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Research paper

Theoretical model and preliminary design of an innovative wet scrubber for the separation of fine particulate matter produced by biomass combustion in small size boilers

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ABSTRACT

Fine particulate matter (PM) emission from biomass boilers for non-industrial heating represents one of the most important causes (together with the transport sector) of air pollution, in particular during winter. Separation technologies for fine PM are already well-known and adopted on an industrial scale, as a consequence of strict limits set by national and international regulations. On domestic boilers, the same technologies utilized on an industrial scale are not feasible due to high investment costs. Moreover, the emission limits for small size biomass boilers are higher than for industrial boilers, so high efficiency separation technologies are not needed, and are sometimes not present at all. The main goal of the paper is the development and testing of a mathematical model that is able to foresee the PM removal efficiency of a wet scrubber device. After an experimental validation based on several tests, it was possible to approach the preliminary design of an innovative wet scrubber, which is described in the paper. The main characteristics are (i) removal efficiency over 99.9%, (ii) specific energy consumption under 36 kJ m^{-3}, which is an industrial reference, and (iii) relatively low investment, operation and maintenance costs.

1. Introduction

The use of biomass combustion for domestic heating has recently grown in many countries, due to government incentives and rising costs of other energy sources, such as traditional fossil-based fuels. Biomass is considered a renewable energy resource with CO_2-neutral balance, which can contribute to climate change mitigation. Therefore, biomass seems to be a realistic alternative fuel that can provide technical, economic and environmental benefits, but there are some critical issues which have limited even further use of this resource [1–4]. Biomass combustion, in particular in small size plants ($<$ 35 kW thermal power), produces higher particulate matter (PM) emissions than other fuels. Specifically, inorganic material in the flying ash and incomplete combustion residues, including soot, condensable organic particles (tar) and char, are the main sources of primary particulate emissions from biomass combustion [5,6]. Incomplete combustion is caused by unfavourable conditions such as inadequate mixing of air and fuel, low combustion temperature or short residence time. The characteristics of the boiler, the operating conditions and the fuel properties significantly affect the combustion process and, consequently, PM emission levels [7–9].

The greatest amount of PM emissions from biomass combustion consists of PM1, which includes particles with an aerodynamic diameter smaller than 1 μm [10]. PM mass size distribution from biomass combustion is similar for different sizes and types of boilers and for various biomass fuels [11–13]. In particular, a peak of PM size distribution was found in the range of 0.1–0.2 μm for a 20 kW pellet boiler, a 40 kW wood chip boiler and a 30 kW wood log boiler [14]. In new and old-type biomass small boilers, size distribution shows a maximum value at an aerodynamic diameter of around 0.13 μm, consistently with other investigations on fireplaces [15,16]. Particles from different biomass fuels (bark pellets, wood pellets and granulates from hydrolysis residues), burned in a 10 kW reactor under identical conditions, have the same size between 0.02 and 0.7 μm [17]. Due to its deep respiratory system penetration, fine PM can cause serious problems to the environment and to human health. Consequently, national and local authorities have set emission limits to reduce the impact of biomass plants, in relation to their size [18]. Since biomass combustion always produces PM, it can be removed from flue gas through separation devices. In Italy, the PM emission limit for boilers with a thermal capacity between 35 kW and 150 kW is 200 mg m^{-3} (considering Normal Temperature and Pressure conditions, which are 273.15 K and 101325 Pa,

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and 11% O_2 content), which is a value high enough to not necessarily require the use of a PM separation device. Moreover, unlimited PM emission for small size plants (< 35 kW) is allowed. The principle behind the limit setting is that a single small size plant produces a lower impact than an industrial one, even if small plant emissions are higher, and that the cost of a PM separation device may become unsustainable for non-industrial applications. However, taking into account the diffusion and areal density of domestic heating systems, if the number of small plants is high in a limited area (e.g. an urban framework), PM1 emissions from biomass boilers can strongly affect air quality and cause unhealthy conditions [19]. Therefore, in order to make biomass a sustainable alternative to traditional fuels and to further increase its spread in the field of domestic heating, it is necessary to limit the PM emission of small biomass plants through a separation device, which has to be suitable for non-industrial applications.

In industrial applications, different separation systems are currently applied to reduce PM emission from combustion plants. Available separation technologies vary in removal efficiency, collected PM size and costs [8,20]. Cyclones force the flue gas to perform a circular motion in order to separate suspended particulate, driven by its inertia. Cyclones, as well as other inertial separation systems [21], have low installation costs but operate on particles with an aerodynamic diameter greater than 10 μm, outside the range presented by biomass PM [22,23]. For sub-micron particle range, fabric filters and electrostatic precipitators (ESPs) have the highest removal efficiency. Fabric filters are mainly based on the sieve effect, produced by filtering textiles on which particles are captured. They have a removal efficiency of 99% for particle diameters lower than 1 μm, but also have high maintenance costs due to the rapid clogging of the filter, which can cause re-suspension of particles previously collected [24–26]. ESPs removal efficiency is 95% for sub-micron particles: PM is separated from the flue gas by the electric force generated by electrodes. ESPs have high investment and operational costs [27–29]. Higher costs make fabric filters and ESPs economically suitable only in industrial applications. Wet scrubbers remove pollutants (both gaseous and solid) through liquid droplets, typically water droplets, which perform one or more removal mechanisms: inertial impaction, direct interception and Brownian diffusion. Particles with diameter greater than 5–10 μm, characterized by a sufficient inertial force, are generally collected by impaction. Particles with a diameter between 0.1 μm and 1 μm do not have sufficient inertia to deviate from flue gas, but when they are close enough to the droplets, particulate collection occurs. Very small-sized particles (with a diameter smaller than 0.1 μm) are subject to Brownian motion and are collected by diffusion [30]. Wet scrubber systems have some advantages over fabric filters and ESPs: scrubbers are smaller and simpler, and also have lower capital and maintenance costs. Collection efficiency of wet scrubbers varies with the particulate size distribution and scrubber type. With design optimization, separation efficiency can be greater than 99% for sub-micron particles [20]. The main operating parameters are particle size distribution, gas velocity or gas flow rate, liquid-to-gas ratio, droplet size distribution, temperature and pressure drop [31,32]. One of the main disadvantages of wet scrubbers is that increased removal efficiency is related to an increased pressure drop across the system. There are many different types of scrubbers [20]. The simplest type of scrubber is the washing tower, in which flue gas contacts a liquid spray produced by nozzles, in counter-current, co-current or in a perpendicular direction. Washing towers have lower capital costs than other wet scrubbers. Washing towers perform particle capture primarily by impaction; in fact, typical removal efficiency can be 90% for particles larger than 5 μm, while below 3 μm the efficiency decreases to less than 50%. Another type of wet scrubber is the Venturi scrubber. In this case, water is injected with high pressure and is atomized to improve gas-liquid contact. Collection efficiency varies from 70% to 99% for particles larger than 1 μm, and is higher than 50% for sub-micron particles [33,34]. Increasing the pressure drop raises collection efficiency, but energy consumption also increases. Venturi scrubbers are therefore more expensive than washing towers for operational costs (while capital and maintenance costs are comparable), but removal efficiency for fine PM is generally greater. Tray tower scrubbers contain several perforated plates with different geometrical shapes in order to provide more gas-liquid mixing and contact. Tray towers have a high efficiency level (greater than 97%) for particles larger than 5 μm in diameter, but do not effectively remove sub-micron particles. Capital and operational costs are moderately higher than simple spray towers, but maintenance costs can be greater due to clogging of perforations by large PM. Packed scrubbers contain packing material, structured or randomly arranged, which provides a large wetted surface for gas-liquid contact [35–37]. Packing materials are available in a variety of shapes, each having specific characteristics, such as specific surface area, pressure drop, weight, corrosion resistance and cost. Bubble-column wet scrubbers represent a promising and interesting alternative for nanoparticle collection. In particular, it has been demonstrated that the most predominant mechanism of PM removal in bubble-column scrubbers is diffusion. So, if appropriately supported by bubble micronization, a bubble-column scrubber can be competitive in terms of nanoparticle removal compared with fabric filters and ESPs, even if studies on the application of bubble-column scrubbing of particles in a real scale plant are not yet available [38].

Table 1
Characteristics of PM separation devices, such as particle size, efficiency, costs and disadvantages.

PM separation technology	Collection Efficiency	Optimized for PM (μm)	Equipment, operating and maintenance costs	Main disadvantages
Cyclones	95% ($d_p > 10\,\mu m$) 80% ($d_p < 5\,\mu m$) 40% ($d_p < 3\,\mu m$)	> 10	Low equipment, operating and maintenance costs	High efficiency only on coarse particles
Fabric filters	99% ($d_p > 0.5\,\mu m$) 95% ($d_p < 0.5\,\mu m$)	> 0.5	Low equipment costs, high operating and maintenance costs	Rapid clogging of the filter
ESPs	95% ($d_p > 0.8\,\mu m$) 85% ($d_p < 0.8\,\mu m$)	> 0.8	High equipment and operating costs	High investment costs for ESP adaptation to residential applications and sophisticated control and safety systems
Washing towers	90% ($d_p > 5\,\mu m$) 50% ($d_p < 3\,\mu m$)	> 5	Low equipment, operating and maintenance costs	High efficiency only on large particles
Venturi scrubbers	70–99% ($d_p > 1\,\mu m$) 50% ($d_p < 1\,\mu m$)	> 1	Low equipment and maintenance costs, high operating costs	High pressure drop and electric energy consumption
Tray scrubbers	97% ($d_p > 5\,\mu m$)	> 5	Low equipment and operating costs, high maintenance costs	Clogging of the plates
Packing scrubbers	99% ($d_p > 2\,\mu m$) 50% ($d_p < 1\,\mu m$)	> 2	Low equipment, operating and maintenance costs	Possible uneven airflow distribution
Bubble scrubbers	95% ($d_p > 2\,\mu m$) 70% ($d_p < 2\,\mu m$) 90% ($d_p < 0.1\,\mu m$)	> 2 < 0.1	Low equipment, operating and maintenance costs	Difficult bubble micronization