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Particulate Matter Emission Reduction from Pellet Boilers: Status, Potentiality and Challenges

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The status of particulate matter (PM) emission reduction methodologies applicable to non-industrial pellet boilers (<500 kW) are summarized and the potentiality of PM emission reduction from these appliances as well as the related challenges are reported. The primary and secondary control methods are presented by indicating the particulate matter removal mechanisms involved and the abatement performances observed.
Primary control measures based on boiler design, air-staging, optimized process control and fuel-quality-enhancement are found to be successfully applied for PM reduction from pellet boilers but may not be sufficient to comply with more and more stringent emission regulations without combination with secondary measures. It emerges that promising results have been obtained for some secondary methods (e.g., metal mesh filters, electrostatic precipitation, wet scrubbers, open-cell ceramic filters) in terms of abatement performance but many operational issues (e.g., deterioration of performances with ageing, high maintenance need, unsustainable pressure drops, eventual waste streams etc.) are still to be minimized for these systems to constitute a feasible solution to PM control especially in smaller appliances for residential heating.

1. Introduction

The European Union has established the objective of a climate neutral Europe by 2050 involving energy transition strategies contemplating decreased greenhouse gas emissions, increasing renewable energy penetration, and maximising benefits from efficiency (Bertelsen and Vad Mathiesen, 2020). A strategy following sustainable and affordable solutions that combines the reduction of greenhouse gases with the reduction of pollutant emissions is imperative. Several decarbonization scenarios with local heat supply strategies (i.e., district heating, state-of-the-art biomass technologies, and heat pumps) are considered. In this context, pellet boilers are reported to constitute an option for the achievement of the climate goals in decentralized heating. In some countries (e.g., Italy), these heating appliances have seen an increased use for residential heating in the past years given the related lower energy costs with respect to natural gas.
In this perspective pellet boilers as a technology offer some advantages over other solid biomass combustion appliances such as fire wood room heaters and boilers or fireplaces. Being a densified fuel, pellets present standardized properties, low moisture and high energy content, high density, homogeneous dimensions, and consequently ease of transport, storage and handling. There is also the advantage over manually fed appliances consisting of automatic feeding in response to variable heating loads, higher efficiency. The feeding system with automatic regulation of the fuel feed according to the boiler load conditions allows the conservation of the optimal air/fuel ratios for complete combustion and cause lower emissions. However, particulate matter (PM) (Vicente and Alves, 2018) and nitrogen oxides (Ozgen et al., 2021) are reported to be the two main pollutants of interest to air quality emitted from these appliances. State-of-the-art technologies are required to limit air quality problems.
The present paper summarizes the status of the PM emission reduction methodologies and endeavours to understand the potentiality of PM emission reduction from residential/commercial/institutional pellet boilers (<500 kW) as well as to highlight some inherent challenges. The paper has the novel characteristic of including the presentation of both primary (i.e., at the furnace level, fuel-oriented) and secondary (i.e., tail-end) control methods usually treated separately.

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2. Particulate matter emissions from pellet boilers

Depending on the technology, fuel characteristics, and operating conditions pellet boiler PM emissions per GJ of energy input range on a wide scale (6 g/GJ - 116 g/GJ) (Ozgen et al., 2021). Advanced technology pellet boilers are reported to be able to further reduce the emissions to lower than 5 g/GJ (Obernberger et al., 2017) with specific design and control of the device. The state-of-the-art best-case emission limit conforming to Ecodesign (2015/1189) requirements indicated in EN 303-5:2021 Part 5 (performance requirements for heating boilers < 500 kW) is 40 mg/m^3 referred to dry exit flue gas, 0 °C, 1013 mbar and 10% of O_2. So, a tail-end intervention on PM emissions with minimum abatement efficiency of about 80% would be required to lower the emissions in case boilers with emission levels at the upper limit of the above-mentioned range were considered (corresponding to approx. 226 mg/m^3). Section 3 of the paper will summarize the available particulate matter abatement methods that can be used for this purpose.

Particle size and chemical composition are among the particle characteristics that may influence the feasibility of application and effectiveness of the PM control methods. Regarding the size of the particles the main contribution to the mass of the particles is given by particles in the range of 50–130 nm (Lamberg et al., 2011). Number size distributions have been shown to peak in the ultrafine particle region (particle diameter< 100 nm) (Ozgen et al., 2012). This means that control methods should be particularly effective for these small sizes. The chemical composition of the particles is dominated by a fine PM fraction mainly constituted by alkali compounds (e.g., K_2SO_4, KCl) formed through the solid-vapor-particle pathway. The particles may also, to a lesser degree, contain inorganic coarse PM of non-volatile ash constituents (e.g., CaO, MgO, SiO_2) formed via the solid-particle pathway (Gollmer et al., 2019). As it will be seen in the following section, the PM composition is important in PM control since it influences some particle characteristics (i.e., resistivity, solubility) which have a fundamental role in secondary abatement.

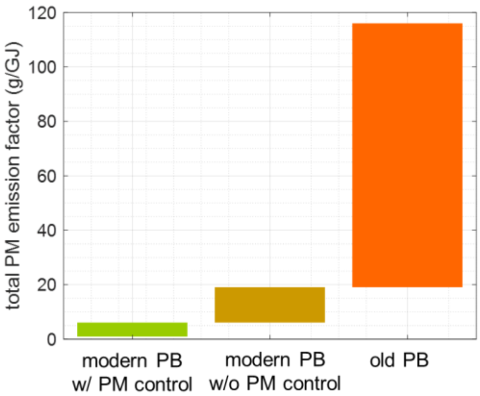

Figure 1: Total particulate matter emission factors for pellet boilers (PM: particulate matter; PB: pellet boiler) (Adapted from: Ozgen et al., 2021)

3. Status of PM control technologies

PM emissions from small-scale pellet boilers are related to both fuel quality (i.e., fuel composition and ash content) and appliance operating conditions (i.e., fuel and air feed) (Rabacal and Costa, 2015). Submicron inorganic particles are generated at high temperatures from aerosol precursors vaporized from the fuel (K, Na, S, Cl, Zn, and in some cases also P), as well as from the fuel/ash particles in the fuel bed or from the ejected char/ash particles in the flame (Wiinikka, 2005). The particles can further evolve in the cooler sections of the flue gas pathway by condensation and/or coagulation. Larger particles can also be released from the fuel bed and entrained with the flue gas. Soot and organic particles on the other hand are formed in poorly oxygenated environments, hence the importance of having adequate operating conditions (Rabacal and Costa, 2015).

The PM control can either target the reduction of the particles directly in the combustion chamber with the so-called “primary control” methods or remove the generated particles with end-of-pipe (i.e., “secondary”) methods at the flue gas exit. The status of the PM control methods applicable to pellet boilers is summarised in Tables 1 and 2. Both primary and secondary methods target the “primary particulate matter”, that is, the particles directly released into the atmosphere. Though some marginal benefit can be obtained by these control measurements, they do not aim to control the “secondary particles” generated by condensation and/or chemical reactions upon release to the atmosphere.

The primary control methods reduce the PM through: (1) combustion optimization which hinders the release of aerosol precursor species through an adequate partitioning of different combustion process steps (drying, devolatilization, gasification, char combustion, and gas-phase oxidation), (2) process control which reduce transitory periods and cycling rates leading to lower emissions and higher efficiency, and (3) fuel quality control and modification mostly directed to reduce the fuel content of aerosol forming species such as potassium. For all these methods a correct boiler grate design is fundamental to ensure a homogeneous distribution of combustion air over the entire fuel bed. The most commonly implemented method for PM reduction is the staged combustion through the regulation of air injection in the combustion chamber. Air staging consists of the appropriate regulation of the combustion air flows which minimizes the excess air and ensures at the same time maximum oxidation of the combustion products (Lamberg, 2014). The combustion air is fed into two key areas of the combustion chamber, that is, the primary air is injected directly through the grate and the secondary air is injected in the burnout zone. The use of minimum primary air ratios leads to a reduction in the release of aerosol forming elements due to limited fuel bed temperatures with the consequence of reduced PM emissions (Wiinikka, 2005). Increased burnout by greater amount of secondary air ensures the reduction of incomplete combustion products while keeping the overall air/fuel ratio unchanged. Decreased primary air amount slows the gas velocity through the bed reducing the risk of disturbances to the fuel bed which may contribute to the re-entrainment of fine ash particles. The advanced regulation of air flows is increasingly applied in new generation pellet boilers. The updraft gasifier directly coupled with a multi-stage gas burner and a boiler with reportedly low emissions (< 5 g/GJ) is such an example (Obernberger et al., 2017). Regarding the process control which conventionally is based on automatic management of the combustion air flow regulation valves via flue-gas-oxygen-sensor readings, a promising solution is offered through the implementation of intelligent regulation algorithms (Golles and Zemann, 2020) to minimize the occurrence of modulation transients, as well as on/off switching frequency with the objective of providing simultaneously good combustion conditions and low oscillations of the water temperature from the desired value. The fuel quality control methods act especially on fuel-potassium content by either blending K-rich biomass (usually non-woody biomass) with a K-poor biomass feedstock (Zeng et al.,2016) or by binding the released potassium in the temperature-stable bottom ash with the use of additives (e.g., kaolin) (Gehrig et al., 2019). The main disadvantages of the mentioned methods are the fuel pre-processing requirement and increased ash disposal need. Washing the raw biomass prior to pelletization is proposed as a fuel pre-treatment to reduce PM emissions, but a risk of increase in the number of ultrafine particles is also indicated (Schmidt et al., 2018). Torrefaction of pelletized biomass pre-treated by water-washing (Abelha et al., 2019) or acid demineralization (Namkung et al., 2021) may prove useful to further decrease the release of ash forming species. The application of these methods requires an adequate adjustment of boiler fuel/air flow ratios to counteract any effect of fuel modification. One advantage of controlling the fuel quality is the possibility of fuel flexibility (i.e., possibility to switch to agricultural, residual or other low-grade biomass pellets which may potentially cover a strategic role in circular economy) since the pre-treatments enhancing different fuel parameters are also beneficial for the minimization of the operational problems such as slagging, fouling, ash handling, and corrosion that occur in case of high-ash content fuels.

The secondary methods reduce the PM in boil-integrated or tail-end devices by either stopping the particles with physical obstacles (e.g., mechanical filters, ceramic-foam filters, wet scrubbers) through impaction, interception, and diffusion of particles, or by exploitation of external forces such as electrostatic force in electrostatic precipitators, or by the influence of driving forces such as thermophoresis and diffusiophoresis active in condensing heat exchangers. There is not one method completely effective for PM reduction. The electrostatic filters are reported to have efficiencies in the range of 50% - 98% on pellet boilers, however, the device performance is strongly subject to ageing, and frequent maintenance may be required (Hartmann et al., 2011). Operational problems and efficiency degradation for low (i.e., soot) and high (e.g., organic carbonaceous) resistivity particles may be encountered, but this kind of particles is usually not characteristic of PM emissions from pellet boilers. Mechanical filters [e.g., precoated filter material (Schiller and Schmid, 2015), metal mesh filters (Baumgarten et al., 2020)] are reported to have good efficiencies (87% - 99%) but are characterized by relatively high pressure drops, require maintenance and auxiliary equipment, and produce liquid wastes in case of water flushed filters. For these reasons their application is more suitable to commercial/institutional (e.g., schools, hospitals) or large-residential building heating boilers. Catalytic filtration [wall-flow (Stoppiello et al., 2014) or open-cell filters (Meloni et al., 2019) treated with catalytic material] is also proposed. Catalytic oxidation is effective for the removal of species from incomplete combustion (e.g., carbon monoxide, volatile organic compounds) and has limited to no effect on particles constituted mostly of alkali salts emitted from pellet boilers. In fact, the reduction of 60% to 90% observed in these devices is mainly due to physical filtration processes (depth+cake filtration) with no contribution from catalytic oxidation. The need for frequent regeneration, high pressure drops, and the limited operating life of the filters makes this solution hardly applicable to residential boilers. Condensing heat exchangers connected to boilers are proposed as a PM abatement solution (Messerer et al., 2007) given the advantage of not requiring an additional PM removal unit and having the benefit of increased thermal efficiency. However, the PM removal is modest (10%-50%) and water discharge should be handled. Good removal efficiencies (80%-95%) are reported for wet scrubbers [e.g., water spray (Blumberga et al., 2021), water atomization+fixed bed filtration (Golfera, 2016), and Venturi bubble column scrubber (Bianchini et al., 2017)] at the expense of increased system complexity, noise, water consumption, high pressure drop, and liquid wastes. Cyclones have low removal efficiencies for submicron particles characteristic of small-scale heating systems (Hartmann and Lenz, 2012), therefore, even though robust and economical, they may find application in the field of domestic biomass boilers only as preliminary treatment. For secondary control units the cleaning system is an integral part of the device since the collection surfaces must be cleaned regularly. Auxiliary equipment requirement to this purpose should also be considered.

Some PM control methods such as advanced air staging or combination of pellet boilers with zero-emission systems (e.g., heat pump or solar thermal system) are already applied in commercial boilers. Innovative solutions such as the exploitation of new discharge electrodes, electrosprays or space charge have been tested in the laboratory but have not yet been demonstrated in field applications.

It should be noted that, any PM control method with the additional benefit of thermal efficiency increase leads to fuel savings with the indirect reduction also of PM emissions.

Table 1: Primary control methods for particulate emissions from pellet boilers

Removal mechanism	Primary control methods
Optimized combustion conditions and hindering the release of aerosol forming species	• Boiler design • Air staging/Advanced air staging • Fuel bed cooling • Dehumidification of combustion air • Deashing-equipment
Optimized operation (e.g., reduce transitory periods, cycling)	• Process control (sensor conrol, advanced control with intelligent management systems) • Heat storage • Coupling with zero emission systems (e.g., solar, heat-pump)
Fuel quality control and modification	• Fuel-blending of different biomass feedstock • Fuel additives (e.g., kaolin, acid modified kaolin) • Water or acid fuel washing prior to pelletization • Torrefaction

Table 2: Secondary control methods for particulate emissions from pellet boilers

Removal mechanism	Secondary control methods
Application of external forces to drift the particle away from the gas streamlines (e.g., centrifugal force, electrostatic forces)	• Electrostatic precipitator • Cyclone
Collection of PM on target obstacles through impaction (effective for larger particles), interception (significant for particles of approx. 0.1–1μm diameter), diffusion (effective for very small particles over small distances from the obstacle)	• Metal mesh filters • Precoated bag filters • Wall-flow silicon carbide filters • Open-cell ceramic foam filters • Wet scrubbers (water atomization, column filling)
Thermophoresis (in the presence of temperature gradient across the gas space) and diffusiophoresis (due to the collision with condensing-species molecules under the effect of the concentration difference between the surface of the target and the bulk gas space)	• Condensing heat exchangers

4. Conclusions on potentiality and challenges

PM control in pellet boilers is less problematic than batch-wise fire-wood heaters due to some inherent characteristics of these boilers such as automatic fuel/air feed (e.g., better combustion conditions, less transitory periods) leading to PM emissions mainly composed of inorganic salts with medium PM resistivity, as well as enhanced applicability of staged combustion.

Even so, there are challenges to overcome, which are associated to economic, technological, and operational factors. Most of the solutions proposed are not cost-effective for small-scale combustion appliances (i.e., excessive costs of the abatement with respect to the heating appliance cost). Many techniques are not feasible or are less efficient when applied to small systems due to technological or operational aspects. For example, the residence time fundamental for efficient PM removal may be limited in the residential appliances because of the relatively small overall dimension of the boiler and control unit. Safety rules and conditions may be difficult to apply in the residential context. Increased pressure drops may lead to high operational costs. Some secondary abatement units may generate liquid wastes or noise emissions that may require to be handled. In this regard, where possible, expanding to centralized heating (district heating) with relatively larger scale appliances may help to overcome the techno-economical barrier in the application of primary and secondary PM control methods. The maintenance need encountered in many secondary control devices to guarantee the safe operation of the unit and to avoid degeneration of the abatement performance with time, should also be considered. The real-life performance is another determinant factor for the potential applicability of any solution to control the particulate matter emissions of a pellet boiler. More systematic research on the application of the existent and innovative solutions to well standardized or upcoming combustion technologies are required to better define the real-life abatement performance and pinpoint the operational problems.

The combination of one or more primary methods followed by a tail-end control device may be envisaged as a default configuration for upcoming advanced boilers to fulfil the requirements of national/international regulations (e.g., Ecodesign directive) that narrow the emission limits and demand thermally efficient cleaner combustion appliances.

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