Waste to Energy: Air Pollutant Emission from the Steam Boiler by Using the Recycling Waste Wood

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Abstract

In Taiwan, combustible wood mostly comes from waste pallets and scrap packaging materials discarded by factories, which produced a total of 278,067 tons of waste wood in 2019. In this study, the heat value of waste wood was 18.3±1.07 MJ kg^{-1}. The measured volatile fraction was 76.5±7.34%, the fixed carbon was 15.7±3.19%, the ash content was 2.96±2.45%, and the moisture content was 21.6±10.2%. The proportions of the elemental constituents of the waste wood were 45.3±4.95%, 46.9±3.94%, 5.9±0.44%, 0.21±0.17%, 0.29±0.26%, and 0.02±0.02% for carbon, oxygen, hydrogen, sulfur, nitrogen, and chlorine, respectively. The average boiler capacity was 11.5±6.84 ton hr^{-1}, the average fuel consumption of the boilers was 1.47±1.81 ton hr^{-1}, the average operating temperature of the boilers was 853±228°C, the average steam generation of the boilers was 7.63±5.97 ton hr^{-1}, and the average exhaust flow rate was 246.6±200.9 m^3 min^{-1}. The main air pollution control systems used in the waste wood combustion boilers were systems combining a cyclone, a

baghouse and a scrubber (37.8%), a cyclone and a baghouse (28.4%), or a cyclone and a scrubber (10.2%), and lastly systems using a baghouse only (9.8%). Based on our fuel consumption data, the air pollutant emission factors were 0.71±1.44 kg per ton of wood for PM, 0.86±1.47 kg per ton of wood for SOx, and 5.24±9.56 kg per ton of wood for NOx. In July 2022, new emission standards for boilers will be implemented, and emission reductions of at least 30% for PM, 35% for NOx and 7% for SO_2 will be required.

Keywords: Waste wood; boiler; air pollution control system; emission factor

1. Introduction

Biomass, with its very specific properties, has been used as a source of energy for thousands of years. However, interest in biomass has been decreasing for some time due to the potential uses as energy sources of fossil fuels such as oil, coal and natural gas, with their prime characteristics of high calorific values, ease of transportation, and ease of storage. Eventually, the resulting appetite for fossil fuel resources has led to their depletion, which experts predict will be complete very rapidly within the next 40–50 years (Saidur et al., 2011), and therefore their market price increases year by year. Biomass is now considered as a renewable energy source that can replace fossil fuels. In fact, carbon dioxide (CO_2) emissions can be significantly reduced if biomass is used to generate electricity instead of fossil fuels. Indeed, unlike fossil fuels, burning renewable biomass is thought to be GHG-neutral.

In 2016, bioenergy was the world's fourth-largest energy source after coal, oil and natural gas, occupying 9.5% of the global primary energy supply and 69.5% of the global renewable energy supply (International Energy Agency, IEA, 2018), and in 2017 it was the third-largest energy source domestically after coal and oil, accounting for 15% of energy consumption (BP, 2018). A recent study suggested that the potentiality of the world's biomass resources will be around 100–600×10^{18} J by 2050 (Slade et al., 2014), which corresponds to 15–65% of the demand for primary energy, based on estimates from the IEA (2014). According to life-cycle analyses, bioenergy can reduce air pollution emissions by a maximum of 4.9–38.7 $GtCO_2e$, or, stated otherwise, to 9–68% of the emissions resulting from the production of fossil fuel-derived electricity and heat, and the use of liquid fuels. In addition, replacing conventional sources of electricity and heat with bioenergy is, on average, 1.6–3.9 times more effective at reducing emissions than the carbon offset resulting from the use of liquid fuels (Staples et al., 2017).

Compared to coal, biomass has low sulfur and ash contents and is carbon-neutral. It benefits from being highly flexible compared with other renewable energy sources, and it can be used to generate electric power (Pfeiffelmann et al., 2021).

In the United States in 2016, biomass and waste fuels were used to produce 71.4×10^{9} kWh of electricity, which was the equivalent of 2% of the total power generation (USEIA, 2017) and is expected to slowly increase to 5.39×10^{15} Btu by 2050 (USEIA, 2021). Based on Global Bioenergy Statistics 2020, Europe, United State, Asia (China and Taiwan) are leading the trend of biomass as renewable heat production.

In China, biomass accounted for 2.4-2.8% of total energy consumption (Alliance experts, 2021). The generation of power from biomass in China increased from 1.4 Gigawatt (GW) in 2006 to 14.88 GW in 2017, and the installed capacity can be raised to 30 GW by 2030 (Fernandez, 2019; Danish and Ulucak, 2020).

In Europe, 43% of solid biomass-generated energy was consumed by the residential sector in EU28 in 2017 (Malico et al., 2019). In addition, the European Union (EU) has set a target of using renewable sources to produce 32% of energy by 2030. Therefore, the consumption of biomass to satisfy the energy demand may increase in the future.

In Taiwan, the use of biomass and waste as sources of energy is expected to increase from 727 MW in 2016 to 813 MW in 2025 (BOE, 2021). Biomass and waste fuels currently account for 1.1-1.3% of the primary energy supply in Taiwan (BOE, 2021). In addition to hydropower, wind power and solar energy, biomass is another option that is available to help the Taiwanese government to achieve its energy goal of obtaining 20% of its energy from renewables by 2025.

With the global demand for energy increasing and the social pressure to decrease the use of fossil fuels, governments and various energy companies are exploring many renewable energy alternatives. Commercial crops and biomass waste streams together are considered as one of the most reliable sources of alternative energy (Zhou et al., 2019). Unfortunately, because of the variability in the composition of fuel, these fuel sources suffer from low combustion stability and boiler efficiency (Demirbas, 2005).

In Taiwan, the availability of wood as a biomass source of energy is limited, and most of the wood that is consumed is imported (>99%). Therefore, waste wood is burned in combustion boilers to produce the steam required by nearby industrial facilities. In Taiwan, wood waste mainly comes from waste pallets, packaging materials, and some construction waste. The combustion process is commonly employed to deal with this waste; however, the air pollution produced as the biomass is incinerated in the boiler is a matter of concern.

In order to reduce particulate matter (PM) emissions, biomass boilers are equipped with air pollution control devices (such as cyclones or multi-cyclones, fabric filters, scrubbers, and electrostatic precipitators) to reduce the particulate matter emission.(Strand et al., 2002; Pagels et al., 2003; Wierzbicka et al., 2005; Lim et al., 2015; Bianchini et al., 2016; Nussbaumer et al., 2016; Mertens et al., 2020; Cornette et al., 2020). These boilers produce small fluctuations in NOx emissions and have low DeNOx efficiency. In addition, burning wood chips has been shown to achieve low precipitation efficiencies of between 30 and 50% (König et al., 2018). Because of the low sulfur content of wood, PM and NOx emissions are a particular source of concern related to the use of wood-fired combustors.

Biomass combustion can cause the formation of particulate matter and the emission of ash particles, the prevention of which is one of the most pressing challenges facing the use of biomass-fired utility boilers. Biomass combustion has been shown to be an important source of air pollution in northern China (Xu et al., 2017; Xu et al., 2020; Xu et al., 2021) and in Europe (European Environment Agency, 2013; European Union, 2015). Many studies have focused on the emissions of NOx and other pollutants (CO, VOCs, PAHs, and metals in PM) (Vamvuka et al., 2020; Poláčik et al., 2021; Zhang et al., 2020; Kong et al., 2021; Jaworek et al., 2021). In order to address the problem of pollution and to reduce emissions, it is important to take into consideration the aspects of combustion efficiency, operating conditions and air pollution control devices (Caposciutti et al., 2020; Oluwoyea et al., 2020).

Emission factors of fine particulate matter are highly correlated with fuel characteristics and burn conditions. Conversely, fuel moisture content and burn conditions have been shown to determine the emission factors of specific organic chemicals (Guillén and Ibargoitia, 1999; Khalil and Rasmussen, 2003).

In this study, wood combustion boilers were investigated to determine how the composition and calorific value of waste wood, the boiler operating parameters, and the air pollution control devices in the boilers affect air pollution emissions. Then, the operating conditions were evaluated in terms of their potential for improving combustion efficiency and reducing air pollution emissions in the future.

2. Experimentation

2.1 Proximate analysis

A proximate analysis was conducted to identify the levels of moisture, ash, and volatile matter in the biomass. The fixed carbon content was determined based on the percentages obtained for ash and volatile matter by an empirical expression. Each sample was analyzed at least three times to show the reproducibility of the results. The proximate analysis followed the testing procedures set out in the regulations of the Taiwan Environmental Protection Administration (EPA) and the Chinese National Standard. All the analysis procedures were similar to those proposed by the American Standard for Testing Materials (ASTM).

2.1.1. Moisture

The moisture of the biomass was measured after each sample had been air-dried for 2–3 days. The experimental process involved measuring the weight difference in a stove, putting the weighted samples in crucibles, and drying the samples in an oven at fixed temperatures between 120 and 150ºC for 3-4 h with a weight difference under 10 mg. The moisture of the samples was determined as follows (ASTM, 2019a):

$$M(\%) = \frac{W_i - W_f}{W_i - W_c} \times 100 \quad (1)$$

where M is the moisture, W_i is the initial weight of the sample, W_f represents the weight of the sample after drying in the oven to remove moisture, and Wc is the container weight.

2.1.2. Ash content

The ash content was determined with the ASTM E1534 standard test method (ASTM, 2019b). A crucible with the dried sample was placed in a furnace at 580-600ºC for 3-4 h. Then, the crucible was taken out of the furnace, put into a desiccator, and cooled down to room temperature. Afterwards, the crucible containing the sample was weighed once more. The ash content was calculated by using the formula below, where W_1 is the initial combined weight of the dried sample and the crucible, W_2 stands for the combined weight of the crucible and the sample after the ashing procedure, and W_c represents the weight of the crucible.

$$\mathrm{Ash}(\%) = \frac{W_2 - W_c}{W_1 - W_c} \times 100 \quad (2)$$

2.1.3. Volatile matter

Volatile matter was analyzed with the ASTM E872 standard test method (ASTM, 2019c) (The control temperature was set at 950±20 ºC). The weight loss was calculated by using the following formula:

$$\mathrm{A}(\%) = \frac{W_i - W_f}{W_i - W_c} \times 100 \quad (3)$$

where Wi represents the initial combined weight of the sample and the crucible with a cover, W_f stands for the final combined weight of the sample and the crucible with a cover after being heated in a furnace, and W_c represents the weight of the crucible and the cover. A(%) expresses the weight loss in percentage terms. The value of A(%) is used in the following formula to calculate the volatile matter (VM) content:

$$\mathrm{VM}\ (\%) = \mathrm{A} - \mathrm{B} \quad (4)$$

where B is the percentage of moisture in the sample, as determined with the ASTM E871 standard test method.

2.1.4. Fixed carbon (FC) percentage

In this study, the released moisture content was included as part of the volatile matter percentage. The fixed carbon content was measured according to the formula FC = 100 - (% Ash + % VM), where FC stands for the percentage of fixed carbon, and VM is the measurement of volatile matter obtained earlier.

2.1.5. Combustible Solid Fractions (Fixed Carbon)

The content of other combustible solid fractions FC (%) was determined based on the following equation:

$$FC = 100 - M - A - V \quad (5)$$

where M is the moisture content (%), A is the ash content (%), and VM is the volatile matter content (%) in the sample.

2.1.6 Calorimetry

The heat value of the waste wood was determined with a static bomb calorimeter (IKA-Calorimeter C4000, IKA-Analysentechik Heitersheim)

2.2 Ultimate analysis

An elemental analyzer (Elementar Vario EL cube MICRO, Elementar Americas Inc. New York, USA) was employed to determine the levels of the carbon, hydrogen, nitrogen, sulfur, and oxygen constituents in the waste wood (ASTM D5373, 2016). Chlorine levels were determined using an electrical furnace in which the furnace gas was absorbed by 3% H_2O_2 and analyzed by means of Ion Chromatography (ASTM D7359, 2018).

2.3 The emission data of TEDS

The Taiwan Emission Data System (TEDS) was established in 1992 and is updated every three years. The TEDS 10.1 was used in this study. In 2016, its emission data were employed to check and adult the consistent with standard tests of flue gas emissions.

2.4 Regular testing for PM, NOx and SOx

Based on the permit licenses, the boilers were selected due to their steam generation produced form waste wood combustion. About 100 waste wood boilers were tested to measure their emissions of PM, SOx and NOx according to the methods proposed by the Environmental Analysis Laboratory (NIEA), under the Taiwan Environmental Protection Administration (TEPA). The NIEA methods A101.76C, A411.75C and A413.75C, are based on the United States EPA Methods 5, 7E and 6C, respectively (US EPA, 2004, 2006, and 2019). The permits for the boilers were checked, and their operating conditions were inspected in the field as part of the regulatory testing to determine the representativeness of our samples. The data of regular testing reports were come from the TEPA and data sheets were rearranged and checked by this study.

2.5 Emission factor

Emission factors were determined by air pollution emission and activity (wood combustion or steam generation)

$$EF=Ei/(A) \qquad (6)$$

Where EF is the emission factor (gram of pollution emission from per ton of wood combustion or steam generation, g ton-wood^{-1} or g ton-steam^{-1}), Ei is i specie pollutant emission (i is PM, SOx or NOx and their units are gram), and A is activity (wood combustion or steam generation and its unit is ton)

3. Results and discussion

3.1 Waste wood characteristics

In Taiwan, combustible wood mainly comes from waste pallets and scrap packaging materials discarded by factories, used decoration materials, and pruned tree branches. According to TEPA data, the sources of waste wood are shown in **Fig. 1(a)**. There were 278,067 tons of waste wood in 2019. Most boilers for waste wood combustion are regarded as waste treatment systems and are used to produce steam. These boilers are used in food and animal feed manufacturing (32%), wood and bamboo product manufacturing (18%), agriculture and animal husbandry (12%), pulp, paper and paper products manufacturing (9%), textiles mills (5%), the laundry industry (5%), the electricity and gas supply (5%), and others (see **Fig 1(b)**). Therefore, waste wood shows potential as an energy source and for disposing of excess waste materials after being properly processed.

The moisture content was 21.6±10.2% (in the range of 10.41-38.8%) (see **Fig 2(a)**). The volatile fraction was in the range of 64.7-85.7% (the average was 76.5±7.3%), and the fixed carbon was 15.7±3.19% (in the range of 10.2-19.0%). The ash content was 2.96±2.45% (in the range of 0.29-7.9%). The heat value of the wood was 18.34±1.07 MJ kg^{-1} (in the range of 16.29-19.85 MJ kg^{-1}).

Fig 2(b) shows the major elemental composition values of the waste wood. The contents of its elemental constituents were 45.3±4.96% for carbon (in the range of 36.0-56.6%), 46.9±3.94% (in the range of 38.1-53.0%) for oxygen, 5.96±0.44% (in the range of 4.94-6.90%) for hydrogen, 0.21±0.17% (in the range of 0.02-0.59%) for sulfur, 0.29±0.26% (in the range of 0.081-0.900%) for nitrogen, and 0.02±0.02% (in the range of 0.0016.0-0.0624%) for chlorine. Some chloride was detected in the waste wood, which could be a sign that some plastic was mixed in with the wood or that chlorinated preservatives have been used on the wood (US EPA, 2021).

Table 1 shows the characteristics of the waste wood used in this study compared with the results of other studies. Our results indicated that the components of the waste wood matched the carbon and hydrogen constituents of spruce pellets and beech wood (Poláčik et al., 2021), certified and uncertified pellets (Vicente et al., 2020), and agricultural residues (Vamvuka et al., 2020). However, a higher moisture content was found in the waste wood as a result of their sources and the fact that it was stored in the open before being used as feedstock in boilers. In addition, highly variable characteristics have been measured for biomass (Saidur et al., 2011) and for forest and biomass (Garćia et al., 2012). Recently, solid recovered fuel (SRF) has been considered as an alternative to using waste wood as biomass. However, there are standards for the allowable quantities of trace elements (Cl:≤ 0.03-0.1%, As ≤ 2.0 mg kg^{-1}, Cd≤ 1.0 mg kg^{-1}, Cr≤ 15 mg kg^{-1}, Cu≤ 20 mg kg^{-1}, Pb≤ 20 mg kg^{-1}, Hg≤ 0.1 mg kg^{-1}, and Zn≤ 200 mg kg^{-1}) present in wood pellets (ISO, 2021) which cannot be ignored. Such high limits for trace element content could be a limitation to the use of waste wood. In addition, the moisture levels measured in this study were rather high (moisture ≤ 10%), which can reduce the heat value, reduce the boiler combustion efficiency, and increase the emission of air pollutants.

3.2 Characteristics of boilers

Table 2 shows the characteristics of the boilers. The average boiler capacity was 11.5±6.84 ton hr^{-1}, and their cumulative capacity from 10 to 90% was from 5.00 to 17.00 ton hr^{-1}. The fuel consumption of the boilers was 1.47±1.81 ton hr^{-1}, and their cumulative consumption from 10 to 90% was from 0.20 to 3.06 ton hr^{-1}. The average exhaust flow rate was 246.6±200.9 m^3 min^{-1}, and the range of their cumulative rate from 10 to 90% was from 69.4 to 450.6 m^3 min^{-1}.

The average operating temperature of the boilers was 853±228ºC, and their cumulative temperature from 10 to 90% was in the range of 500-1200ºC, reflecting a 2.4-fold difference. The average temperatures were slightly lower than the typical temperatures for biomass combustion in fluidized bed boilers (900-1000ºC) (Vakkilainen et al., 2017).

The average steam generation of the boilers was 7.63±5.97 ton hr^{-1}, and their cumulative generative capacity from 10 to 90% was in the range of 1.50-14.0 ton hr^{-1}, reflecting a 9.3-fold difference. Based on the calculations related to wood consumption and steam generation, the level of energy efficiency was approximately 76%, which is slightly lower than the typical level of 80-94%. This discrepancy could be explained by the moisture content of the wood pellets and the operating conditions of the boilers (Scottish Forestry, 2021).

3.3 Air pollutant concentrations and emission factors

The average concentrations of PM, SOx and NOx emissions are shown in **Fig 3**. The average fuel consumption was 1.47±1.81 ton hr^{-1}, and the range of cumulative consumption from 10 to 90% was from 0.20 to 3.06 ton hr^{-1}, reflecting a 15.3-fold difference. The average concentration of PM was 36.3±36.0 mg Nm^{-3} and the cumulative concentration from 10 to 90% was from 3.0 to 86.9 mg Nm^{-3}, reflecting a 29.0-fold difference. The SOx concentration was 17.4±20.8 ppm, and the cumulative concentration from 10 to 90% was from 3.0 to 38.6 ppm (8.6-110.3 mg Nm^{-3}), reflecting a 12.9-fold difference. The NOx concentration was 126.4±60.1 ppm, and the cumulative concentration from 10 to 90% was from 60.4 to 211.2 ppm (124.0-454.2 mg Nm^{-3} as NO_2), reflecting a 3.5-fold difference. The emissions from the combustion of wood chips of PM were 16-18 mg Nm^{-3} and the emissions of NOx were 101-122 mg Nm^{-3} with an O_2 content of 10.8-10.9% and an exhaust temperature of 154-179 °C (König et al., 2018). The concentrations of emissions from the waste wood combustion boilers used in this study were higher than those identified in other studies (König et al., 2018).

Calculated over an entire year, the level of air pollutant emissions was 2.38±4.40 ton yr^{-1} for PM, 4.03±7.25 ton yr^{-1} for SOx, and 24.9±34.7 ton yr^{-1} for NOx. The cumulative emission level from 10 to 90% was from 0.06 to 5.36 ton yr^{-1} for PM, from 0.04 to 10.34 ton yr^{-1} for SOx, and from 2.04 to 64.11 ton yr^{-1} for NOx. There was an 85.2-fold for PM, 271-fold for SOx and 31.5-fold for NOx.

The quantity of air pollutants based on the level of fuel consumption can be expressed as 0.71±1.44 kg ton-$wood^{-1}$ for PM, 0.86±1.47 kg ton-$wood^{-1}$ for SOx, and 5.24±9.56 kg ton-$wood^{-1}$ for NOx. The cumulative emission factor from 10 to 90% was from 0.01 to 1.51 kg ton-$wood^{-1}$ for PM, from 0.01 to 2.04 kg ton-$wood^{-1}$ for SOx and from 0.80 to 10.76 kg ton-$wood^{-1}$ for NOx. There was a 178.7-fold for PM, 212.2-fold for SOx and 13.5-fold for NOx. With a calorific value of the waste wood of 18.3 MJ kg^{-1}, the air pollutant emission factors can be converted to 38.7 mg MJ^{-1} for PM, 46.9 mg

MJ^{-1} for SOx, and 285.7 mg MJ^{-1} for NOx. The level of emissions of PM was lower than that of another study (51-53 mg MJ^{-1} for PM) and 2.98-3.86 folds of NOx emission factor (74-96 mg $MJ^{-1}$for NOx) (Win, 2015). Based on the AP-42 emission factors, the value for PM was 0.22-0.56 lb $MMbtu^{-1}$ (0.511-1.301 g MJ^{-1}), for NOx it was 0.22-0.49 lb $MMbtu^{-1}$ (0.511-1.138 g MJ^{-1}), and for SOx it was 0.025 lb $MMbtu^{-1}$ (0.058 g MJ^{-1}) (USEPA, 2001).

In terms of steam generation, the emission factors were 0.21±0.89 kg per ton of steam for PM, 0.29±0.66 kg per ton of steam for SOx, and 1.09±2.92 kg per ton of steam for NOx. The cumulative emission factor from 10 to 90% was from 0.0018 to 0.197 kg ton-$steam^{-1}$ for PM, from 0.0017 to 0.309 kg ton-$steam^{-1}$ for SOx, and from 0.121 to 1.688 kg ton-$steam^{-1}$ for NOx. There was a 111.4-fold for PM, 186.1-fold for SOx and 14.0-fold for NOx.

Fig 4(a) shows the correlations among boiler capacity, fuel consumption and steam generation. Results indicate strong correlations between boiler capacity, on the one hand, and, on the other, both waste wood feedstock (r^2=0.57) and steam production (r^2=0.64).

Fig 4(b) shows correlations of r^2=0.41 between the PM emission factor (based on steam production) and the level of SOx emissions and r^2=0.81 between the PM emission factor and the level of NOx emissions. Results indicate a strong correlation between the PM emission factor and the level of NOx emissions in relation to steam generation.

3.4 Air pollution control system

The air pollution control devices used in this study are shown in **Fig 5**. Boiler exhaust control systems usually include a combination of various types of equipment. The most common combination includes a cyclone, a baghouse and a scrubber (39.5% of systems), followed by the combination of a cyclone and a baghouse (29.6%) and a cyclone and a scrubber (10.6%), and lastly systems using only a baghouse (10.2%).

The cyclone pressure drop was 169±104 mmH_2O, and the inlet exhaust temperature was 151±86ºC. The liquid-to-gas (L/G) ratio of the scrubber was 6.5±6.1 L m^{-3}, the median value was 4.60 L m^{-3} and the pressure drop was 131±97 mmH_2O. The inlet exhaust temperature was 131±82ºC. The L/G ratios of the scrubber are in the range of 0.5-3.0 L m^{-3} (Richards, 1995). Some operating conditions may increase the L/G ratios up to 5.35-20.0 L m^{-3} (40-150 gal (1000 $scfm)^{-1}$) for high efficiency or toxic mercury (US EPA, 2002).

The air-to-cloth ratio of the baghouse was 1.92±2.29 m min^{-1}, the median value was 1.18 m min^{-1}, and the pressure drop was 229±97 mmH_2O. The inlet exhaust temperature was 143±66ºC.

Generally speaking, the analysis of cyclones has shown them to have a lower control efficiency for particle sizes smaller than 5 μm, and the Venturi scrubber has proven to be effective for particles larger than 1 μm (approximately 96% efficient) (Wakelin et al., 2008). In addition, the baghouse and electrical precipitation have been shown to be effective at removing particles of sizes in the submicro range (approximately 95-97% efficient) (Wakelin et al., 2008).

Table 3 shows the concentrations of PM, SOx and NOx emissions after the air pollution control system. In the system combining a cyclone, a baghouse and a scrubber, the average concentrations of PM, NOx and SOx were 33.2±39.9 mg Nm^{-3}, 132.6±65.5 ppm (average concentration: 272.3 mg Nm^{-3}) and 17.9±24.7 ppm (average concentration: 51.1 mg Nm^{-3}), respectively. For the system combining a cyclone and a baghouse, the average concentrations of PM, NOx and SOx were 32.4± 32.3 mg Nm^{-3}, 111.4±49.0 ppm and 17.4±21.0 ppm, respectively. For the baghouse system, the average concentrations of PM, NOx and SOx were 29.1±33.1 mg Nm^{-3}, 163.3±59.0 ppm and 22.0±14.6 ppm, respectively. For the system combining a cyclone and a scrubber, the average concentrations of PM, NOx and SOx were 49.1± 29.1 mg Nm^{-3}, 99.6±46.2 ppm and 12.2±11.4 ppm, respectively.

The temperature of the flue gas, the boiler's inlet and outlet water temperatures, and the gaseous emission rates were scaled to specific feed and air flow rates while combustion and efficiencies of boiler were controlled. Throughout the whole operation, CO and NOx emissions from all fuels were below regulatory limits, while SO_2 emissions were insignificant because of the low sulfur content of wood.

Combustion efficiencies were satisfactory, ranging between 84 and 86% (Vamvuka et al., 2020).

In relation to the $PM_{2.5}$ removal efficiency, results indicate the $PM_{2.5}$ concentration was 141±5.18 mg Nm^{-3} for the washing tower, 81±6.74 mg Nm^{-3} for the bubble-column scrubber, 78±7.85 mg Nm^{-3} for the Venturi scrubber, and 10-20 mg Nm^{-3} for the combined Venturi and bubble-column scrubber (Bianchini et al., 2016). Results indicate the PM concentration was 77.6±19.4 mg $Nm^{-3}$for the system using only a scrubber, which is lower than the findings of other studies on systems incorporating a washing tower, a bubble-column scrubber, and a Venturi scrubber.

The emission concentration of NOx was 150-195 mg Nm^{-3} and that of SO_2 was 2.9-5.0 mg Nm^{-3} for a medium-scale boiler at a rated power of 5.0 MW_{th} that was equipped with a multi-cyclone followed by a baghouse filter (Cornette et al., 2021). These SOx and NOx concentrations were higher than those found in other studies (Cornette et al., 2021).

The current boiler emission standards for Taiwan of 30 mg Nm^{-3} for PM, 50 ppm for SOx, and 100 ppm for NOx were announced on 1 July, 2020 and will be implemented on 1 July, 2022. The regular testing of boilers shows emissions of 45.5% for PM, 59.8% for NOx and 6.1% for SOx, which are in excess of the new emission standards. Therefore, revised emission reduction and control strategies are required to address these unacceptably high levels of emissions. In order to comply with these stringent emission standards, emission reductions should be made of 137 ton yr^{-1} (a 30% reduction) for PM, 1690 ton yr^{-1} (a 35% reduction) for NOx, and 25 ton yr^{-1} (a 7% reduction) for SOx.

According to the new emission standards, the operating conditions of the air pollution control systems on the boilers (including the frequency of filter cake removal and filter bag replacement for the bag filter, inspection and maintenance schedules, etc.) should be modified to improve the PM control efficiency. Using a bag filter can be sufficient to prevent PM emissions under the proper conditions, especially when combined with the pretreatment of the cyclone for the removal of large PM during wood boiler combustion. In this study, there was no proper treatment system for NOx. Therefore, equipping boilers with a dedicated NOx removal system such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) might make it possible to reduce NOx emissions to fewer than 100 ppm.

The 100 industrial-sized wood combustion boilers investigated in this study operated in the range of 3 to 86.9 mg Nm^{-3} (10-90% cumulative concentrations) with an average of 36.3±36.0 mg Nm^{-3}. Since the average particle size of combustion particulates is fine, mechanical collectors like cyclones usually cannot achieve emission levels lower than 30 mg Nm^{-3} for wood combustion (using grate or suspension burners). The cost of the air pollution control equipment (an electrostatic precipitator, ESP, or a fabric filter) may exceed the cost of the combustor for smaller combustion boiler units. In this study, the waste wood combustion boilers were equipped with a combined air pollution control device for PM emission control. Nevertheless, the concentration of PM emissions was still high. Results suggest that regularly inspecting and maintaining the devices, employing experienced operators, and optimizing the operating conditions could significantly improve the combustion efficiency of the boilers and the efficiency of the air pollution control system.

Therefore, regulating the air-fuel ratio, maintaining good combustion conditions, and using wood of high quality and with low moisture content are methods that have been proposed to mitigate the impacts of the direct exposure of an urban population to the pollution produced by wood combustion boilers (Sarigiannis et al., 2015). For instance, it costs 2.5 times as much as the boiler at 1.5 MW, while the costs of the air pollution control systems and the combustors were close at 5.5 MW (Wakelin et al., 2008). In this study, approximately 65% of the boilers were larger than 5.5 MW. It shows that boilers are more sensitive to increasing the air pollution control devices and cost of pollution reduction. It accounts for 50% or more of their capital costs compared to larger-sized boilers.

The wood used in this study was obtained from construction and/or demolition waste, which may affect the fuel characteristics and make it impossible to stay under low emission limits.

High-performance flue gas cleaning equipment, ESPs, and fabric filters seem inappropriate for use with smaller applications. Current technologies are available to reduce particulate emissions to extremely low levels. However, the optimization and maintenance of the boiler combustion system and the air pollution control system are crucial to being able to achieve low emission targets. The significance of employing experienced operators to ensure good control and to carry out proactive maintenance duties becomes more important as allowable emission limits decrease. Conversely, smaller installations become more difficult to adapt under these conditions because of escalating costs.

Conclusions

The most common sources of combustible waste wood are waste pallets and scrap packaging materials discarded by factories used decoration materials, and pruned tree branches. Most waste wood is consumed by food and animal feed manufacturing (32%), wood and bamboo products manufacturing (18%), agriculture and animal husbandry (12%), and pulp, paper, and paper products manufacturing (9%). In this study, we examined waste wood combustion boilers used for steam generation, with particular attention placed on the functioning of the air pollution control system. The results showed that air pollution emissions were high, with an average PM concentration of 36.3±36.0 mg Nm^{-3}, a SOx concentration of 17.4±20.8 ppm, and a NOx concentration of 126.4±60.1 ppm. A portion of the boiler emissions (45.5% of PM emissions, 59.8% of NOx, and 6.1% of SOx) exceed the new emission standards (PM: 30 mg Nm^{-3}, NOx: 100 ppm, and SOx: 50 ppm). NOx control devices such as SCR and SNCR are necessary to reduce NOx emissions to below 100 ppm. In addition, the cyclone and the baghouse system seem to reduce PM emissions to less than 30 mg Nm^{-3} under optimal operating conditions. Otherwise, it would be necessary to use more effective PM removal devices to reduce emissions. Based on our fuel consumption data, the air pollutant emission factors were 0.71±1.44 kg per ton of wood for PM, 0.86±1.47 kg per ton of wood for SOx, and 5.24±9.56 kg per ton of wood for NOx. In July 2022, new emission standards for boilers will be implemented, and emission reductions of at least 30% for PM, 35% for NOx and 7% for SO_2 will be required.

Acknowledgements

The authors express their sincere thanks to the Ministry of Science and Technology, Executive Yuan, Republic of China (Taiwan) for research funding (MOST 109-2622-E-224-014).

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Table and Figure Captions

Table

Table 1 Physiochemical characteristics of scrap wood and biomass

Table 2 Air pollutant emission concentrations for different control systems

Figure

Figure 1a Sources of waste wood

Figure 1b Sources of boilers

Figure 2a Approximate analysis of waste wood

Figure 2b Elemental constituents of waste wood

Figure 3 Operating parameters of boilers: (a) operating temperature, (b) boiler capacity, (c) fuel consumption, (d) steam generation, and (e) flue gas flow rate

Figure 4 PM, SOx and NOx concentration distribution

Figure 5a Relationships of boiler capacity with wood consumption and steam generation

Figure 5b Relationships of PM emission factor with NOx and SOx based on steam generation

Figure 6 Air pollution control system of waste combustion boiler

Table 1 Physiochemical characteristics of scrap wood and biomass used 100 industrial-sized wood combustion boilers

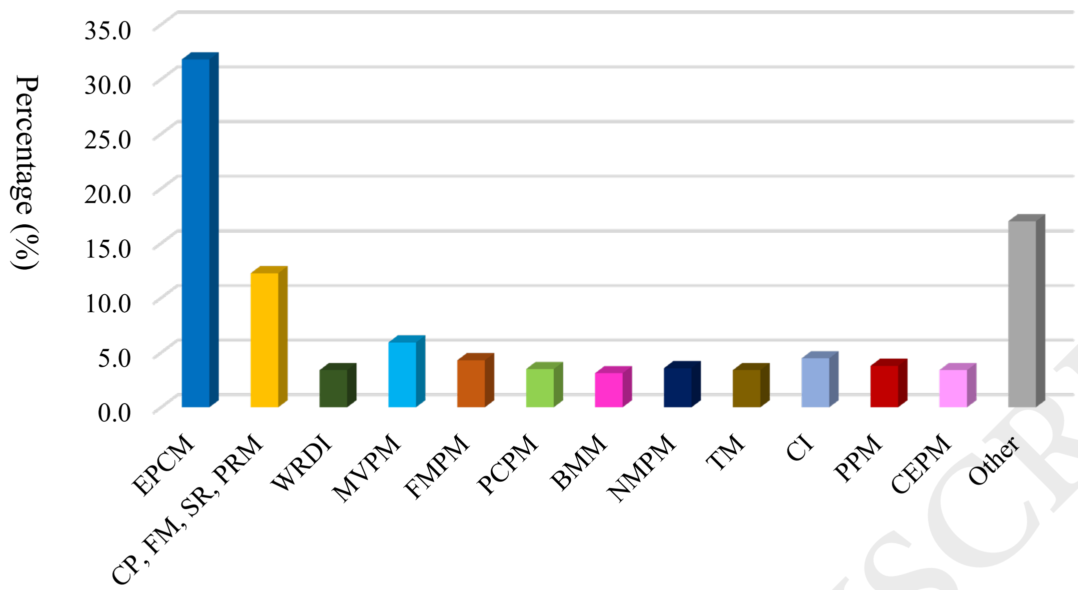
Items	Biomass	Forest and biomass	Agricultural Residues	Certified and uncertified pellets	Spruce pellets and Beech wood	Waste wood
C	38.45-57.00	24.51-97.18	46.5-49.5	48.7-49.7	42.7-43.7	45.34±4.96
H	4.50-10.20	0.27-11.55	5.7-6.3	6.1-6.3	5.5-5.7	5.96±0.44
S	0.01-0.60	0.10-1.48	<0.05	<0.01	0	0.213±0.173
N	0.1-3.4	0.07-3.94	0.8-2.2	0.71-1.02	0.6-0.7	0.288±0.255
Cl	0.01-1.50	-	-	-	-	0.022±0.017
O	33.9-47.1	0-73.80	36-43	42.5-43.7	40.3-41.2	46.95±3.94
Ash %	0.10-20.26	0-22.9	1.4-7.3	0.43-0.84	0.3-2.3	2.96±2.45
Volatile fraction (%)	57.2-87.4	26-86.5	72.1-81.4	-	-	76.5±7.34
Fixed carbon (%)	7.42-29.30	1.0-50.17	13.11-26.5	-	-	15.7±3.19
Calorific Value MJ/kg	8.0-22.08	11.87-23.0	17.5-20.4	18.47-18.53	18.04-18.24	18.34±1.07
Moisture %	5.43-9.53	5.10-43	-	7.2-8.0	7.9-9.5	21.55±10.21
Remark	Saidur et al., 2011	Garćia et al., 2012	Vamvuka et al., 2020	Vicente et al., 2020	Poláčik et al., 2021	This study

Table 2 Operation parameters of boilers

Parameters	Boiler capacity (ton hr^{-1})	Operation temperature (°C)	Fuel consumption (ton hr^{-1})	Steam generation (ton hr^{-1})	Flue gas flow rate (Nm^3 min^{-1})
10%	5.00	500	0.20	1.50	69.35
25%	6.00	600	0.38	3.70	111.75
Median	12.00	900	0.82	5.50	189.20
75%	15.00	1050	2.00	10.80	327.77
90%	17.00	1200	3.06	14.00	450.57
Min-Max	1.80 - 40.00	500 - 1,200	0.02 - 15.00	0.06 - 38.0	10.6 - 1,282.1
Mean	11.50	852.5	1.47	7.63	246.59
Standard deviation	6.84	228.2	1.81	5.97	200.96

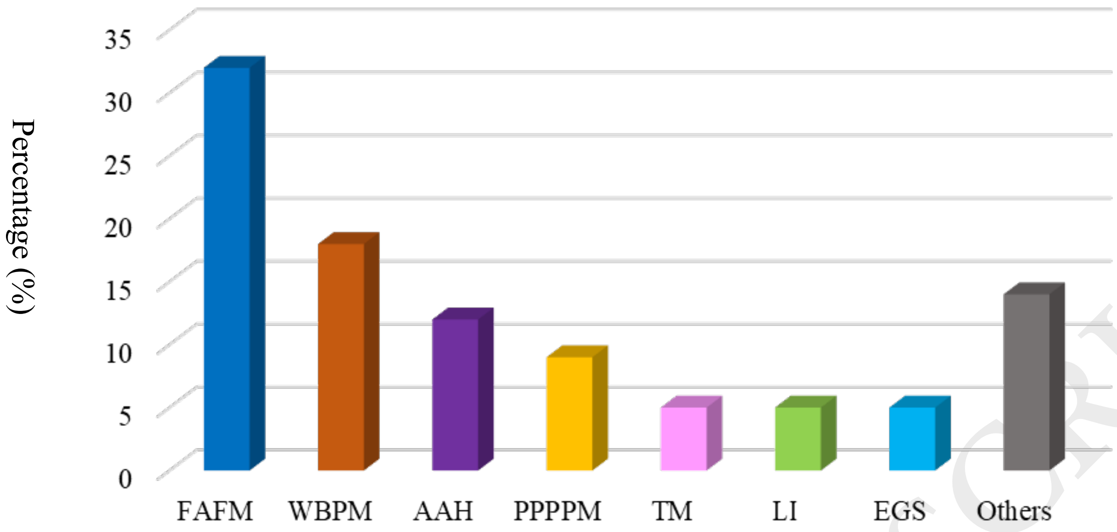
Table 3 Air pollutant emission concentrations for different control system

APCD	PM (μg m^{-3})	SOx (ppm)	NOx (ppm)
Cyclone+Scrubber+Baghouse	33.2±39.9	17.9±24.7	132.6±65.5
Cyclone+Baghouse	32.4±32.3	17.4±21.0	111.4±49.0
Cyclone+Scrubber	49.1±29.1	12.2±11.4	99.6±46.2
Baghouse	29.1±33.1	22.0±14.6	163.3±59.0
Scrubber	77.6±19.4	11.5±12.4	110.9±26.2
Cyclone	55.7±34.8	17.3±4.3	134.3±39.0
Scrubber+Baghouse	58.8±22.5	26.4±4.4	144.2±35.9



EPCM:Electronic Parts and Components Manufacturing,
CP, FM, SR, PRM: Chemical Products Manufacturing, Fertilizers Manufacturing, Synthetic Resin, Plastic and Rubber Materials Manufacturing,
WRDI:Waste Removal and Disposal Industry,
MVPM:Motor Vehicles and Parts Manufacturing,
FMPM:Fabricated Metal Products Manufacturing,
PCPM:Petroleum and Coal Products Manufacturing,
BMM:Basic Metal Manufacturing,
NMPM:Non-metallic Mineral Products Manufacturing,
TM:Textiles Mills,
CI: Construction Industry,
PPM:Plastic Products Manufacturing,
CEPM:Computers and Electronic Products Manufacturing, Others:

Figure 1a Sources of waste woods as biomass energy in Taiwan



FAFM: food and animal feed manufacturing,
WBPM: wood and bamboo products manufacturing,
AAH: agriculture and animal husbandry,
PPPPM: pulp, paper and paper products manufacturing,
TM: textiles mills,
EGS: electricity and gas supply,
LI: Laundry industry, and others

Figure 1b Sources of boilers for waste wood combustion

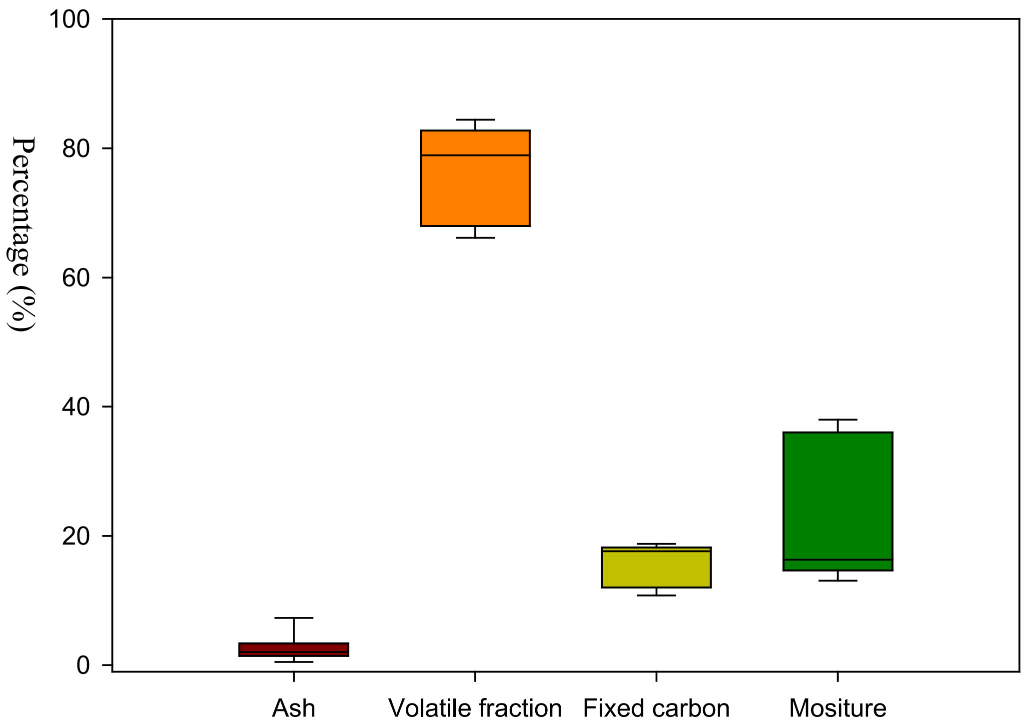


Figure 2a Approximately analysis of waste woods from 100 industrial-sized wood combustion boilers

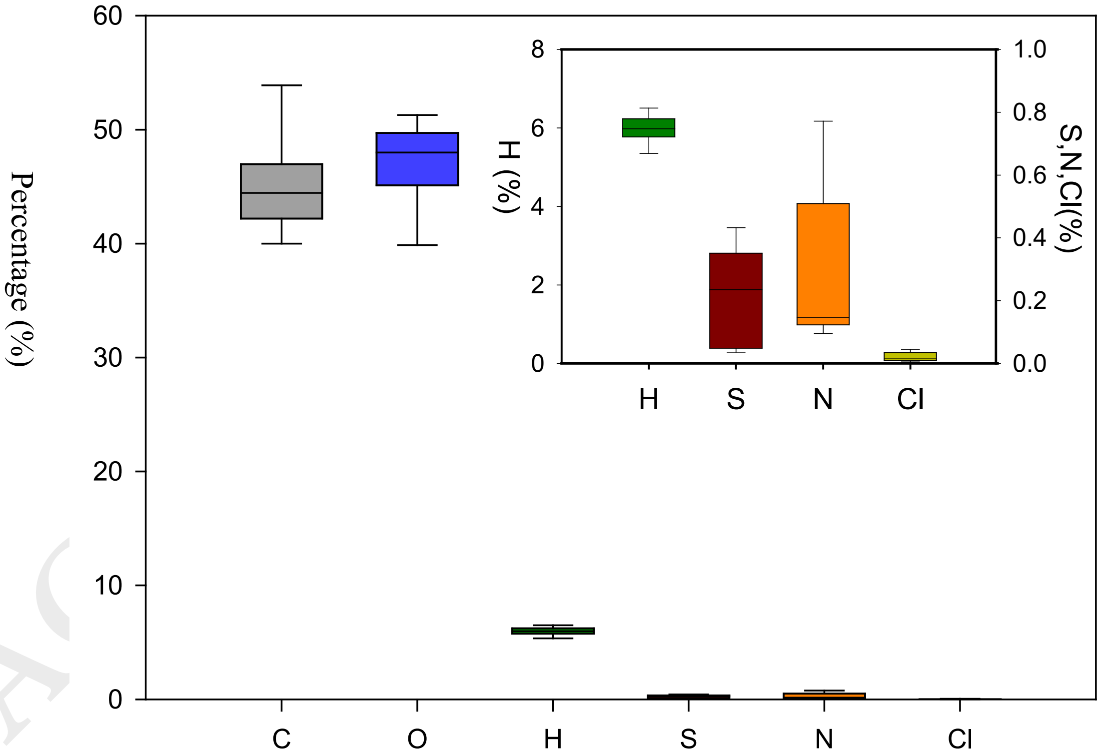


Figure 2b Elemental constituents of waste woods from 100 industrial-sized wood combustion boilers

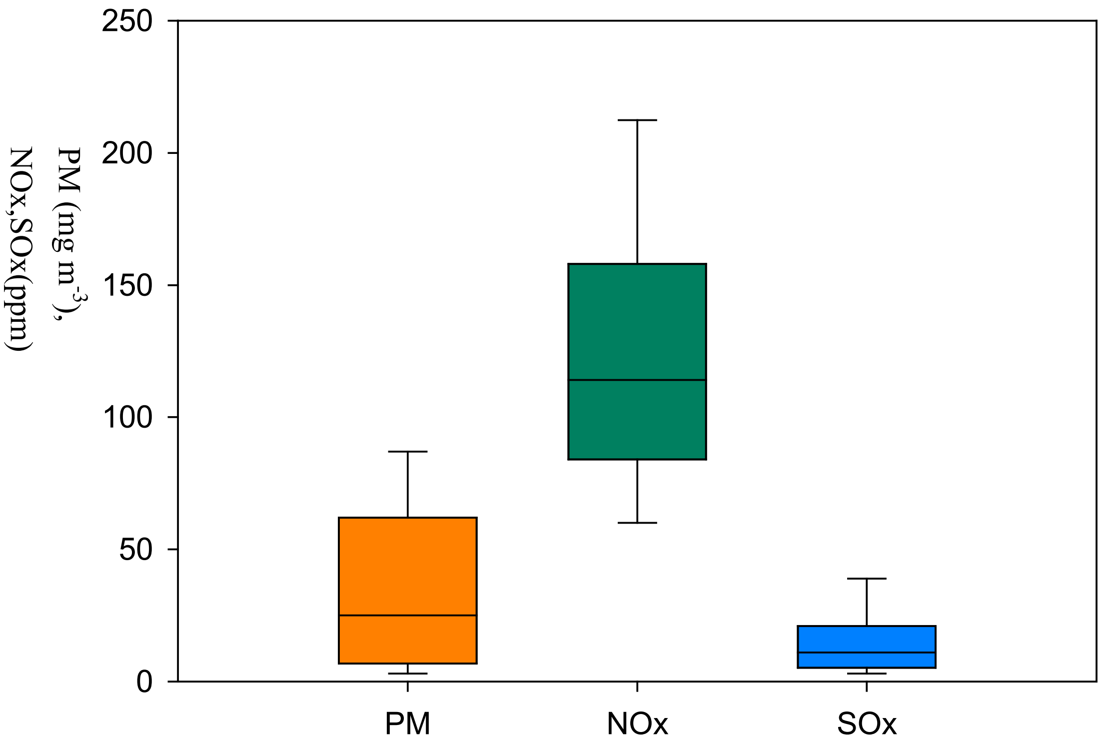


Figure 3 PM, SOx and NOx concentration distribution

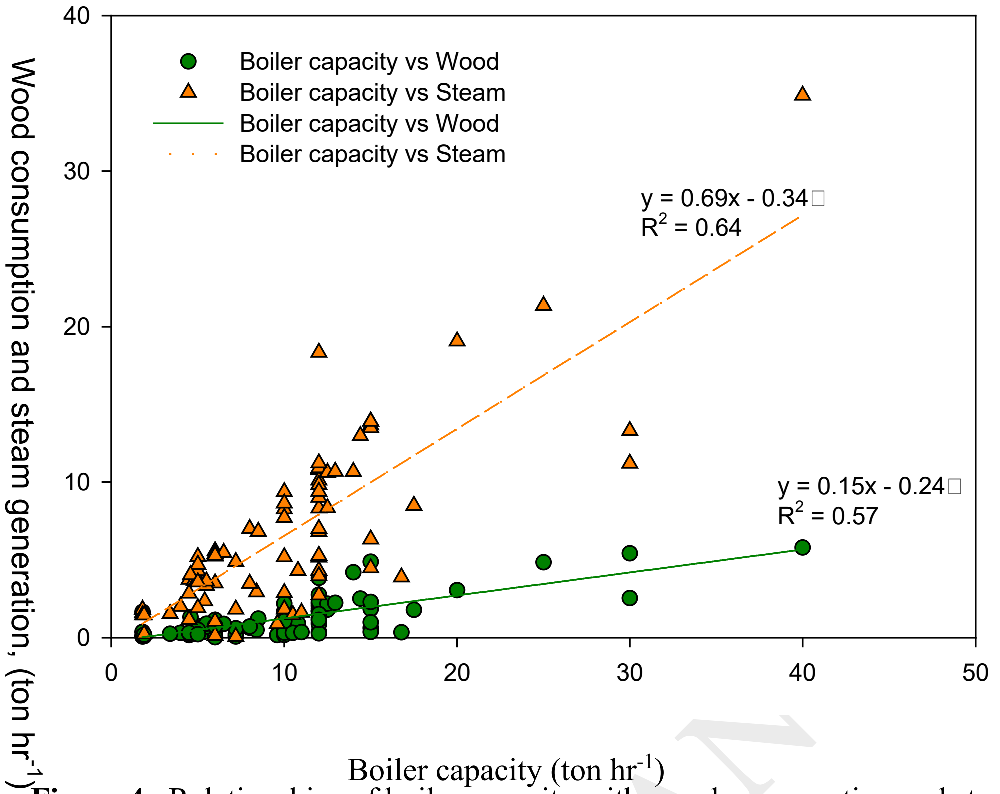


Figure 4a Relationships of boiler capacity with wood consumption and steam generation

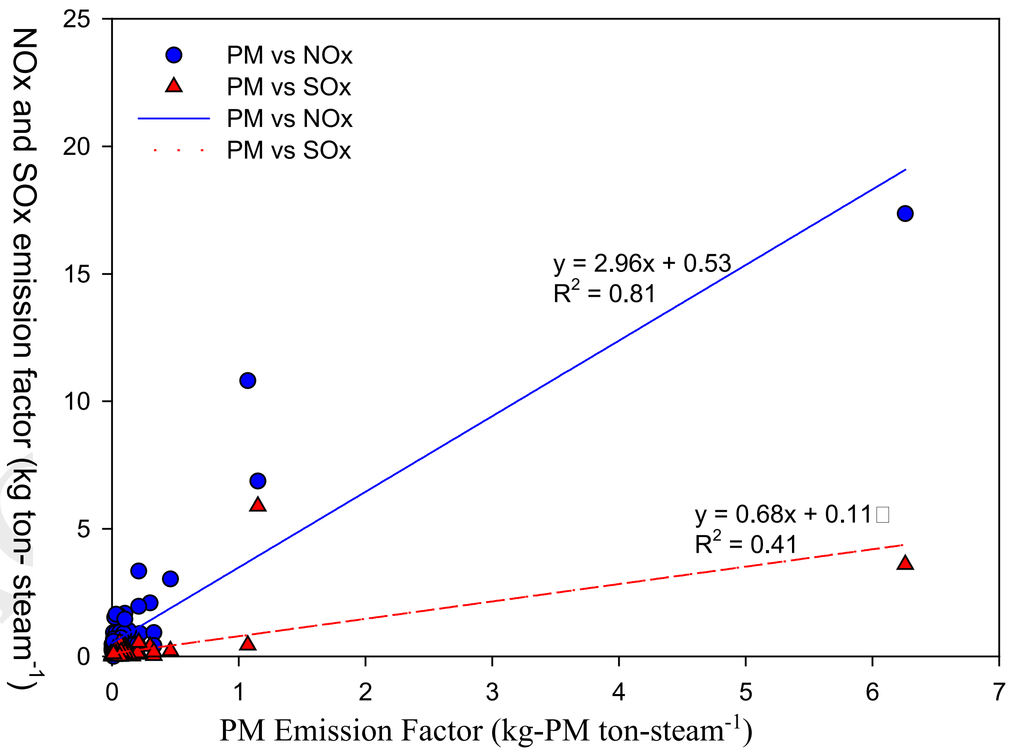


Figure 4b Relationships of PM emission factor with NOx and SOx based on steam generation

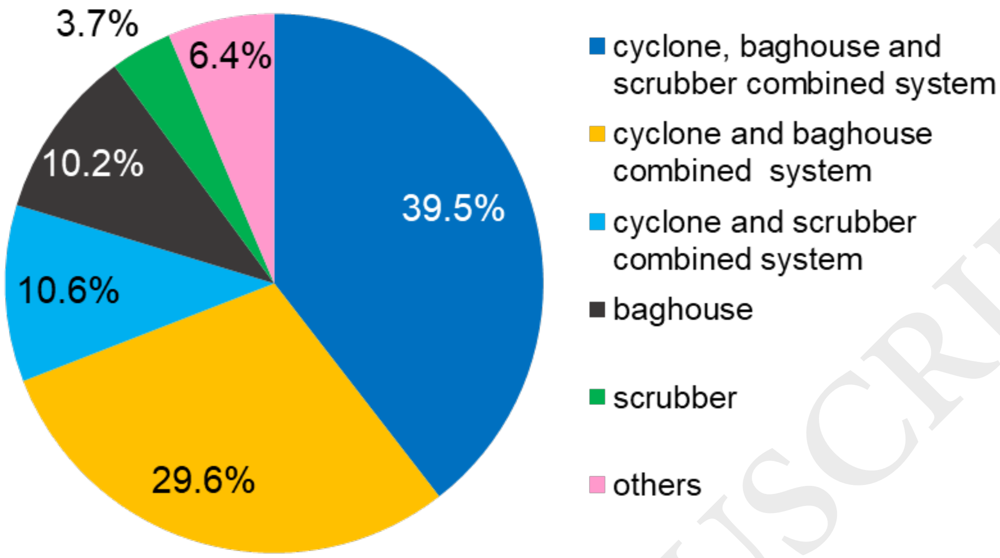


Figure 5 Air pollution control system of waste combustion boiler