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Article

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Emissions mitigation by control of biomass feeding in an industrial biomass boiler

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Abstract

The objective of this work is the experimental investigation and characterization of the influence of biomass feeding on combustion efficiency of an industrial biomass boiler. The collected experimental data relate the biomass feeding control with the operating conditions and boiler performance parameters. Two different methods to control of the biomass feeding are considered. One consists on the manually controlled biomass feeding through the boiler control system. The other consists on an automatic control, with the screw-feeder controlled by the boiler control system. Boiler control system governs the introduction of the biomass material into the furnace based on the O₂ content of the combustion flue gas stream. Results show that the biomass feeding into the furnace significantly affects the combustion process and the pollutant emissions (e.g., CO and NO).

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Keywords: Biomass; Feeding system; Fixed grate industrial boiler; O₂ content; CO; NO

1. Introduction

Development and application of control policies to reduce harmful substance emissions to the environment and human health are critical and urgent. Measures to improve ambient air quality and to control the emission of pollutants in Europe are defined and established on Directive 2008/50/EC [5] of European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe with guidelines “designed to avoid, prevent or reduce harmful effects on human health and the environment as a whole”. Directive (EU) 2015/2193 [6]

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of European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants “lays down rules to control emissions of sulfur dioxide (SO₂), nitrogen oxides (NO_x) and dust into the air from medium combustion plants, and thereby reduce emissions to air and the potential risks to human health and the environment from such emissions. This Directive also lays down rules to monitor emissions of carbon monoxide (CO)”.

There is a lack of information and of scientific work concerning medium-scale biomass combustion systems for thermal energy production and especially related with the characterization and monitoring of those systems. Once this information available, it allows the parametric optimization corresponding to the efficient use of different types of biomass fuels (pellets, woodchip, straw, etc.), ensuring a low level of pollutants emissions and reducing the common problems of slagging and fouling. Additionally, the study of these systems allows to improve the development of the best-operating conditions of combustion systems, improving the performance parameters of the combustion process, and increasing the energy and financial efficiency of these biomass to energy conversion systems.

Several challenges have been identified following the adoption of biomass as a renewable energy source. One of the challenges is biomass fuel quality. Biomass fuel can be a heterogeneous mix (different types of biomass fuels with different properties) and this variability can cause different effects on the combustion system. These heterogeneous characteristics of the biomass can cause large fluctuations on process parameters as the temperature and gas composition during the combustion process, creating challenges in biomass combustion control and an increase in pollutants emissions [1,2].

The biomass feeding process plays an important role in biomass furnaces and boilers since it directly influences the operating process and related efficiency. Biomass properties such as moisture content, density, shape, particle surfaces (smooth, rough or sharp), different size distributions, different compressibility's, among other properties, may cause problems in stability of feeding flow [4]. Thus, selection, design, and localization of the feed method depend on the properties of biomass and system requirements [3].

Ventil is a leading Portuguese company on the field of manufacturing industrial medium-scale furnaces able to process a distinct set of biomass fuels, among them residual biomass and sub-products. The company offers products, integrated furnaces and boilers for hot liquid water production ($T < 109\text{ }^{\circ}\text{C}$), with well-defined characteristics, like underfeed system by screw feeder, vertical heat exchange system and three different sections to combustion air introduction, including, on a single product, a set of features not properly studied in medium-scale products present on the international market. Thus, characterization of these systems has been a challenge and has been regarded by the company as an important supporting tool for technology development and an effective added value to the state-of-the-art of the technology on the field of biomass combustion. This work focuses on the influence of the biomass feeding control on the combustion process efficiency and related pollutant emissions in a biomass furnace/boiler manufactured by Ventil. The experimental results obtained in a real scale combustion system are an effective contribution to fulfill the present lack of information concerning this technology, towards the improvement of operation and process efficiency of these biomass to energy conversion systems. Characterization of the operating conditions (including flue gas characteristics and temperature profiles along time) of the biomass boiler has been carried out during combustion experiments in a real scale boiler using wood pellets as fuel.

2. Experiments, materials and methods

2.1. Description of biomass combustion system

The experimental work has been developed on a fixed bed grate medium-scale biomass industrial boiler, with biomass underfeed system (underfeed stoker). Liquid water is at temperatures lower than $109\text{ }^{\circ}\text{C}$ and pressures are lower than 3 bar. The medium-scale biomass combustion system/boiler (CVT model from Ventil) with $581\text{ kW}_{\text{th}}$ nominal power was used for the experimental work. The system was located at Ventil–Engenharia do Ambiente, Lda. facilities, and was developed for industrial research and development purposes (see Fig. 1).

Ventil biomass boilers have a generic structure regardless of their nominal power. To maximize heat exchange between the flue gas and water VENTIL boilers (fire tube boiler) have a vertical triple heat exchange system, the flue gases flowing inside the tubes. Inside the furnace (first gas pass) water (and thus indirectly water) receive heat mainly by radiation, and thereafter the flue gases flow inside heat exchanger tubes (second and third pass) immersed in water (and thus indirectly water) receive heat mainly by convection. The boiler was designed with a special



Fig. 1. Experimental medium-scale combustion CVT system at Ventil–Engenharia do Ambiente, Lda. facilities.

configuration, allowing monitoring of the combustion parameters (measurement ports, allowing sensors insertion, are located at different positions along the combustion flue gas path). The furnace is composed by a primary and a secondary combustion chamber. Combustion air is distributed through three different sections. Primary air is supplied into the fixed bed through the circular grates. Secondary and tertiary combustion air are supplied through ports located at distinct heights in the furnace walls above the biomass bed. The combustion system has a bin and a volumetric screw-feeder, which allows biomass feeding into the combustion chamber. Biomass feeding is controlled through the rotation speed of the screw-feeder, acting over the operating frequency of the geared motor. A gradual and controlled feeding process allows an improved sequence of biomass to energy conversion (by this order: drying, devolatilization, and char and volatiles combustion) as it moves towards the combustion front. A multicyclone is placed downstream of the boiler to remove particulate matter from the flue gas exhaust stream. Ventil boilers' configurations allow combustion of a large range of biomass fuels (i.e., different types of biomass, different moisture contents and/or particle size and shape) over a wide thermal output ranging from 350 kW_{th} up to 7 MW_{th}.

2.2. Biomass feeding system calibration

Wood pellets of commercial quality (standardized and certified) were used for the experimental work.

The experimental furnace/boiler incorporates an underfeeding system, integrating a screw-feeder, with a maximum of 12 rpm (100% of the operating frequency of the geared motor), that inserts the biomass fuel into the bottom part of a circular fixed bed inside the bottom part of the furnace. This allows the gradual and controlled introduction of biomass into the bottom of the furnace. As biomass moves upward in the fixed bed and approaching the upper bed combustion front, it is possible to control the combustion process and promote the material pre-drying. The biomass feeding system used in these boilers is designed to allow the use of different types of biomass, inhibiting compression of the material (thus avoiding obstructions and/or blockages).

Screw feeder calibration allows knowledge of the biomass flow rate introduced into the furnace as depending on the screw rotational speed. The geared motor driven the screw feeder works with a maximum frequency of 50 Hz and a minimum frequency of 5 Hz (100% and 10% of the nominal operating frequency, respectively). The operating frequency of the geared motor when wood pellets are used ranges between 10% (1.2 rpm) (minimum allowed by the system) and 30% (3.6 rpm) (maximum feeding required by this type of biomass).

2.3. Biomass feeding system's control

The boiler's control system is of the 'Start and Stop' type, acting over the boiler's electrical and mechanical equipment (e.g. valves opening/closing). Control system stops the boiler (boiler resting phase) whenever the required water temperature is reached.

One of the objectives of this work is to experimentally investigate the influence of biomass feeding on the combustion efficiency. Taking this into account, data were obtained based on the variables of biomass feeding

control. Boiler control system controls the rotational speed of the screw feeder, and sets the operating frequency of the geared motor, triggering screw rotation according to the O_2 concentration (wet gas) in the flue gas. The O_2 concentration in the exhaust flue gas is measured using a lambda sensor located downstream the multicyclone and upstream the exhaust gas extraction fan.

Two different biomass feeding control methods were considered in this work in order to evaluate the influence of the biomass feeding conditions. One consists on the manually controlled biomass feeding through the boiler control system. In other words, the introduction of biomass into the furnace (start and stop system) is imposed by the operator according to the system's needs. The other consists on an automatic control, according which the screw-feeder is automatically controlled by the boiler's control system. Comparison of the two operating modes will also allow understanding if the automatic mode leads to an efficient combustion process, and if its optimization is possible.

The combustion flue gas sampling and composition monitoring was performed by continuous extraction at exhaust duct of the combustion system, using a water-cooled stainless-steel probe including a type-N thermocouple (0–1250 °C).

2.4. Flue gas composition monitoring

The water-cooled stainless-steel probe has three high temperature resistant stainless-steel concentric tubes, with different diameters but equivalent annular areas. This assembly allows circulation of cooling water between outer tubes, for sample gas quenching, and the incorporation of a type-N thermocouple and the suction of flue gas through the inner tube. The sample gas conditioning unit CSS-V1, M&C[®] works continuously and allows supply of the flue gas sample to the online gas analyzer. The combustion flue gas was analyzed with the ABB Continuous Gas Analyzer, Easyline EL3000 Series, Model EL3040, with an infrared photometer Uras26 (used to measure the concentration of CO, NO, and CO_2) and a paramagnetic O_2 analyzer Magnos206; upstream the online gas analyzer a gas conditioning unit was used to remove water, because the gas analyzer works on a dry gas sample. The measuring ranges defined for each chemical species are: CO: 0–10 000 ppm; NO: 0–2000 ppm; CO_2 : 0–25 vol% and O_2 : 0%–25%, all in dry gas volumetric basis.

2.5. Control and monitoring systems

The furnace/boiler monitoring and control system allow acquisition of many variables, including furnace pressure, water temperature, flue gases temperature and flue gases composition (e.g., CO_2 , CO, NO, O_2), allowing also control and monitoring of all ancillary combustion system's mechanical equipment. Control system displays all information concerning the progress of the combustion process along time on an interactive board. The settings and control of the combustion parameters (i.e., water temperature, screw feeder rotation speed, combustion air flowrate, etc.) are set through the interactive board. A database allows structured storage of the experimentally acquired variables. Information from the measurement equipment (thermocouples, moisture sensors, flue gas analyzer, etc.) and sent by the control system is stored in the database, allowing integrated and real-time monitoring and control.

3. Results

3.1. Screw feeder calibration

Relating the biomass flow rate forced by the screw feeder system with the rotational speed of the geared motor system allows calibration of the biomass feeding system. The solids' flow rate can be estimated according to the quantity of biomass passing through the screw feeder. Screw feeder calibration shows that every additional rotation of the screw feeder results on a biomass flow rate increase of 17% (average). A rotational speed of 1.2 rpm (corresponding to 10% of the nominal operating frequency of the geared motor) allows introduction of 155 kg h^{-1} of biomass into the furnace, and a rotational speed of 3.6 rpm (corresponding to 30% of the nominal operating frequency of the geared motor) allows the introduction of 495 kg h^{-1} of biomass into the furnace. It was observed that the biomass flow rate increases nearly linearly with the rotational speed of the screw feeder.

3.2. Flue gas composition as a function of biomass feeding conditions

Figs. 2 and 3 show the biomass flow rate and O₂ flue gas content (given by the lambda sensor) profiles corresponding to manual and automatic control modes, respectively. Under manual operation mode, the biomass feed and rest time periods are imposed by the operator in order to develop a stable operating regime. By comparing the two operating modes, it is possible to observe that the manual operation mode promotes the reduction of stopping periods (reduction of boiler resting phases). Conditions developed by the manual operation mode allow more efficient biomass combustion, without sudden disturbances or fluctuations on the system's operating conditions of the system (i.e., feed interruption), thus reducing the emission of compounds as CO in the flue gases.

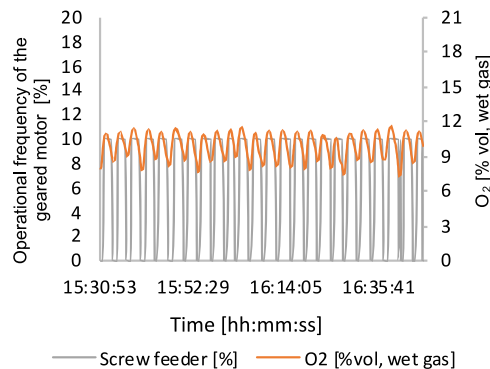


Fig. 2. Profile of biomass feeding and O₂ flue gas content (lambda sensor) obtained under manual operation mode.

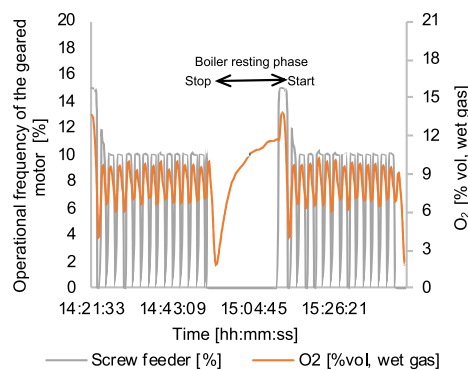


Fig. 3. Profile of biomass feeding and O₂ flue gas content (lambda sensor) obtained under automatic operation mode.

Figs. 4 and 5 depict the correlations between CO, NO and O₂ concentrations (dry gas) in the combustion flue gas. CO is an indicator of fuel conversion efficiency, and thus of the combustion process quality. For the manual operation mode (with a lower frequency of stop and start periods of the biomass feeding system) the CO profile presents an average concentration of 57 ppmv, NO an average concentration of 113 ppmv, and O₂ an average concentration of 10%vol. Under normalized conditions, for 11% reference O₂ concentration (dry gas), CO concentration is of 64 mg Nm⁻³ and NO concentration is of 136 mg Nm⁻³. Normalized volume conditions (e.g., Nm³) refer to a pressure of 1.013×10⁵ Pa and a temperature of 273 K.

Profiles of CO, NO and O₂ concentrations in the exhaust combustion flue gas obtained in automatic operation mode show average values of 716 ppmv, 106 ppmv and 9%vol., respectively. Under normalized conditions, for 11% reference O₂ concentration (dry gas), CO concentration is of 1472 mg Nm⁻³, and NO concentration is of 233 mg Nm⁻³.

An adequate supply of secondary combustion air to promote high-temperature regions at the secondary chamber ensure low pollutants (such as CO) emissions. More steady temperatures, such as those developed under manual

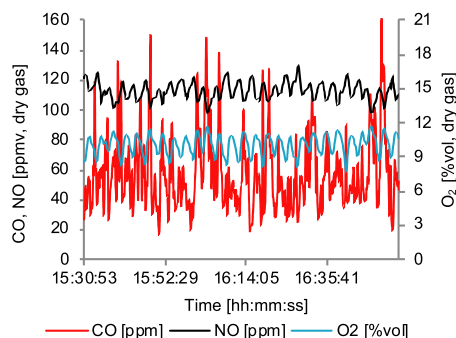


Fig. 4. Exhaust gas profiles of CO, NO and O₂ concentrations (flue gas analyzer) evolution, obtained under manual operation mode.

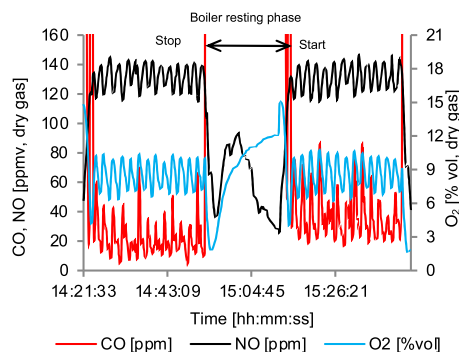


Fig. 5. Exhaust gas profiles of CO, NO and O₂ concentrations (flue gas analyzer) evolution, obtained under automatic operation mode.

operation mode, allow a more complete combustion without sudden disturbances/fluctuations in the system's operating conditions (by decreasing the frequency of stopping/starting the biomass feeding system). This mode of operation allows reduction of the pollutants (such as CO) emissions. Reduced O₂ availability in the reaction zone allows reduction on the flame temperature, thus decreasing the NO formation.

Manual and automatic operating modes of the biomass feeding system lead to different combustion regimes. The results obtained in this work show the need to optimize the control of the automatic operation mode of the combustion system. The improvement of the furnace/boiler's control algorithm will allow more suitable biomass feeding into the furnace, by reducing the frequency of stopping/starting the biomass feeding system, under automatic operation mode. Process optimization will allow efficiency increase and the boiler's performance improvement. Biomass properties such as moisture content, density, particles' surface area, particles' size distribution, compressibility, and heating value, among others, can have a direct influence on the results obtained, and this must be an object of further research.

4. Conclusions

This work deals with the influence of the on-off control system (Start and Stop' type) on the biomass feeding system over the pollutants emissions during biomass combustion in an industrial furnace/boiler. Results show a more stable regime and more efficient combustion when under manual operating mode than when under automatic operating mode. Well designed and optimized control will allow more stable biomass feeding and thus also more stable combustion of the biomass. The lambda sensor for O₂ concentration monitoring is essential for the efficient operation of the furnace/boiler under automatic operation mode, as the biomass feeding rate is controlled based on the O₂ content of the flue gas and a low or high excess of O₂ has a direct influence on the CO emissions.

It was observed that distinct modes/strategies of biomass feeding control influence the CO and NO emissions during biomass combustion in industrial furnaces. This observation suggests that it is possible to improve the

performance of these combustion systems by developing and implementing an optimized control algorithm, allowing more suitable biomass feeding into the furnace when under automatic operating mode. The suitable PID controller must be established to develop sustainable automatic biomass combustion processes.

This is a specific case study, performed for the first time in this CVT furnace/boiler model from Ventil. However, the main conclusions can be used to support the development of optimized operation conditions of other biomass furnace/boiler types using wood pellets as fuel.

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References

- [1] Boriouchkine A, Sharifi V, Swithenbank J, Jämsä-Jounela S-L. A study on the dynamic combustion behavior of a biomass fuel bed. *Fuel* 2014;135:468–81. <http://dx.doi.org/10.1016/j.fuel.2014.07.015>.
- [2] Boriouchkine A, Zakharov A, Jämsä-Jounela SL. Dynamic modeling of combustion in a BioGrate furnace: The effect of operation parameters on biomass firing. *Chem Eng Sci* 2012;69:669–78. <http://dx.doi.org/10.1016/j.ces.2011.11.032>.
- [3] Dai J, Cui H, Grace JR. Biomass feeding for thermochemical reactors. *Prog Energy Combust Sci* 2012;38:716–36. <http://dx.doi.org/10.1016/j.pecs.2012.04.002>.
- [4] Dai J, Grace JR. Biomass screw feeding with tapered and extended sections. *Powder Technol* 2008;186:56–64. <http://dx.doi.org/10.1016/j.powtec.2007.10.033>.
- [5] Directive 2008/50/EC of European Parliament and of the Council of 21 2008 on ambient air quality and cleaner air for Europe.
- [6] Directive (EU) 2015/2193 of European Parliament and of the Council of 25 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants.