Guidelines for the design and application of particle precipitators for residential biomass combustion

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Preface

ERA-NET Bioenergy is a network of national research and development programmes focusing on bioenergy which includes 14 funding organisations from 10 European countries: Austria, Denmark, Finland, France, Germany, Ireland, The Netherlands, Poland, Sweden and the United Kingdom. Its mission is to enhance the quality and cost-effectiveness of European bioenergy research programmes, through coordination and cooperation between EU Member States. The project *FutureBioTec* (Future Low Emission Biomass Combustion Systems) has been supported in the period between October 2009 and September 2012 by ERA-NET Bioenergy under the joint call on Clean Biomass Combustion from 2009.

The European Union and its member States aim at an increased use of renewable energy in order to avoid a further increase in atmospheric CO_2 concentrations and therefore, the European Commission actively supports the utilisation of biomass for energy production. However, this aim must be achieved without increasing other harmful emissions such as fine particulate matter ($PM_{2.5}$), nitric oxides (NO_x), carbon monoxide (CO) and organic compounds (OGC, PAH). Therefore, especially regarding the small and medium-scale heating sector, where a great potential for biomass utilisation all over Europe exists, the promotion of energy from biomass must be accompanied by further technology development towards low emission combustion systems.

Against this background, the project *FutureBioTec* aimed to provide a substantial contribution concerning the development of future low emission stoves and automated small and medium-scale biomass combustion systems (<20 MW_{th}). Considering the different states of development of the combustion technologies and capacity ranges addressed, the project focused on the following main objectives.

- The further development of wood stoves towards significantly decreased CO, OGC, PM and NO_x emissions by primary measures (air staging and air distribution, grate design and implementation of automated process control systems).
- The improvement of automated furnaces in the residential and the small to medium-scale (<20 MW_{th}) capacity range towards lower PM and NO_x emissions by primary measures (staged combustion, utilisation of additives as well as fuel blending).
- The evaluation, development and optimisation of secondary measures for PM emission reduction in residential biomass combustion systems.

In order to reach these objectives, a consortium of 8 research organisations and 2 industrial partners from 7 European countries collaborated within FutureBioTec (see next page).

This document summarizes experiences from comprehensive test runs of existing particle precipitation devices for residential biomass combustion systems. The target groups of this report are manufacturers of residential combustion devices, retailers, and central authorities. Furthermore, the report may also be of interest to consumers and researchers.

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Industrial partners

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Table of contents

1 Introduction and objectives

Residential biomass combustion is one of the main sources of PM2.5 in ambient air, besides traffic and industry. High concentrations of PM2.5 in the air are a health risk and consequently are regulated in an EU directive [1]. Ways to reduce particle emissions from small-scale biomass combustion systems are primarily the utilization of modern combustion technologies and secondarily the use of small-scale precipitation devices as it is estimated that it might be challenging to reach future ambitious emission limits even for new combustion systems. At present, there are several small-scale precipitation devices (primarily electrostatic precipitators) under development and some are already available on the market [2].

1.1 Target group

The aim of this work is to present generic guidelines for the design and application of electrostatic precipitators for residential biomass combustion systems. Criteria to be fulfilled by a residential ESP that works well are provided. The target groups of this report are manufacturers of residential combustion devices, retailers, and central authorities. Furthermore, the report may also be of interest to consumers and researchers.

2 Definitions and limitations

2.1 Basic definitions

Electrostatic precipitators (ESPs) have been used for decades to clean particles from flue gases in large-scale industrial processes. To clean such relatively large gas volumes, the most suitable ESP design is usually of the parallel-plate type, as outlined to the left in Figure 1. On the other hand, for the smaller gas flow of a residential furnace, a tubular ESP design (to the right in Figure 1) may be preferred because it is easier to accommodate either in or on top of the chimney.

The main (vital) parts of an ESP are:

- Discharge electrode (which confers a charge on the particles entering the ESP)
- Collecting electrode (to which the charged particles are attracted)
- High-voltage power supply

Necessary auxiliary parts include high-voltage insulators, a control system and a system to remove dust collected on the collecting surfaces.

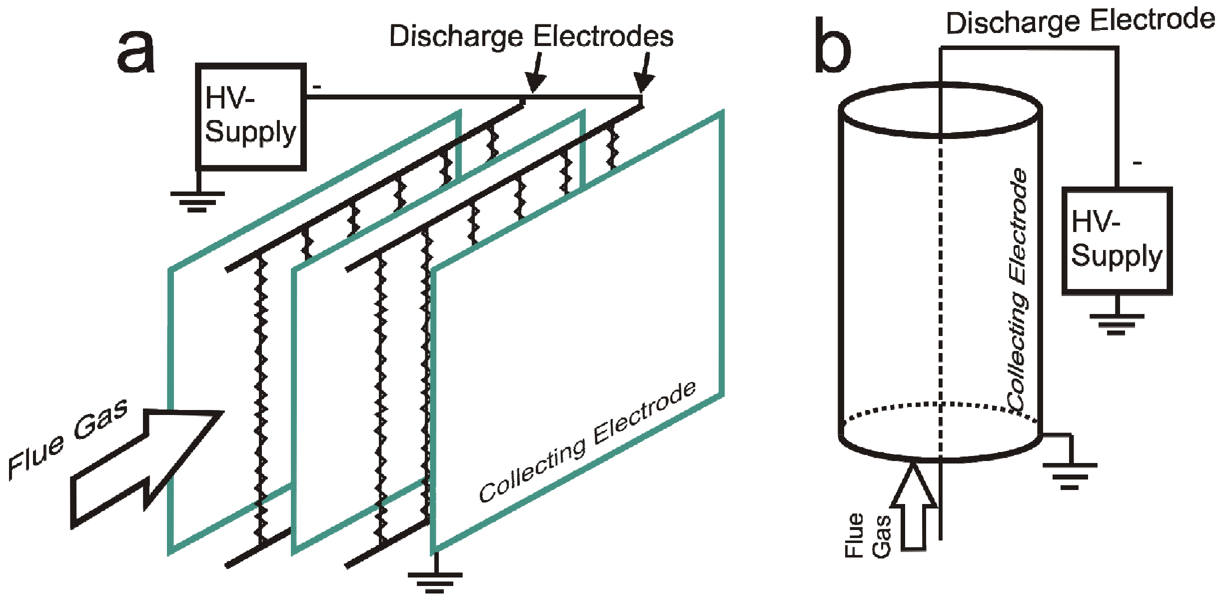

Figure 1: Principles of two common ESP designs: a) Parallel plates, b) Tubular.

An ESP for residential furnaces may be placed somewhere between the furnace and the exit of the chimney. For example, if the house has a boiler, the ESP can be placed in the boiler room. For a chimney stove, the ESP may be placed either next to the stove, in the flue gas duct, or outdoors on the top of the chimney.

2.2 Limitations

The present guidelines cover electrostatic precipitators for residential biomass combustion systems with a nominal boiler capacity up to 50 kW as well as for residential wood stoves. Furthermore, these guidelines are limited to generic descriptions of what to expect from a residential ESP. How this can be accomplished is not described in detail, although a few examples are given in certain instances in order to improve understanding of the issue.

3 Design criteria

Design criteria can be derived from the basic technological functions of ESP systems as well as from a practical user’s perspective, i.e. the ESP should be easy to use. In these guidelines, both aspects are covered together.

3.1 Technology

Electrostatic precipitators seem to be the most promising option for small-scale residential applications. Other options such as as catalytic converters and ceramic filters may exhibit a high pressure drop. Catalytic converters are typically not available during start-up (where high emissions occur) and may show problems regarding deactivation and deposit formation.

3.2 Efficiency

An ESP should aim to considerably reduce particle emissions and meet emission requirements (for example 40 mg/m_N^3, at 13 % O_2, for wood stoves in Germany after 01/01/2015 [3]). To meet such requirements, a residential ESP should typically show a collecting efficiency of at least 75% during normal operation. In large-scale ESP systems, the collecting efficiencies are usually higher than 90% and that should also be the target for small-scale filters.

There are many design parameters of the ESP as well as process parameters of the combustor that determine the actual collecting efficiency. Basically, under ideal conditions (turbulent flow, perfect mixing and immediate charging etc.) the collecting efficiency (η) may be estimated from the Deutsch equation [4]:

$$\eta = 1 - e^{-De}$$

in which *De* is the Deutsch number:

$$De = \omega \frac{A}{Q}$$

where ω is the migration velocity of particles, *A* the surface area of collecting electrodes and *Q* the volumetric gas flow.

The Deutsch equation shows that the collecting efficiency increases with the ratio between collecting surface area and gas flow. For instance, this ratio can be improved by using longer electrodes in a tubular ESP, although a larger surface area might also increase the power required to operate the ESP. Another way to expand the collecting surface area is by enlarging the diameter of a tubular ESP. In this case, the longer distance between electrodes calls for an increased voltage between electrodes to attain the same electrical field strength. Another consequence is that the particles in the flue gas will have to migrate a longer distance, on average, perpendicular to the direction of the flow to reach the collecting electrode. Thus, in practice, the ESP performance will deteriorate if the distance between electrodes becomes too wide. The Deutsch equation also shows that the collecting efficiency is improved by lowered flue gas temperature (which affects *Q*). The temperature also affects the resistivity of the fly ash, which is one of many process parameters that determine the value of the migration velocity (ω) in the Deutsch equation. This ω is a key design parameter for ESPs and it depends on a large number of factors such as: particle size distribution, particle density, gas velocity, gas composition, gas temperature, etc. It is also affected by the voltage between electrodes since the force acting on charged particles depends on the electrical field strength. A deeper and more detailed explanation, as well as calculation of the migration velocity, can be found in [5]

It is important to be aware of the fact that for low resistivity dust, such as fly ash from wood, the collection efficiency of an ESP increases with the power consumption, which can be controlled by the high-voltage supply unit. This trend holds up until a threshold voltage is reached where sparkovers or even arcs start to form between electrodes. At the onset of sparks, a further increase of power does not improve ESP performance, rather on the contrary. For maximum collecting efficiency, the voltage between electrodes should be as close to the onset of sparks as possible. However, in some cases it may be possible to significantly lower the power consumption while maintaining sufficiently high collecting efficiency. Nevertheless, when comparing ESP performances it is important to compare both collecting efficiency and power consumption.

The collecting efficiency of an ESP will generally benefit from clean electrode surfaces, because dust build-up in the filter may cause entrainment of dust into the gas stream and/or lower the sparkover onset voltage. Both these processes reduce the collection efficiency. Therefore, it should be a goal of an ESP-designer to keep surfaces clean during long term operation, for instance by including some kind of cleaning mechanism in the system.

3.3 Installation

Correct installation is crucial for the function of an ESP. Installation should be performed by a professional. To ensure proper installation, a well-written manual should be available. For chimney-top devices, lightning protection shall be considered.

3.4 Pressure drop

A design with a low pressure drop over the ESP is required in order to avoid influences on the boiler/stove operation. Otherwise, a high pressure drop may cause poor combustion conditions and decreased burnout quality due to reduced combustion air supply which typically results in increased CO, OGC and PM emissions. The low pressure drop is particularly important for stoves and other combustion systems that depend on natural draft to supply the air.

3.5 High voltage and electrode

A residential ESP needs a high-voltage power supply, typically a voltage in the range of 15-30 kV. Furthermore, the recommendations with respect to high voltage and the discharge electrode are:

- Thin discharge electrodes with sharp surfaces are preferred to achieve a high charging efficiency (e.g.: needle or sawtooth profile, etc.)
- Frequent sparkovers should be avoided by the high-voltage control system (since they are noisy, reduce the collection efficiency and increase the power consumption). Some observed reasons for frequent sparkovers are:
    - Too flexible discharge electrode, which can start to vibrate during operation

- Poorly aligned electrodes, with locally too short distance between electrodes
- Conductive deposits on insulator parts
- A high moisture content in the flue gas and an ESP temperature below the dew point causes condensation
- Deposition of particles as well as surface condensation of condensable organic vapours on the insulator (should be avoided, by e.g.: purge air, heating or an appropriate geometric design)

3.6 Control system

A control system is important for the function of an ESP.

For automated boilers and stoves, an interface between the ESP and the control system of the stove/boiler should be provided to appropriately manage start-up and shut down procedures. For stove and boiler systems without automatic control, the ESP control system should detect start-up and shut down of the furnace by using a temperature sensor in the flue gas duct, e.g. by temperature changes in the flue gas.

The control system should also include the operation of a cleaning system for the electrode and the collection surfaces. It should also be possible to manually suppress the cleaning process, e.g. in case of chimney sweeper’s measurements.

3.7 Maintenance and availability

A basic requirement is that an ESP should be available for a whole heating season without any maintenance, except for cleaning by a chimney sweeper, if required. A robust design is necessary to avoid damages during the sweeping process. Simple, safe and quick access should be provided for cleaning and inspection. Weak points may be the insulators and the high voltage system. Robust and well-proven technical solutions are a basic requirement in order to ensure reasonable availability.

There is a need to consider how the efficiency and the availability are influenced by condensable and sticky particles present in the flue gas as a result from poor combustion conditions, which are typical for old stoves/boilers as well as during start-up. For instance, an appropriate automatic cleaning system may prevent deteriorated performance from particulate fouling.

It is useful to have internal logging of the ESP operation versus operation of the combustion device in order to determine the unit’s availability and to be able to prove the operation to any authority, if such information is collected during inspection routines.

3.8 Applicability

There should be a special focus on the applicability of filters for old systems which exhibit great particle reduction potentials and rough operation conditions (high amounts of condensable organic compounds and soot). Moreover, an ESP precipitator can also be suitable for stoves, although in this case only roof-top or in-chimney applications make sense.

Suppliers should be asked for the applicability of their ESP for different combustion devices and be able to provide references that the ESP can fulfill required collecting efficiency and reasonable availability.

3.9 Cleaning

The dust collected on the surfaces in the ESP has to be removed sooner or later. There are two main methods to accomplish this:

- The ESP is equipped with an efficient, automatic cleaning system (at least for the collecting surfaces but it is also recommended to clean the high voltage electrodes). This is typically done by either: vibration, a brush, or a water spray.
- Cleaning by the chimney sweeper or the user.

Automatic cleaning systems for the electrode and the collection surfaces are strongly recommended.

3.9.1 Solid waste: ash, coke and soot

Irrespective of the cleaning method there will be a solid waste product consisting of ash, coke and soot. This solid waste may contain harmful substances and should be handled as hazardous material. It has to be handled according to the legislation in the respective country. Direct contact and inhalation of the particles should be avoided.

3.9.2 Waste water

If waste water is produced (e.g. by using a water spray cleaning system) it has to be handled according to the legislation in the respective country.

3.10 Safety

For safety reasons the ESP has to be a closed system to prevent leakage of flue gas to the surroundings, unless it is outdoors on the top of a chimney. Other safety aspects that should be considered are risks connected to the use of high voltages. Because of this, grounding of the ESP in a correct manner is important. As mentioned, chimney-top devices need to be provided with lightning protection. A minimum requirement is a potential equalization.

High temperature surfaces should be avoided to prevent burn injuries.

Fire safety shall be guaranteed during soot fire in the chimney, see for example the German safety test program [6]. The regulations may differ between countries and may also be less strict for chimney-top installations [7].

Safety instructions should be available on or close to the filter where maintenance and cleaning procedures are performed and ports should be labeled to prevent opening during operation.

3.11 Noise

Noise is a basic design criterion which should be considered. The origins of noise from an ESP could be for example from sparkovers, cleaning equipment and ventilation. However, there is no known information about acceptable noise levels available today. A certain level of noise should be acceptable if the ESP is on top of the chimney or placed in the boiler room. More work is needed to define acceptable noise levels. As already mentioned frequent sparkovers should be avoided by the high-voltage control system since they are noisy and also reduce the collecting efficiency.

3.12 Weather conditions

In many cases, residential ESP units are located on top of the roof or directly in the chimney. In such cases it is important to ensure that the ESP withstands different weather conditions, for example rain, snow and storms.

3.13 Costs

The costs of a residential ESP should be reasonable with respect to the costs of a stove or a residential boiler. Thus, rather simple and robust solutions are required for residential applications.

Furthermore, the operational cost of an ESP unit should be reasonable. Operation costs are directly proportional to power consumption if the pressure drop of the ESP system is small.

4 Quality assurance

The function of an ESP should be verified by an independent testing laboratory (especially its efficiency and availability). However, no common standard test method is currently available for type testing of residential ESPs. Therefore, it is difficult to compare test results from different laboratories. Below, some recommendations concerning the evaluation of the performance of residential ESPs are given.

4.1 Testing methods

General aspects regarding measurements at ESP units:

- The influence of charged particles on particle losses in sampling lines is not fully understood yet. More investigations are needed to provide recommendations with respect to this.
- The collecting efficiency of filters located on chimney tops cannot easily be evaluated in the field. Thus, appropriate test-stand measurements are needed. Furthermore, their availability must be monitored – e.g. by logging the voltage of the system together with the flue gas temperature as an indicator of the furnace operation.
- At test stand measurements, the field operation conditions of a specific filter have to be considered:
  - The position of the filter (directly coupled to the stove/boiler versus in-chimney or roof-top) should be comparable to the foreseen installation, because the position has a strong influence on flue gas temperature and aerosol formation from organic compounds.
  - The temperature at the filter inlet should be comparable to field conditions.
  - Temperature losses over the filter should be considered in the evaluation due to possible formation of organic aerosols.
  - Simultaneous dust measurements before and after the filter are recommended.
- As a recommendation, the test report shall provide the following information:
  - Mean collecting efficiency
  - Minimum collecting efficiency (at a confidence level of 95%, calculated from a number of replicate tests performed)
  - Average PM-concentration in the clean flue gas
  - Description of combustion system used
  - Fuel specification
- Test measurements should preferably be performed after the filter has been in operation for a considerable time, because the collecting efficiency is usually unrepresentatively high when the unit is new and clean.

Considering these aspects two different evaluation criteria for combustion systems equipped with an ESP can be defined:

1. **The mean and minimum collecting efficiencies** of the ESP calculated from the PM concentrations in the flue gas at ESP inlet and ESP outlet. This criterion is of interest from a technical viewpoint.
2. **Emissions of the system** calculated from the PM emission in the flue gas at ESP outlet. By measuring in diluted flue gas (diluted to below 50°C), the measured particle concentration will include condensable organic compounds that still are in gas phase at the ESP outlet. This measurement technique provides a more relevant value from an environmental viewpoint.

For combustion systems operating at high efficiencies (low flue gas temperatures) and good burnout (low amounts of condensable organic compounds), no significant difference is expected between measurements performed in diluted and undiluted flue gas. On the other hand, for old systems (poor burnout, high flue gas temperatures) significant differences may occur. For old systems, lowering the operating temperature in the ESP improves the precipitation of particles. Moreover, lower operating temperatures typically reduce the stickiness of the particles and enhance the formation of particles from gaseous organic species upstream the ESP, which improve the precipitation potential. Lower operation temperatures can be achieved by chimney top applications.

A standard test method for determining the collecting efficiency of a particle precipitator is currently being elaborated in Germany. This VDI Guideline 33999 [8] will have the status of a full national standard. It is supposed to be suitable for secondary retrofit units applying electrostatic, filtering, catalytic, condensing, washing or centrifugal principles, or a combination of these.

5 Conclusions

Electrostatic precipitation (ESP) of fly ash is a well-established technique for flue gas cleaning in industrial processes. Smaller scale versions, to suit residential furnaces, are under development. In order to become widely used, such ESPs have to meet some criteria regarding efficiency, cost and availability. Furthermore, aspects of safety, noise and convenient installation have to be considered.

There is a lack of commonly accepted methods for testing the efficiency of residential ESPs. The set-up and sampling methods used may considerably affect the test results. Thus, caution should be applied when comparing results from ESPs tested under different conditions.

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