon manual stoked batch straw boiler. The boiler meets the requirements according to CO content in the flue gas for class 5 manual stoked boilers according the CEN 305-5 Heating boilers – Part 5 European standard.

Subsequently, tests were conducted concerning purification of the flue gas for particle matter by connecting the ESP to the boiler exhaust gas outlet. Results from the tests are shown in table 3.

Table 3: ESP for batch stoked straw boiler. Results on wheat straw bales in a 150 kW Alcon boiler.

Operating set-up	Test no.	Flue gas		Mass collection efficiency
Boiler: Alcon 1220 BA Boiler capacity: 150 kW		Inlet	Clean gas	
		PM, mg/Nm^3 (10% O_2)	PM, mg/Nm^3 (10% O_2)	%
Wheat straw bales	1	158	8	95.1
	2	148	7	95.4
	3	163	6	96.2
	4	348	9	97.6
	5	354	14	96.4
	6	336	16	92.1
	Avg.	251	10	95.5

When combusting baled wheat straw in the Alcon batch stocked boiler, a purification efficiency of 95.5 percent was achieved. The PM of the purified flue gas was 10 mg Nm^{-3} and thus below the limit value of 60 mg Nm^{-3} for manual stocked batch fired boilers (CEN 2012). In general, the particle emission is lower for the automatically stoked plants compared to manually stoked batch boilers. Therefor it can be assumed that this ESP also will be sufficient for automatically stoked straw boilers with the same nominal heat output.

4 CONCLUSIONS

ESP's have been developed and tested for particulate matter purification of flue gas from small scale biomass boilers. A major challenge has been the development of an ESP for manual batch stoked straw boilers, where the ESP must be running throughout the entire combustion period, including start up and extinguishing of the combustion. For manual batch stocked straw boilers a system for heating up the insulators in the ESP to prevent condensation and sparks due to moisture were successfully developed and tested.

The ESP components, such as rotating plate collectors, discharge electrodes, high voltages supply and the control unit have provided a sufficient and steady design through the experiments and test.

Results from experiments with an ESP for small wood pellet boilers showed sufficient performance when using a simple control unit applying a constant filter voltage. The cleaning efficiency decreased slightly compared to the test with a more advanced controller. However, even with the simple control unit a high cleaning effect was obtained and the PM of the purified flue gas was about 5 mg Nm^{-3}, and the mass collection efficiency 88 percent.

Automatic control system where the applied voltage and current are regulated and optimized near as possible to the sparking limit and thus the highest possible cleaning efficiency is obtained, have been tested on ESP's for automatically stoked biomass boilers in the range of 20 – 40 kW heat output. High cleaning effect was obtained and the PM of the purified flue gas was for wood pellets and straw pellets 2 and 16 mg Nm^{-3} respectively. A mass collection efficiency of 97-98 percent was achieved.

For a set-up with a 150 kW manual batch stoked straw boiler and an ESP with the automatic control system where the applied voltage and current are regulated and optimized as near as possible to the sparking limit, a filter mass collection efficiency of about 95 percent was achieved. The PM in the cleaned flue gas was 6-16 mg Nm^{-3}. The developed technique for heating up the high voltage insulators in the filter prior start of the boiler and filter, secured steady run of the ESP throughout the entire combustion period.

The developed system with a separate ESP unit is very flexible. The ESP don't have to be used in combination with or adapted to a specific boiler type or a particular boiler mark. ESP's of various sizes have been developed and thereby solutions are available and might be adapted to the current boiler heat output and the current type of biofuel used.

The developed ESP technology has proven good overall effect in lowering the dust concentration of exhaust flue gas from biomass combustion. Thus, the system can contribute to increase the use of biomass and help in reducing in overall CO_2 emissions by substitution of fossil energy with renewable biomass e.g. straw and wood.

5 REFERENCES

[1] Rückerl, R., Schneider, A., Breitner, S., Cyrys, J., Peters, A., 2011.Health effects of particulate air pollution: a review of epidemiological evidence. Inhal. Toxicol., 23 (10), pp. 555-592

[2] Kristensen, J.K., 1999. Smoke purification for small straw boilers. Electrostatic precipitator. (In Danish) DJF Rapport Markbrug nr. 20, Danmarks JordbrugsForskning.

[3] Berhardt, A; Lezsovits, F; Groß, B., 2017. Integrated Electrostatic Precipitator for Small-Scaled Biomass Boilers. Chemical Engineering & Technology, Volume 40 (2), pp 278 – 288.

[4] Kristensen, E. F., Kristensen, J. K., Speiermann, M., Linnemann, N., 2016. Development of electrostatic precipitators for small biomass-fired boilers. Proceedings of the 24th European Biomass Conference and Exhibition. ETA - Florence Renewable Energies, 2016. p. 661-665.

[5] Bologa, A., Paur, H. R., Woletz, K., 2011. Development and study of an electrostatic precipitator for small scale wood combustion. International Journal of Plasma Environmental Science and Technology, Vol.5, no. 2.

[6] Schmatloch, V., Rauch, S. 2005. Design and characterisation of an electrostatic precipitator for small heating appliances. Journal of electrostatics, 63(2), 85-100.

[7] Carroll, J, Finnan, J., 2017. Use of electrostatic precipitators in small-scale biomass furnaces to reduce particulate emissions from a range of feedstocks. Biosystems Engineering, Volume 163, pp 94-102.

[8] Bafver, L. S., 2008. Particles from biomass combustion-characteristics and influences of additives. PhD thesis, Chambers University of Technology, Goteborg, Sweden.

[9] Nussbaumer, T. (2003). Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. Energy Fuels, 17(6), 1510 - 1521.

[10] Johansson, L. S., Tullin, C., Leckner, B. Sjovall, P., (2003). Particle emissions from biomass combustion in small combustors. Biomass and Bioenergy 25, pp 435 – 446

[11] CEN, 2012. 305-5. Heating boilers – Part 5. Heating boilers for solid fuels, manually and automatically stoked, nominal heat output up to 500kW - Terminology, requirements, testing and marking. European Committee for Standardization

[12] White, H. J. 1963. Industrial Electrostatic Precipitation. Addison-Wesley Publishing company, Inc. Pergamon Press.

[13] Jaworek, A., Krupa, A., Czech, T. 2007. Modern electrostatic devices and methods for exhaust gas cleaning: A brief review. Journal of Electrostatics

[14] Poskas, R., Sirvydas, A., Jankauskas, J. 2014. Investigation of the removal efficiency of an ESP in a residential biomass boiler. Recent Advances in Environmental Science and Biomedicine

[15] VDI 3678, 1980. Elektrische Abscheider. VDI-Richtlinien.

[16] Dastoori, K., Kolhe, M., Mallard, C., Makin, B. 2011. Electrostatic precipitation in a small scale wood combustion furnace. Journal of Electrostatics, 69(5), 466-472.

[17] Nussbaumer, T., Lauber, A., 2016. Monitoring the availability of electrostatic precipitators (ESP) in automated biomass combustion plants. Biomass and Bioenergy, Volume 89, pp. 24-30.

[18] Navarrete, B., Vilches, L.F., Rodriguez-Galan, M., Alonso-Fariñas, B., Cañadas, L. 2014. A pilot scale study of the rapping reentrainment and fouling in electrostatic precipitation. Environmental Progress & Sustainable Energy 34.1.
[19] Jaworek, A; Czech, T; Rajch, E; Lackowski, M., 2006. Laboratory studies of back-discharge in fly ash. Journal of Electrostatics, Volume: 64 Issue 5, pp. 306-317.
[20] Fischer, T., Graß, N. Zouzou, N.Dascalescu, l.,Greil, R., Hopf, N. 2014. Smart Home Precipitator for Biomass Furnaces: Design Considerations on a Small-Scale Electrostatic Precipitator. IEEE Transactions on Industry Applications, Vol. 50, no.3.

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