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Research paper

Performance analysis of different scrubber systems for removal of particulate emissions from a small size biomass boiler

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ABSTRACT

Biomass boiler plants of small thermal power (under 35 kW thermal), in particular for domestic heating, have greatly contributed to the rise in particulate emissions. Several technologies, like fabric filters or electrostatic precipitators, can achieve high particulate removal efficiency, over 99%. However, the application of these technologies is limited by excessive prices and operational problems, since the high cost does not allow their use in small size plants. The paper shows a comparative performance analysis of different scrubber systems which have been designed, realized and tested with flue gas produced by biomass combustion in a 25 kW thermal boiler. The experimental campaigns were realized in the laboratory of the Department of Industrial Engineering of the University of Bologna. Experimental results demonstrate the achievements of particulate removal efficiency which is comparable with the efficiency of industrial technologies. Moreover, a preliminary energy balance was carried out to assess the energy cost of the different scrubber systems tested.

1. Introduction

The use of renewable bioresources as energy sources or as alternatives to fossil-based feedstock for the production of thermal or electric energy, or both simultaneously [1], has recently received much attention. Biomasses in general seem to be realistic alternative fuels leading to environmental, technical and economic benefits. In fact, if compared to other renewable technologies such as solar or wind energy, biomass has few problems with energy storage because, in a sense, biomass is stored energy. Furthermore, biomass is a versatile fuel that can be used as gaseous, liquid or solid fuel. However, in order to further increase the share of energy produced from biomass plants, it is necessary to improve the critical issues which to date have limited their spreading. In particular, environmental impact and reliability [2] are identified as the most determining limits. The environmental impact due to conversion of solid biomass into energy, in particular in the combustion process in small size plants, is related to particulate matter (PM) emissions [3], which become a critical aspect if compared with the considerably lower PM emissions from a methane boiler (up to 1000 times lower PM emissions per kWh than a biomass boiler [4]).

PM from biomass combustion can be classified either as inorganic material, soot, or organic material, and the distribution varies with the combustion conditions for different fuels in different appliances. The amount of organic material is influenced by the combustion process efficiency, which can be negatively influenced by high moisture content of the fuel, reduced excess of air with respect to the necessary or imperfections in the design of the boiler [3,5]. The inorganic material emissions depend on the characteristics of the fuel. The fuel characteristics that mainly affects the PM creation are [6–8]: moisture and ash content lead to an increase in PM mass concentration; moreover, the composition of the ash may vary including problematic elements such as potassium, sulfur, sodium and zinc, which could lead to increased emissions.

The greatest amount of PM emissions from biomass combustion consists in particles with an aerodynamic diameter smaller than 2.5 μm [3,6,7,9], the so-called PM2.5. PM2.5 can be suspended in the air for a long time and carried away over long distances. Moreover, PM2.5 can cause serious problems to the environment and human health due to deep penetration into the respiratory system, where it can cause cancers and diseases. PM2.5 is also the main transporter of dioxins and the major factor responsible for global obscuration. Italy has transposed EU directive 2008/50/EC about the limits of PM2.5 in the air with the Legislative Decree 155/2010 establishing 25 $\mu g\ m^{-3}$ as the maximum annual average value.

Once PM is produced through a combustion process, a part

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would be removed from flue gas to complying with the emission limits set by national and local authorities, according to plant size [10]: for example, in Italy the PM emission limit for boilers below 150 kW thermal is 200 mg m^{-3} [11], which is a value high enough to not necessarily require the use of a PM filtration system. Allowing a higher PM emission limit for small size plants is reasonable since it takes into account both the impact on plant cost of the separation system (which may become unsustainable for non-industrial applications) and the lower impact which produces a single plant of small size, albeit characterized by higher emissions, compared to an industrial size plant. Nevertheless, the diffusion and density of small plants should also be considered: so, if numerous small size plants are present in a limited area (for example, in an urban framework), PM2.5 emissions from biomass boilers can strongly contribute to the local increase of pollution and unhealthy conditions.

Different technologies can be theoretically applied to further reduce, even below emission limits, the PM content in the flue gas produced by small size biomass boiler plants. Fig. 1 [12] shows the removal efficiency η, defined as in Equation (1), of different industrial separation systems according to PM size.

$$\eta = \frac{C_{IN} - C_{OUT}}{C_{IN}} \cdot 100 \quad (1)$$

C_{IN} is the PM concentration at the inlet of the filtration system, while C_{OUT} is the PM concentration at the separation system outlet, each concentration being expressed in mg m^{-3}, where m^3 is a unitary volume of air calculated under NTP conditions (273.15 K, 101.325 kPa).

Fabric filters [12–18] and electrostatic precipitators (ESPs) [18–20] have the highest removal efficiency (above 95% for ESPs, above 99% for fabric filters) for micron particle ranges. So, fabric filters and ESPs are the best technological options for biomass boilers. However, fabric filters have a high maintenance cost due to rapid clogging of the filter. Moreover, dust unclogging may be the cause of problems such as re-suspension of nanoparticles previously collected. Therefore, fabric filters are economically sustainable only in industrial applications. ESPs have a low maintenance cost, but high investment and operational (due to electricity consumptions) costs. Cyclones [21,22] as well as other inertial separation systems [23] present a very low installation cost, but work

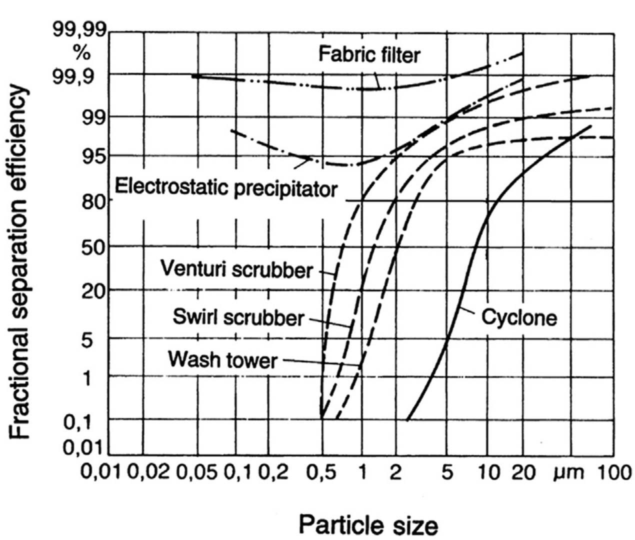

Fig. 1. PM removal efficiencies of conventional flue gas filtration system according to PM size [12].

well with a particulate size bigger than 10 μm, which is outside the desired application range (PM2.5). Scrubber removal efficiency is influenced by the capacity of each single water droplet to collect particles by using one or more of the scrubbing mechanisms, which are diffusion, interception and inertial impaction [24,25]. Diffusion is a particle capture mechanism based on Brownian motion and it is the dominant scrubbing mechanism for small particles (diameter lower than 0.1 μm), since small particles attain a high diffusion coefficient. Even if the trajectory of a particle does not depart from the streamline, a particle may still be collected through the interception mechanism if the particle passes within one particle radius from the droplet surface. Interception is the main mechanism for capturing particles with dimensions between 0.1 μm and 1 μm. Finally, inertial impaction is the predominant removal mechanism for scrubbers with particles larger than 5 μm, since it is influenced by droplet and particles size as well as their relative velocity. Fig. 1 clearly shows that common scrubbers, like Venturi or Swirl scrubbers as well as washing towers, have relatively high PM removal efficiency (over 95%) for PM size above 2–5 μm, diameters which are too high for biomass boiler flue gas. Bubble-column wet scrubbers represent a promising and interesting alternative for nanoparticle collection. In fact, starting from the first theory of absorption of particles in gas bubbles during their rise through a liquid (developed in the '60s) and coming to the more recent experimental studies [26,27], it has been demonstrated that the most predominant mechanism of PM removal in bubble-column scrubber is diffusion. So, a bubble-column scrubber, if opportunely supported by bubble micronization, has the potential to be competitive in terms of nanoparticle removal if compared with fabric filters and ESPs. However, few studies on bubble-column scrubbing of particles have been reported and none of them deal with the application in a real scale plant.

This paper shows the comparative performance analysis of different scrubber systems, including a washing tower, a Venturi scrubber, a bubble-column scrubber and a combined Venturi and bubble-column scrubber, which was carried out on the basis of experimental results regarding the removal efficiency of PM from flue gas produced by a 25 kW thermal biomass boiler.

2. Material and methods

2.1. Experimental test plant

An experimental test plant was designed to verify and evaluate how different scrubber systems can perform under the same working conditions. The Process Flow Diagram (PFD) of the pilot test plant is drafted in Fig. 2.

The core of the pilot test plant is a biomass boiler of 25 kW thermal heating capacity; produced by AL.PI, model RPM20.

Fig. 3 shows air and flue gas circulation in a biomass boiler. The air inlet takes place through the depression created inside the combustion chamber, when the extraction fan (A) is working. The air flowmeter is installed on the duct that leads to the air distribution chamber (B), before a manual valve (VC in Fig. 2) which is used for air flow regulation.

The air flow passes through the radial holes arranged around the top edge of the brazier (C), reaches the base of the flame and feeds it. The fuel hopper (D) is in the upper part of the boiler. A horizontal screw conveyor (E) transports the fuel from the base of the hopper up to a point where it falls (F) by gravity directly into the brazier. Fuel flow rate can be regulated through working time setting of the fuel feeding screw.

The energy released by the fuel combustion process in the brazier (shown in Fig. 4) is converted into heat in the combustion chamber by contact and irradiation, as well as through the cooling