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Improving the Operation of an Automatic Wood Chip Boiler by Optimizing CO Emissions

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ABSTRACT: In wood chip boilers, CO emissions can be reduced by improving the control over the combustion process. To minimize emissions and optimize efficiency, the excess air ratio, the primary and secondary air distribution systems, and the fuel feed rates must be adjusted to maintain stable combustion. An extensive series of wood combustion tests was performed in a grate automatic 180 kW_{th} boiler. The level of influence exerted by wood parameters, such as the origin, particle size, and moisture content, and combustion parameters, such as the excess air ratio, air distribution, and boiler load, were studied. The most important characteristic of wood with regard to CO emissions is the moisture content. The combustion tests with both types of wood chips and sawdust show that the CO emissions and excess air ratio decline when the fuel power increases. The direct relationship between the excess air ratio and the level of power facilitates the optimization that minimizes the CO emissions. The control system must be based on a fluctuating O_2 concentration in the exhaust gas by varying the excess air ratio relative to the power demand. The excess air ratio needed to implement the optimal conditions should be between 2.0 and 2.5 at 100 kW_{th}, between 1.9 and 2.1 at 135 kW_{th}, and between 1.7 and 1.9 at nominal power.

1. INTRODUCTION

Today, combustion remains the most common bioenergetic technology used to produce heat and power.[1] Biomass is an important renewable energy source that has been extensively studied toward combustion technology at all scales.

Wood combustion is mainly used to produce heat in small- and medium-scale units, such as wood stoves, wood log boilers, pellet burners, and automatic wood chip furnaces, which may provide from a few kW_{th} up to more than 100 MW_{th}.[2] Heat from biomass is economically feasible in residential or collective heating applications, and its efficiency is considerably high, ranging from 84 to 90%, according to Good et al.[3]

In France, extensive efforts have been made toward bioenergy development following the objectives of Comition Operational number 10 (COMOP 10) of the Multiannual Investment Program (PPI); specifically, a 4-fold increase in the consumption of biomass by collective heating systems between 2012 and 2020 should be enacted.[4]

Biomass combustion generates lower CO_2 emissions during heat production compared to fossil energy. According to greenhouse gas emissions from collective heating systems, 490 and 242 kg of CO_2 equv/MWh are emitted when using oil and natural gas, respectively, while 24 kg of CO_2 equiv/MWh are generated by biomass fuel.[5]

The combustion of solid fuel generates various substances, such as carbon monoxide (CO), volatile organic compounds (VOCs), soot, tar, and polycyclic aromatic hydrocarbons (PAHs), formed by incomplete combustion and pollutants, such as NO_x, SO_x, ash, acid gases (HCl), polychlorinated dibenzodioxin (PCDD)/polychlorinated dibenzofuran (PCDF), heavy metals, and particulate matter [PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and total suspended particulate (TSP)], formed during combustion because of the constituents of natural fuel.[4,6−10] Those components must be mitigated and treated.

The three possible paths toward emissions management and thermal efficiency during wood combustion for heating devices include the following: improving the combustion in an existing device (optimizing operating conditions),[11,12] redesigning the boiler configuration (modifying the furnace itself or the air entrances),[13,14] and depollution of the exhaust gas through physical and chemical technologies (filters, cyclones, electrostatic precipitator, wet scrubber, etc.).[2,8,15−17]

Several studies have illustrated the complexity of biomass combustion on a small scale (<70 kW) by optimizing different variables for combustion while reducing emissions and retaining a high thermal efficiency;[18,19] however, the results are not comparable to medium-scale (from 70 kW to 10 MW) experiments because of differences in burner design, combustion operation, and control.[2]

The state-of-the-art method includes measuring combustion parameters in existing medium-scale devices, showing good results for CO emissions. The emissions remained below the limits set by the EN 303-5 norm[20] at all times, although limiting the fuel characteristics[13,21] or power.[14]

Wood combustion requires a balance between the air and wood supply to minimize CO production. The presence of carbon monoxide in the flue gas, in addition to being a pollutant, indicates a decrease in efficiency.[1]

Staiger et al.[13] studied CO emissions during combustion tests using a 450 kW_{th} boiler with a moving grate furnace operation through a counter-current combustion system. Combustion tests using wood chips with different moisture contents showed that the power range of the boiler varies from one-third of its nominal power.

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Lundgren et al.[14] studied the impact of boiler power modulation on a 500 kW_{th} boiler used for a district-heating network and concluded that the optimal oxygen levels necessary to limit CO emissions vary significantly depending upon the heat output.

During wood combustion, organic compounds must be reduced to improve the burnout quality. The factors that might affect the formation of pollutants during these processes include excess air as well as the combustion temperature, residence time, and turbulence.[1,22] In medium-scale combustion devices, the CO emissions will be lower for a specific air/fuel ratio. Consequently, controlling the introduction of air might reduce CO emissions.

The mixing of combustible gases and air often limits the burnout quality.[23] If good mixing occurs, operation at low excess air levels is possible (i.e., $\lambda < 1.5$), enabling high efficiency and high temperature with complete burnout. Consequently, the concentrations of unburned pollutants can be reduced to levels near zero.[2]

The emissions were characterized, and the efficiency was measured, for three midsized high-efficiency wood boilers fed with wood chips and commercial wood pellets. The low concentrations of CO during steady-state boiler operation indicated that good combustion had occurred. The thermal efficiencies of the wood pellet boilers ranged from 70 to 86% for the 150 kW_{th} boiler tested and between 75 and 91% for the 500 kW_{th} boiler.[24]

The current study was developed in LERMAB Institute at Lorraine University in France under the sponsorship of ENERGICO to optimize the performance of automatic boilers that burn wood chips. An automatic boiler can burn various types of biomass and respond to the needs of the user. Therefore, instead of modifying the boiler design, the conditions used within the same device were optimized to accept variation in fuel characteristics or power.

This experimental research determines the optimal combustion parameters for decreasing CO emissions in flue gas; these emissions are a primary indicator of combustion quality and an important air contaminant. CO is diagnostic for good combustion: the amount of CO emissions eliminated during the combustion of wood is proportional to the reduction in unburned PAHs, VOCs, CH_4, and PM.[12,25,26] This paper describes the tests used to characterize the wood and adjust the combustion parameters in the automatic boiler, as developed by Bernard.[27]

2. MATERIALS AND METHODS

The equipment used during the experiments and measurements is a 180 kW_{th} industrial boiler located in Epinal, France. On the basis of a technology of the grate-firing system; this boiler is a commercial model fabricated by COMPTE.R, a French company, used to heat water for collective and industrial heating applications.

This technology is displayed in Figure 1 and includes the following: a fuel feeding system, an automatic biomass boiler, and a cyclone to clean the stack gas.

The boiler is fed through an on/off-controlled feeding screw with a 1.99 m^3/h maximal volume flow rate.

The volume of the vacuum combustion chamber is 620 L. The vault in the combustion chamber is modular, enabling the removal of some elements during instrument placement or the transformation of the burner geometry from "co-current" to "counter-current". The grate-firing boiler has seven cast iron grates: four are stationary, and three are moved via a hydraulic cylinder.

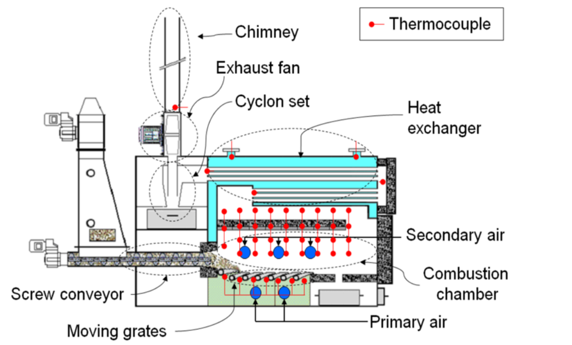

Figure 1. Schematic figure of the experimental combustion system. The scheme identifies the primary components of the boiler and instrumentation.

The boiler is equipped with two primary air stages driven by one electric engine each, enabling control over the air injection in two separate zones under the moving grates. Similarly, three secondary air stages are used to distribute air on the combustion bed. Each primary air fan can provide a maximum of 300 N m^3 h^{-1}, while each secondary inlet provides 43 N m^3 h^{-1}. Each of these air inlets is provided with a sealing shutter actuated with a servomotor to manage the pressure drop in the air injection nozzle and fully control the air flow rates.

The flue gas is distributed in six cyclonic dust collectors before conduction to the chimney.

2.1. Test Facility Modifications. The boiler system was modified slightly for the present study, distinguishing it from the commercial models.

2.1.1. Boiler. The burner with co-current geometry in the combustion system was chosen for the experiments because of the moisture content of the wood. When the wood is too wet, more energy is required to dry it before burning. Subsequently, the flue gases are introduced in the burner to heat the fuel. According to Thunman and Leckner,[28] co-current behavior is common with very moist fuel.

The air inlets in the furnace were multiplied to study the influence of the injected air and its distribution in the combustion chamber.

2.1.2. Instrumentation. This industrial boiler was outfitted with numerous sensors for continuously monitoring the temperature in the furnace, the incoming and outgoing airflow, the wood and flue gas, and the composition of exhaust gases, as shown in Figure 1.

The instrumentation used to obtain the necessary measurements for the study is connected to a central data acquisition unit that simultaneously collects the values of each instrument before sending the data to a computer for storage and analysis. These measures include the temperature, gas velocity, and gas composition.

Gas velocity in the boiler is measured using vane anemometers installed in ducts with known diameters. Because of the high flue gas temperature (between 150 and 250 °C), humidity, and solid particulate load in the exhaust gas outlet, a pitot tube was used.

Finally, the O_2, CO, NO, and NO_2 concentrations in the exhaust gases were measured continuously with a TESTO 350 XL analyzer, and further, oxygen measurements were collected using the existing λ probe.

2.2. Boiler Control System. Initially, the boiler control system was adapted toward heat production through the heating network. Therefore, three variables were controlled: (1) The water outlet temperature in the pipeline is the temperature measured in the water leaving the heat exchanger compared to a set point usually defined at 90 °C. The difference between the measured water temperature and the set point determines the load of the boiler, enabling calculations for and variations in the inlet wood and primary air flows to produce energy sufficient to maintain the water temperature in the heating network. (2) The oxygen rate in the dry flue gas is the measured oxygen level compared to a set point generally equal to 10%. When the difference between the value measured and the set point reaches a certain level, a secondary air fan is activated to adjust the air ratio. During experiments, this variable has been studied using various set

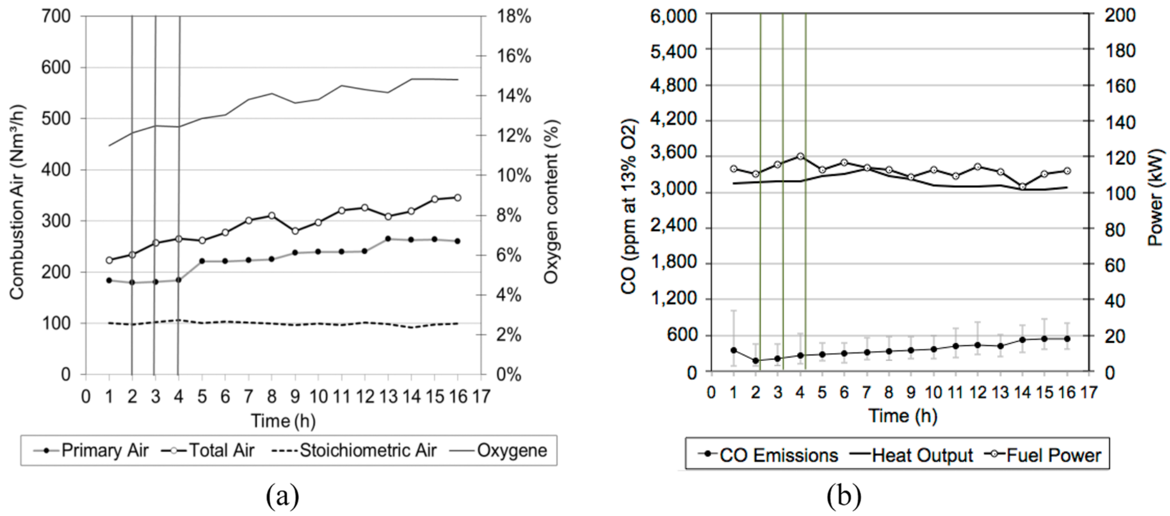

Figure 2. Combustion test at 110 kW_{th} using wood chips with a 15% moisture content.

points. (3) The differential pressure measurement is used to adjust the rate of extraction for the flue gas with a set point at 100 Pa. If the pressure difference decreases, the rate of extraction increases.

Specific software was developed to reprogram the existing regulating control system and enable variations in the air and wood flow relative to the fuel quality and boiler load during the overall combustion tests. The wood fuels were chosen with different qualities that naturally complemented the range of experiments, facilitating the optimization of combustion conditions.

The software includes four portals with connections to the three main instruments that record the measurements: the acquisition central, the gas analyzer, and the programmable logic controller (PLC). Each port can be managed independently or together when connecting to any of the three instruments.

3. EXPERIMENTAL SECTION

Numerous tests under known and variable conditions were performed. For each sample, a 15−40 m^3 batch was delivered in one portion by the same supplier to limit variability. For each batch, the sample was characterized and the influences of the primary and secondary air flows were assessed.

3.1. Fuel Characterization. For this study, the wood has not undergone any special treatment aside from shredding. The samples come from two sources: (1) a sawmill containing sawdust and wood chips and (2) a forest grinding company, who collected wood chips with variable moisture contents. The first category is termed "wood co-products from the first transformation", while the second is called "forest residues from harvesting systems".

From each batch, a 50 L sample was collected at random, homogenized, and assessed for its bulk density. After re-homogenization, 49.5 L was extracted for the particle size test and 0.5 L was used for the moisture test. This last amount of dried sample was crushed; one-third was used for a higher heating value (HHV) test and elemental analysis, while the other two-thirds were subjected to an ash test.

3.2. Adjustment of the Boiler. Preliminary experiments were carried out to determine the stable state of operation for the boiler and define the duration of the experiments. The boiler was run for at least 2 h before the measurement cycles to allow for adjustments to the wood and total air flows.

This adjustment consists of determining the rotation frequency for the feed screw on the boiler needed to obtain the required fuel power. Afterward, the boiler is turned on for about 1 h to verify the heat output and adjust the wood flow. The extreme values for the total air flow are then implemented. These values vary between 1.5 and 3 times the stoichiometric air flow, corresponding to an oxygen rate in the flue gas between 6 and 15%. The measured oxygen rate is used to adjust the extreme values of the operating air flows.

3.3. Combustion Test and Operating Conditions. The combustion experiments were carried out for each type of wood with a set fuel power; in addition, several "modes" are performed. The duration of the each mode was 1 h and 10 min: 10 min of stabilization of combustion and 1 h of operation were used to obtain the averaged results for each experiment. The number of modes in one experiment depended upon the amount of wood available for each batch. One "mode" involved a test with fixed operating conditions and variables that were measured and calculated.

The fixed parameters include the woody product type as well as the origin, moisture content, particle size, and boiler load of the wood. The variable parameters include the total air flow rate and the distribution between the primary and secondary air flow rates. The measured parameters are the O_2 and CO data, while the calculated parameters include the stoichiometric air and fuel power.

Different operating regimes between 60 and 180 kW_{th} were studied using the boiler. For each experiment, the feeding screw was adjusted and maintained.

The air flow was adjusted from 0 to 100% in each air inlet, adapting electrical frequency and flap position. Afterward, four primary air flow rates were gradually used for each primary air level and at least four secondary air flow rates were considered. Each action was maintained for 1 h. The PLC was programmed to maintain the primary air flow while increasing the secondary air flow for each level.

Figure 2 shows an example of an experiment at 110 kW_{th} using wood chips with a 15% moisture content. Each point shows the average of the results for each mode. The stoichiometric air (a) and fuel power (b) are calculated. The vertical lines in the graphs indicate the CO emissions obtained from the modes.

3.4. Data Treatment. The measurements are acquired every 20 s, generating 180 measurement points per mode. Figure 3 describes the method used to treat the recovered data.

For each measurement, 129 instantaneously measured values are registered to calculate the following values: excess air, energy efficiency, oxygen content in the dry flue gases, and CO emissions in the exhaust gases. After the boiler was adjusted, as explained in section 3.2, the averaged values calculated from the instantaneous measurement in each experiment were reliable.

4. RESULTS AND DISCUSSION

4.1. Fuel Characterization. The average values for the physical characteristics of the wood are displayed in Figure 4 and Table 1. The particle size distribution (Figure 4) was obtained following the Austrian standard, önorm M 7133.[29] This wood fuel contains only a small quantity of fly ash; less

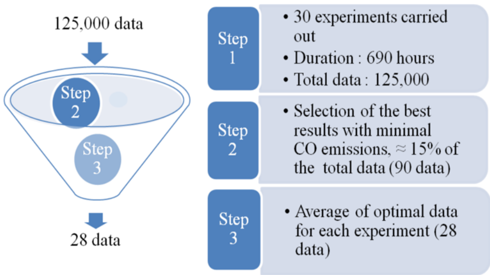

Figure 3. Methodology of the data treatment.

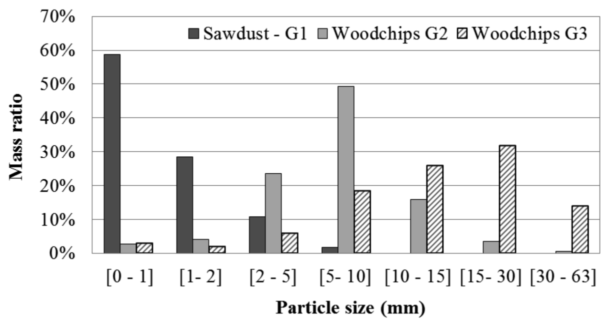

Figure 4. Particle size distribution of wood fuel burnt during the experiments. G1, fine sawdust (0−5 mm); G2, small wood chips (2−15 mm); and G3, medium wood chips (5−63 mm).

Table 1. Wood Sample Characteristics

parameter	unit	standard test	sawdust G1[a]	wood chips G2[b]	wood chips G3[c]
origin			1[d]	2[e]	1 and 2
dry bulk density	kg/m^3	NF B 51-005[31]	105	157	171
ash content	(wt %, db)	NF M 03-003[32]	1	1	3

[a]G1 = fine sawdust (0−5 mm). [b]G2 = small wood chips (2−15 mm). [c]G3 = medium wood chips (5−63 mm). [d]1 = wood co-products from the first transformation. [e]2 = forest residues from the harvesting systems.

than 3% of the total is attributed to square pieces, 1 mm per side. More than 90% of the total weight is attributed to square pieces, 15 mm per side, allowing the feeding screws to work optimally. Consequently, the wood fuel flows steadily during the test period.

The typical elemental composition for wood [carbon, 48.7% (db); oxygen, 44% (db); hydrogen, 6% (db); nitrogen, 0.3% (db); and ash, 1% (db)] was obtained for the two fuels studied. The HHV can be considered constant, regardless of which fuel is used; the HHV was measured following the NF M 03-005 standard[30] (20 510 kJ/kg ± 0.4%).

The bulk density of a pile of wood depends upon moisture, but the dry bulk density only depends upon the shape and arrangement of the particles. The higher the dry bulk density, the larger the particle size distribution.

The moisture content was determined according to standard NF B 51-004.[33] This important characteristic of wood is very variable. It must be measured on each wood sample to each combustion test in the experimental analysis (Table 3).

4.2. Combustion Test. After the experiments, each fuel input used during the combustion test is listed in Table 2. This table summarizes all of the fuel data and visualizes various measured or calculated parameters.

Table 2. Characteristics of the Fuel Considered for Experiments

sample name[a]	wood origin[b]	particle size[c]	woody product type	moisture content (wt %, wb)	fuel power (kW_{th})
WS 15	1	G2	wood chips	15	65, 110, 150
WS 51	1	G2	wood chips	51	70, 80, 130, 160
SS 42	1	G3	sawdust	42	80, 130, 190
WF 28	2	G1	wood chips	28	90, 100, 120, 170
WF 30	2	G2	wood chips	30	100, 120, 180
WF 36	2	G1	wood chips	36	90, 100, 140, 150, 175, 180
WF 51	2	G2	wood chips	51	110, 150, 190

[a]WS, wood chips from 1; SS, sawdust from 1; WF, wood chips from 2. [b]1, wood co-products from the first transformation; 2, forest residues from the harvesting systems. [c]G1, fine sawdust (0−5 mm); G2, small wood chips (2−15 mm); G3, medium wood chips (5−63 mm).

4.2.1. CO Emissions. The results show the impact of the input parameters, moisture content, and source of feedstock on the carbon monoxide production. The optimal CO emissions are presented in Figure 5. The main conclusion is that, the higher the fuel power, the lower the CO emissions, regardless of the moisture content and origin of the fuel.

CO emissions, as defined in the European norm (EN) 303-5,[20] are established for boilers with nominal outputs ranging from >150 to ≤500 kW_{th} that fire standardized wood fuels. The maximal limit of CO emissions of 698, 582, and 291 ppm at 13% O_2 corresponds to classes 3, 4, and 5, respectively. The results comply with the norm, except when the boiler load is 50% of the nominal power and the wood chips have a >40% moisture content.

Fuels with moisture contents between 28 and 36% comply with the characteristics for class 5 boilers; therefore, the CO emissions do not exceed 291 ppm at 13% O_2, regardless of the power. CO emissions using wood chips with 15% moisture content do not surpass the limit for class 5 according to the norm. Higher emissions are observed for drier fuel because the water present in the feedstock facilitates the oxidation of CO. Therefore, for overly dry fuel, the CO emissions increase if the control parameters for the combustion remain unchanged.

The results for fuels with 42 and 51% moisture contents exceed the limit for CO emissions from class 3 when the experiments are performed at a partial load. Combustion with sawdust provides lower CO emissions than wood chips with 51% moisture content.

The origin of the fuel slightly affects the emissions of CO; the materials from the harvested forest residues emit less CO emitters. However, the composition of the woody products from either origin remains constant, reducing the impact on the emissions.

These results coincide with those from Bignal et al.;[26] the species of tree used to produce the woodchips was less important than the moisture content or boiler operating conditions with regard to the pollutant concentrations.

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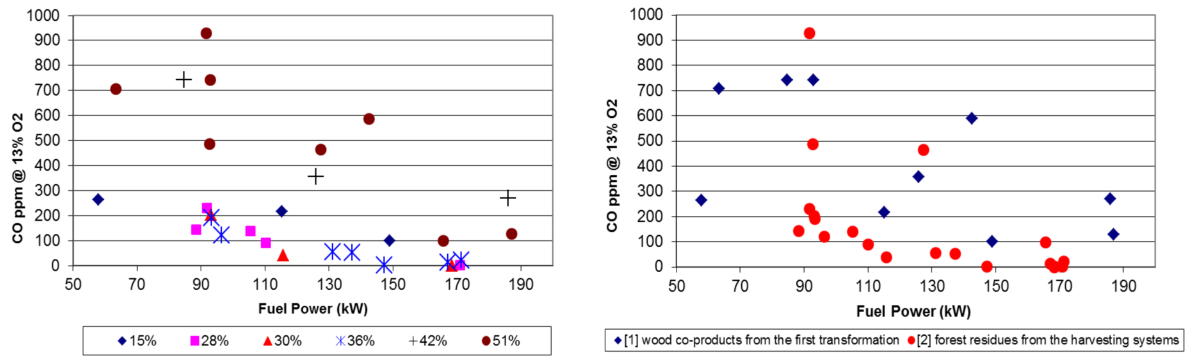

Figure 5. CO emissions as a function of fuel power depicted by the origin (on the right) and moisture content (on the left).

In addition, the size of fuel chips does not significantly influence the amount of CO emissions most likely because the feedstock in either form is likely burning several tens of kilograms per hour simultaneously in the furnace.

The combustion thermal efficiency was calculated using the direct method[3] shown in Figure 6. For a given load in the boiler, an optimal excess air ratio that minimizes CO emissions and maintains efficiency exists.

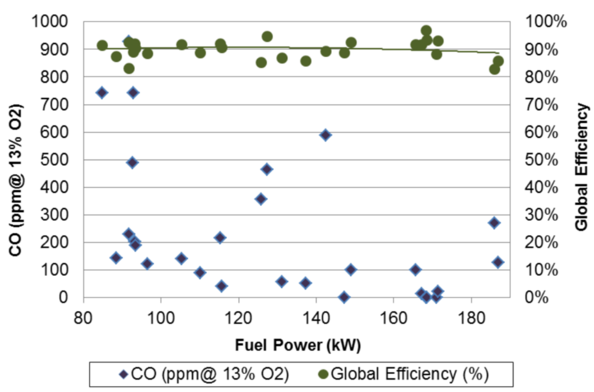

Figure 6. Optimal CO emissions and efficiency as a function of the fuel power.

4.2.2. Total Air Flow. The relationship between the optimal total air flow and the fuel power is presented in Figure 7. This relatively linear progression shows an increase in total air flow as a function of the fuel power, regardless of the moisture content.

A slight trend relates the origin of the wood with fuel power. Forest products lower total air flow. According to the study by Strehler,[34] the combustion characteristics of wood and other biomass sources depend upon their moisture content, chemical characteristics, and physical structure.

4.2.3. Oxygen Content in the Dry Flue Gases. The optimal points for oxygen content relative to fuel power are presented in Figure 8. The oxygen content decreases when the power increases, regardless of the moisture content.

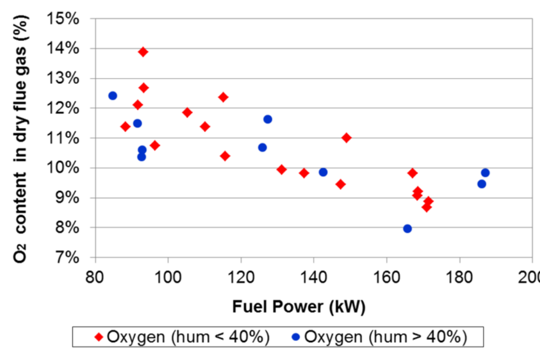

Figure 8. Oxygen content of the dry flue gas as a function of the fuel power.

4.2.4. Distribution of Air. Figure 9 shows the distribution of the secondary air reports on the total air. The secondary air injection could be between 17.5 and 22.5% of the total air for the optimum combustion of wood chips with high moisture contents. This result is coherent because wetter fuels need additional primary air for drying and burnout during combustion. However, an air ratio between 22.5 and 27.5% of total air is better for dry fuels. In this case, additional

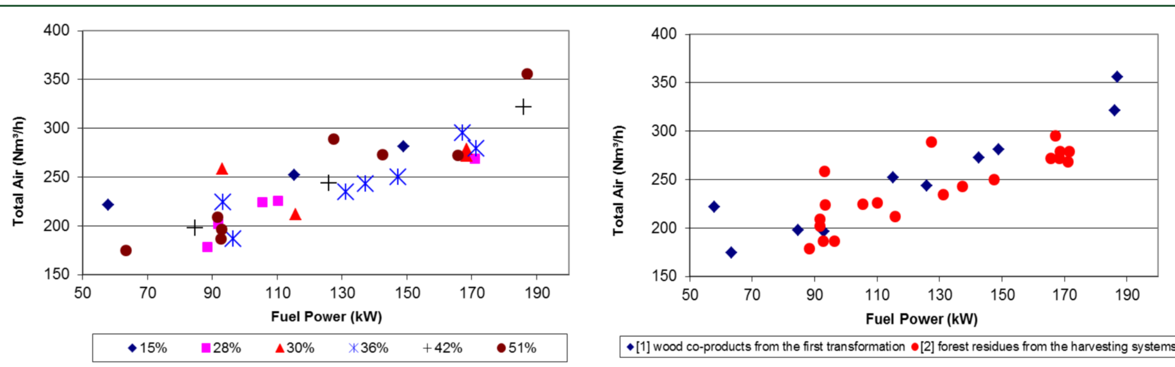

Figure 7. Total air flow as a function of the fuel power depicted by the origin (on the right) and moisture content (on the left) of the fuel.

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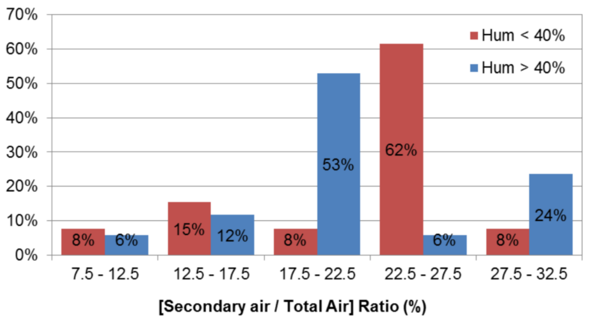

Figure 9. Distribution of the secondary and total air ratios. The blue bars denote wet wood chips, while the red bars are dry wood chips.

secondary air is necessary because of the faster devolatilization of the wood during combustion.

Therefore, the air distribution is as follows for optimal combustion in this boiler under these conditions: 75−80% of primary air and 20−25% as secondary air in the total injected flow. These results agree with the conclusions by Staiger et al.;[13] to guarantee complete burnout for wet fuel on the grate during load fluctuations, the systems are usually operated using high primary air ratios.

Nevertheless, the data set generated by the present study is not broad enough to provide completely reliable results regarding the impact of the fuel moisture and boiler load on the air distribution. This variable should be optimized.

4.2.5. Excess Air Ratio (λ). The excess air ratio represents the ratio between the total and stoichiometric air flows. This parameter was evaluated relative to the amount of emitted CO according to the conditions of the operating boiler: required power, excess air ratio, and wood moisture content. Figure 10 was constructed using all of the data from the set of experiments.

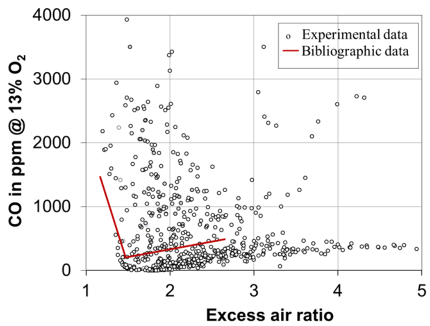

Figure 10. Representation of CO as function of λ for automatic furnaces in the literature[2] (in red) and experimental measurements of CO as a function of λ (circles).

Figure 10 represents the following: (1) results agree with the literature;[2] (2) on the basis of the results, a larger database was generated than in the literature for this type of technology because the moisture content and boiler load were varied; and (3) comparing the results to the literature shows that, if λ is low, the flame temperature is high and the reactions derivate because of the local lack of oxygen, producing high CO concentrations. With an optimal λ, the reactions are completed with enough oxygen and high flame temperatures, generating low CO emissions. Finally, with a high λ, the CO emissions increase because of the low temperatures.[2]

The results of the excess air ratio in Figure 10 were separated by the power and moisture content parameters in Figure 11.

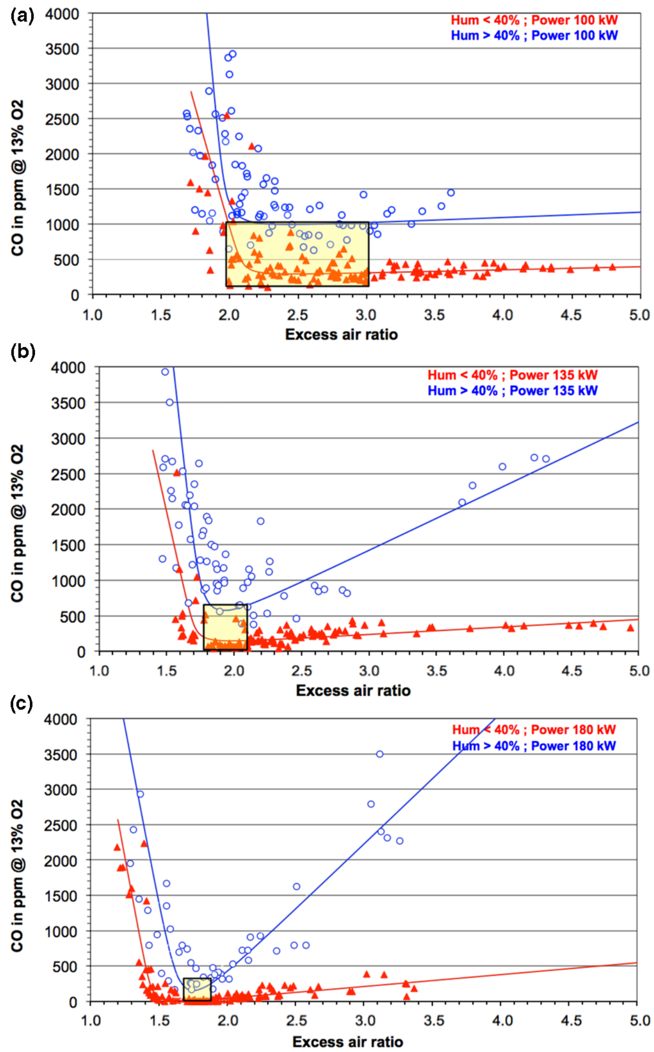

Figure 11. CO emissions versus the excess air ratio for two wood moisture contents at (a) 100 kW_{th}, (b) 135 kW_{th}, and (c) 180 kW_{th}.

Two classes of moisture content were considered: <40% (the three lowest from Table 2) and >40% (the three highest from Table 2). In addition, three power categories were used: 100, 135, and 180 kW_{th}, representing 56, 75, and 100% of the nominal power, respectively.

The load distribution in these three categories is as follows: the data between 85 and 115 kW_{th} are similar to the 100 kW_{th} category; the data between 125 and 150 kW_{th} are similar to the 135 kW_{th} category; and finally, 180 kW_{th} summarizes the power data between 165 and 190 kW_{th}.

The optimal ranges for the excess air ratio while minimizing CO emissions are framed by the square.

This figure shows the direct effect of power on the optimal excess air ratio; when the fuel power increases, the optimal excess air ratio decreases. Moreover, when the moisture content is higher, the optimal excess air ratio increases moderately with the CO emissions, but this range is narrower.

For the first approach, the optimal excess air ratio for minimizing the CO emissions can be chosen independent of the moisture content when the load of the boiler is between 75 and 100%. However, to cover most types of fuels with high

Table 3. Optimal Excess Air Ratio and CO Emissions Relative to the Moisture Content and Fuel Power

	100 kW_{th}		135 kW_{th}		180 kW_{th}	
	λ	CO (ppm at 13% O_2)	λ	CO (ppm at 13% O_2)	λ	CO (ppm at 13% O_2)
humidity < 40%	2.2−3.0	90−231	1.8−2.1	1.0−99	1.7−1.9	0−22
humidity > 40%	2.0−2.5	488−742	1.9−2.1	356−588	1.7−1.9	99−269

moisture contents, the excess air ratio for the feedstock with more than 40% moisture content should be referenced. For 180 kW_{th}, the range for dry fuels is wide (between 1.5 and 2.2); for wet fuels, this range is very limited.

The previous analysis traced the route of the optimization toward optimal wood combustion with minimal CO emissions, enabling the following: (1) estimating the influence of the fuel power and fuel moisture content on the equilibrium between the fuel and oxidizer and (2) determining that the excess air ratio is the most important parameter in this equilibrium as a function of the power and moisture content. In Table 3, the optimal excess air ratio range is extracted from Figure 11.

The differences in the excess air ratio range are more representative of the power evolution compared to the variations in the moisture content. For a nominal condition, the moisture content has no impact, coinciding with the literature results;[35,36] Obernberger et al.,[36] while using a horizontally moving grate at 180 kW_{th}, defined an optimal excess air ratio between 1.66 and 1.96 at nominal load. At partial loads, the range for the λ factor when reducing the CO emissions is wider. The lower the moisture content, the higher the range of the optimal excess air ratio.

Consequently, to optimize combustion in this industrial boiler, determining an optimal excess air ratio that primarily depends upon the power and fuel moisture content to a lesser extent is necessary.

These consistent results allow us to imagine boiler operation controlled by the excess air ratio. However, the excess air ratio is not directly measurable. Fortunately, this parameter is directly related to the oxygen rate. The oxygen content is measured continuously by the λ probe that fits most automatic boilers; the boiler will be controlled using this measurement.

Moreover, the regulations for existing commercial boilers do not index the set point of oxygen on the heat output; this set point is kept constant, regardless of the fuel power.

5. CONCLUSION

The experimental study characterizes the combustion of various woody fuels from different sources in an automatic boiler and optimizes the combustion by minimizing the CO emissions by modifying the boiler control program instead of changing the design of the device.

Fuel power is the most important parameter that affects CO emissions. The most important characteristic of wood influencing combustion is the moisture content. When the level of moisture increases, the CO emissions also increase. In addition, the particle size does not have a significant impact.

Although the CO emissions are lower when 20−25% of the air injected is added as secondary air, the optimal air distribution requires more investigation to validate this range.

The boiler control system in the current automatic devices is based on a constant level of the O_2 concentration in the exhaust smoke. The present study shows that this system is not optimal. To reduce CO emissions, the control system focus on a fluctuating O_2 concentration in the exhaust gas by varying the excess air ratio relative to the power demand. The excess air ratio should be between the range suggested for the wet fuels (between 2.0 and 2.5 at 100 kW_{th}, between 1.9 and 2.1 at 135 kW_{th}, and between 1.7 and 1.9 at nominal power). With this type of regulation, the CO emissions should be reduced.

To optimize wood combustion, reduce CO emissions, and maintain good efficiency, the excess air ratio should be changed as a function of power. Tests are needed to evaluate the influence of the excess air ratio ranges on the boiler control system and implement these changes.

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Notes

The authors declare no competing financial interest.

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