

Review of critical parameters in biomass combustion emissions control by means of hybrid filter

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Abstract. Control of particulate matter emissions by means of hybrid filter has been included in the experimental plan of a research project in the field of Mediterranean agro-forestry waste biomass combustion at medium scale. Application of hybrid filters to biomass combustion has not been thoroughly experimented so far. An identification of the most important parameters in particulate matter emissions control by means of a hybrid filter was undertaken. The filter involves two of the most significant technologies in fly ash emission control, electrostatic precipitation and fabric filtration. A discussion of these parameters and principles of operation of said technologies is presented, as well as the final selection of parameters to be included in the experimental matrix of the project in regards to emissions control. A novel approach is proposed for testing of filtration velocity influence in fabric filter module without impacting on operation of electrostatic precipitation module.

1. Introduction

The project "Integrated strategy to predict, monitor and ensure the sustainability of the combustion of agricultural and forestry waste biomass"(CLEANBIOM) is intended to facilitate the management and sustainable operation of medium scale decentralized combustion units, firing Mediterranean agro-forestry waste biomass. Its general objective is to develop a comprehensive strategy, for the prediction, control, and minimization of the pollutants generated in the combustion process of waste biomass in the Mediterranean basin region. Fly-ash is prominently included among these pollutants. Mediterranean biomass may show significant differences in composition from North European sources, since species are different. Also, biomass waste consists mostly on small branches and bark which show composition peculiarities compared to other plant parts [1].

The experimental data on combustion and emissions control will be obtained in CEDER-CIEMAT, on a scale comparable to actual production plants, aimed to combine comprehensive and size segregated characterization of primary and secondary atmospheric pollutants, ashes and precursors of corrosion. The pilot plant incorporates a bubbling fluidized bed combustion plant (1 MW nominal output) and emissions treatment line provided with control sensors and sampling stations. This line has a hybrid filter that integrates electrostatic precipitation (dry, wire-parallel plates) and fabric filter modules, which has been previously used in other research



projects [2]. Very little research work has been done so far on the application of hybrid filters to biomass combustion [3].

The project work plan includes an exhaustive identification of all and each one of the parameters that can influence the process of combustion (efficiency) and emissions and their control through the application of different technologies. Afterwards, a plan of experiments that will ensure the attainment of objectives will be designed. In this sense, the critical parameters in the control of particulate matter emissions have been identified. A necessarily limited selection of the most relevant parameters for inclusion in the experimental matrix of the project has been conducted.

2. Fundamentals of electrostatic precipitators and fabric filters operation

2.1. *Electrostatic precipitators*

The operation of an electrostatic precipitator (ESP) involves basically two physical phenomena [4]:

- Electric charging of particles (by diffusion and field charging).
- Movement (migration) of charged particles in an electric field to the collection electrodes.

The charging mechanism is based on the migration of ions present in the gas towards the surface of the particles, either by Brownian diffusion (key for particles smaller than 0.2 μm), or driven by electric field (key for particles larger than 1 μm). Ions are produced in the precipitator continuously by a corona discharge (localized electrical breakdown) in the region near the emitting electrodes.

The simplest approach at ESP efficiency modeling is based on a material balance on particles in a cross section of the precipitator. The following expression for overall collection efficiency of an electrostatic precipitator, known as the Deutsch-Anderson equation [5], is derived:

$$\eta = 1 - \exp \left[-w \left(\frac{A}{Q} \right) \right]$$

where:

η : Mass collection efficiency of the precipitator (ratio between the mass concentrations of fly ash at the exit and at the entrance of the precipitator $\eta = C_1/C_0$).

w : Migration velocity of particles (terminal velocity of charged particles in the electric field)

A : Surface area of collection electrodes exposed to electric field.

Q : Volume flow rate of gas through the precipitator.

Migration velocity, from theoretical considerations, should be proportional to the diameter of the particle and to the product of charging and collecting electric fields (in single-stage precipitators one single field plays both roles), as shown in the following expressions, applicable to coarse and fine particles, respectively:

$$w = \frac{\varepsilon \varepsilon_0}{\varepsilon + 2} \frac{d_p E_c E_m}{\mu}$$

$$w = \varepsilon_0 \frac{d_p E_c E_m}{\mu} C_c \left[\left(1 + \frac{2\lambda}{d_p} \right)^2 + \frac{2}{1 + \frac{2\lambda}{d_p}} \frac{\varepsilon - 1}{\varepsilon + 2} \right]$$

where:

$\varepsilon, \varepsilon_0$: Particle and vacuum dielectric constant, respectively

μ : Gas viscosity
 λ : Gas mean free path
 d_p : Particle diameter
 C_C : Cunningham correction factor
 E_c, E_m : Charging and collecting electric field, respectively.

In industrial practice, use of Deutsch-Anderson model presents constraints due to its numerous assumptions (plug flow, absence of particle diffusion, uniform distribution of particles) and the lack of consideration for practical adverse phenomena (bypass flow, collected ash resuspension, etc...). In addition, fly ash is usually polydisperse rather than of a uniform particle size. Migration velocities are difficult to estimate on a purely theoretical basis, thus experimental values obtained for aerosols of different nature are essential to be used.

A model similar to the Deutsch was proposed by Matts-Ohnfeldt [6]:

$$\eta = 1 - \exp \left[-w_k \left(\frac{A}{Q} \right)^k \right]$$

where:

w_k : Average migration velocity

k: Constant, usually between 0.4 and 0.6

This model modifies the relationship between the specific collection area (A/Q) and precipitator efficiency, reflecting the fact that, in practice, the area increases needed for a given improvement of efficiency are greater than those estimated by the Deutsch model.

Since the modern development of electronics provided widespread access to massive calculation capabilities, many procedures based on computational flow modelling have been used for the study and design of electrostatic precipitators,. However, in order to discuss the influence of the various factors involved, simple models such as those presented are enough.

2.2. Fabric filters

In fabric filter collectors dust is removed from the gas stream when dust-laden gas flows through a fabric. Woven fabrics or felts can be used, sometimes superficially coated by a porous membrane [7]. A wide range of materials is available (nylon, PTFE, etc...). A plate holding the sleeves or bags of filter media divides the filter module in raw and clean gas.

As filtration proceeds, retained dust forms a dust layer on the surface of filter media, known as filter cake, thus increasing the pressure drop across the filter. Therefore, it is necessary to periodically proceed to the cleaning of the filter, removing the dust cake to begin a new cycle of filtration.

According to the cleaning method, three sorts of fabric filter designs can be distinguished: shake, reverse flow and air pulse cleaning filters. In pulse cleaning filters the open ends of the sleeves are placed at the top. The gas flows from the outside towards the inside of the sleeves, leaving the dust retained on the sleeve's outer surface. A brief pulse of compressed air is released during the cleaning, typically in the order of 0.1 second, towards the inside of each sleeve through a nozzle located over its open end. In this way, a reverse flow of clean gas is induced through the fabric. Pulse air and clean gas expand the sleeve, forcing the release of the deposited dust. The pulse pressure is sufficient to dislodge dust without interrupting the flow of gas through the filter.

Particle penetration tends to be extremely low, except immediately after filter cleaning. There are models for the estimation of particle filtration efficiency in a porous medium [8]. However, in contrast to the electrostatic precipitator, filtration efficiency has no obvious relationship with the sizing of the equipment. The models usually used for filter sizing are those who estimate the pressure drop across the filter. The process involves the specification of gas flow rate and average pressure drop, from which the minimum required filter media area is

determined. The most widespread model for the relationship between pressure drop and gas flow rate treated in a filter sleeve is the following [9]:

$$\Delta P = \Delta P_r + K \cdot W \cdot \frac{Q}{A}$$

where:

ΔP : Pressure drop

ΔP_r : Residual pressure drop of a newly cleaned sleeve. Dependent on filtration velocity, the nature of the filter media and cleaning conditions.

K : Specific resistance of the dust cake

W : Surface mass load of dust over the filter media. Dependent on the dust concentration in the raw gas, filtration velocity and the time elapsed since the last cleaning.

The Q/A ratio is usually known as gas-to-cloth ratio or filtration velocity.

3. Critical parameters associated with the operation of electrostatic precipitators

As we have seen, the efficiency of an electrostatic precipitator depends on a number of basic parameters:

- Treated gas flow rate (gas velocity or residence time).
- Collection area. This parameter and the former are often grouped into what is called specific collection area (Q/A), the collection area to gas flow ratio.
- Applied electric potential.

Essentially, these are the parameters included in Deutsch, Deutsch-Anderson and Matts-Onhfeld equations for estimation of efficiency.

In addition to influencing the efficiency through specific collection area, it has been found that the *axial velocity of the gas* between the electrodes has an influence on migration velocity [10]. The typical minimum gas velocity is 1 m/s. Migration velocity increases with increasing axial gas velocity up to ≈ 2 m/s. For higher gas velocities resuspension of collected ash results in lower effective migration velocity.

Terminal migration velocity is conditioned by the *physico-chemical properties* of gas and particles, which determine their dielectric properties and the particle charging process. In this sense, and in addition to the variables listed in the equations, there is another fundamental parameter for the operation of the precipitators, the *resistivity of the particles*. This has two basic components: volumetric conductivity and surface conductivity. The first depends on the chemical composition of the particles and the second on the species adsorbed on the surface and the gas composition (water vapor, sulfur oxides, ammonia, and some other compounds). Resistivity also depends on the temperature. Increasing temperature increases electrical resistivity up to a maximum. Then, total resistivity drops as a result of lower surface resistivity at higher temperatures. For a given type of particle emission, the usual way of controlling the resistivity is by means of operating temperature of the gas and, on occasions, through the modification of the composition of the gas. To that end, injection of agents such as ammonia, water vapor or SO_3 has been used.

When the resistivity increases above $10^{11} \Omega \text{ cm}$, dust deposited on the collection electrode releases its electrical charge very slowly, which gives rise a potential difference through the layer of dust which partially neutralizes the electric field in the precipitator. The so-called reverse ionization or back corona occurs in extreme cases. Both effects adversely affect the efficiency of the precipitator. Low resistivities result in resuspension when collected ash easily releases its electrical charge, thus significantly decreasing the electrostatic force that holds ash to the collection electrode.

Regarding the resistivity values in the case of emissions from biomass combustion [11, 12], significant differences have been found between the soot, condensable organic compounds and

inorganic matter. Condensable organic matter presents the highest resistivity ($10^{10} \Omega\text{cm}$ at 150°C). That of soot is the lowest ($10^6 \Omega\text{cm}$ at 150°C). Inorganic matter resistivity values are intermediate, very close to the ideal for the operation of electrostatic precipitators ($10^9 \Omega\text{cm}$ at 150°C). However, the resistivity of the inorganic matter at temperatures under 120°C is reduced below the ideal value, approaching the lower acceptable limit for the operation of electrostatic precipitators.

Regarding the influence of the *granulometry of ash particles* of, fine particles hinder collection and favor resuspension. Electrostatic precipitators typically have a minimum fractional efficiency in the range between $0.4 - 0.5 \mu\text{m}$ [13].

4. Critical parameters associated with the operation of fabric filters

Too high *filtration velocity* leads to higher average pressure drop, which increases penetration of particles through the filter (lower efficiency) and necessitating a more frequent cleaning, which negatively affects the life-span of the filter media. On the other hand, too low filtration velocity results in excessively large and expensive equipment. So, this parameter influences both investment and operation costs. It also alters the balance between depth and surface filtration mechanisms, influencing the penetration of particles through the filter.

Regarding *particle size distribution* of the ash, finer particles lead to the formation of more densely packed cakes resulting in higher pressure drop for a given filtration velocity. The nature of the particles can be problematic, if adhesive or capable of strong electrostatic interactions that attach them permanently to the filter media. The impossibility of removing them will prevent the continuation of the filtration process.

With regard to the *composition and temperature of the gas*, it is crucial to avoid the condensation of water vapor that would result in an increase of pressure drop, and possible corrosion problems. On the other hand, the operating temperature must be below the maximum tolerated by the material of the filter media.

5. Parameters selected for experimental trials

To select the parameters to be tested it must be taken into account which of them show the highest potential influence, as well as the practicality of manipulation in the experimental facility, and which parameters are already given or limited by the type of fuel used, the combustion conditions, etc. For example, since the hybrid filter processes the whole of the combustion plant flue gas, it is not easy to modify the treated gas flow rate. The total collection area of the electrostatic precipitator is not easy to modify. Two parameters have been finally selected for trials in the project: the potential applied in the electrostatic precipitator and the filtration velocity in the fabric filter.

The first parameter affects various aspects of the process, such as the relative distribution of the captured fly ash between two modules in the hybrid filter, or the energy consumption of the process. At the same time, the proportion of fly ash passing to the fabric filter module affects the dynamics of this module, its energy consumption, the penetration of particulate matter through the filter media, etc. This is because, through migration velocity, the applied potential crucially influences the efficiency of electrostatic precipitator [14].

As stated, filtration velocity in the fabric filter module is another fundamental parameter. The usual approach of varying gas flow rate is problematic. Thus, to vary the filtration velocity the available surface area of the filter will be reduced by removing some filter bags in some experiments. Moreover, this procedure is advantageous in that it has no impact on the electrostatic precipitator module operation.

Different fuels will be tested within the project. This presumably will give rise to different combustion gas compositions, particularly in what refers to water vapor, and perhaps to fly ash

of different characteristics (particle size distribution, chemical composition, resistivity, etc...). So the occasion to observe the effects of other factors could present itself.

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