ENERGY EFFICIENCY AND EMISSION QUANTIFICATION FOR A SMALL CYCLONIC BOILER RUNNING ON BIOMASS SAWDUST

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Abstract. *The biomass, as an energy resource, is an alternative to decrease the environmental issues once it is not a fossil fuel. Cyclonic combustor is well known as fluidized bed reactor that promotes high efficiency combustion but experimental data is hard to obtain in the literature. This work presents data from a laboratory boiler with a cyclonic combustor equipped with an innovative calorimeter to measure steam quality. Data measured leads to the quantification of boiler thermal efficiency and gas species concentration.*
The experiment was performed with Cedrela fissilis biomass as sawdust which was previously energetic characterized. Results showed a thermal efficiency of 38%, biomass energy conversion through combustion was 98% and a CO emission in the eluded gases was less than 158 ppm. It shows that this boiler is efficient and compact to test different species of biomass.

Keywords: *steam generation, biomass, energetic efficiency, steam quality*

1. INTRODUCTION

Historically, biomass is the main energy source of humankind, being gradually replaced by other fuels such as coal and oil from the nineteenth and twentieth centuries. However, today many developing countries or industrialized ones use it as an energy source, with simple or modern conversion technologies. The simple forms of energy conversion consist of the traditional use of biomass, inefficient processes that must be replaced by new technologies that best utilize the energy potential that this fuel has to offer. The cyclonic combustor for biomass burning is a technology that enables stable flame along with a more efficient mixing of the fuel with the oxidant in more compact than conventional reactors.

Data on cyclone combustor are rare in the literature but indicate a vigorous and stable combustion but with difficulty to identify the best reactor diameter/length ratio and there are references of increasing on NOx emissions when compared with fired bed boilers.

Skopec *et al.*, 2014 has conducted a study about the specific emissions from biomass combustion on a commercial pellet-fired boiler, observing the peaks of CO and other species emissions for two types of biomass. In this work, these data were used as a reference once both boilers run burning biomass waste.

The cyclonic boiler used in this work was a research project with the objective of providing knowledge about local biomass waste used in power thermal generation. Gazel (2010) has developed the boiler air and fuel supply system, and instrumentation to extract data for efficiency calculation. This work presented the difficulty to obtain the boiler thermal efficiency once the steam production were not saturated. Moura (2012) developed a new type of calorimeter to determine the steam quality in a steam line. This calorimeter was tested in a laboratory setup and was not tested in a prototype boiler.

The goal of this work is to calculate the boiler thermal efficiency using the direct method due the combination of the instrumentation of air and fuel supply system and the new calorimeter, making also an emission monitoring.

2. EXPERIMENTAL PROCEDURES

2.1 Cyclonic boiler

Cyclonic combustor consists of rotational flow inside a chamber. Reactant are inject tangentially at the external diameter. The rotational speed increases toward the flame region and decay (Sired, 2004) in post flame zone. The boiler used in this experiment was designed and constructed at Universidade Federal do Pará (UFPA). The main difference between the boiler used in this work and the commercial found technology, is its "water wall". It means that the fuel burn while performing tangential movement in relation to the furnace axis line and exchange heat with the water flowing outside the reactor wall (Gazel, 2010). Figure 1 illustrates a schematic transversal cut of the equipment components. Lower part is the cyclonic combustion chamber (internal) with the water wall to remove heat. Upper part is the convective heat transfer with the smoke pipes and steam accumulator.

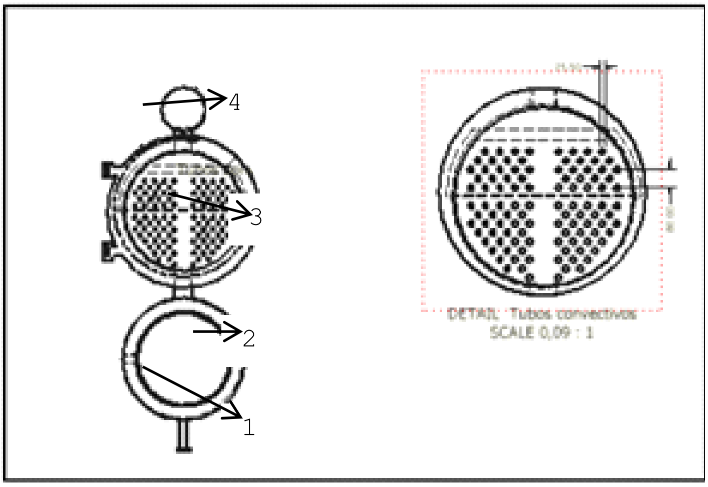

Figure 1. Cyclonic Boiler Scheme

1: Cyclonic Combustion Chamber
2: Water Wall
3: Smoke Pipes
4: Steam Accumulator

2.2 Calorimeter

The electric and throttle calorimeter, named Calorimeter Elecmento, was developed with the purpose of providing data to the steam quality determination (MOURA, 2012), see figure 2. Saturated steam pass through the main pipe and an extraction leads some steam into the calorimeter throttling. The first set of resistances, just after the throttling, turns saturated steam into superheated steam with addition of heat. The second set of resistances measures the mass flow of steam on calorimeter. Two thermocouples and a pressure transducer measure the superheated steam properties before and after the last set of resistances. Once the superheated steam state is identified, the steam mass flow rate though the calorimeter is determined and the heat transfer to the steam is known, the quality is calculated.

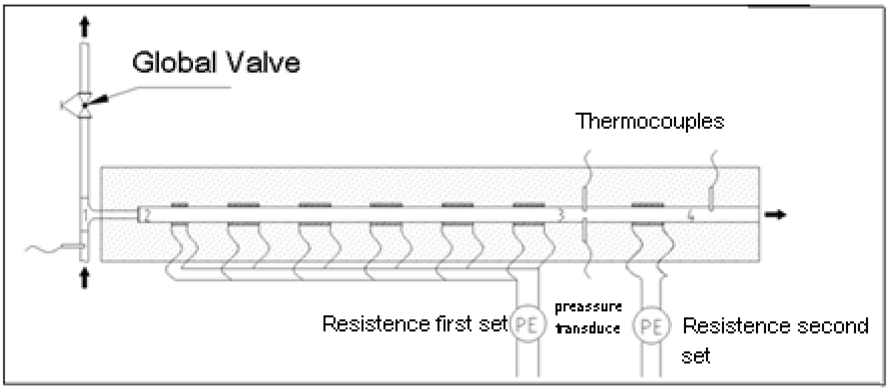

Figure 2. Calorimeter Scheme

2.3 Methodology

The cyclonic boiler can be divided in 4 main systems: water supply system, fuel supply system, monitoring system and combustion gases treatment system. Figure 3 shows the full boiler scheme as well as its main internal systems.

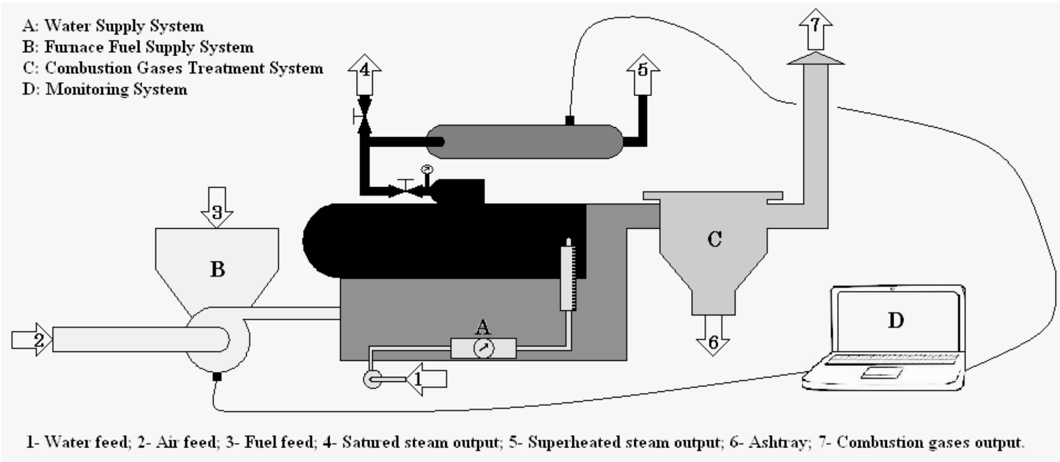

Figure 3. Cyclonic Boiler Full Scheme

The water supply system presented in Fig. 3, has a water pump, security level and water volumetric flow meter. The pump starts when the security level is below the established limit due to the boiler steam loss. The water flow meter measures the volume variation during the boiler filling, making it possible to estimate the mass flow of steam between the water replenishment cycles using Eq. (1) which is based on the conservation law for a mass control volume.

$$\dot{m}_s = \frac{\Delta V}{\Delta t \,.60. v} \tag{1}$$

where:
$\dot{m}_s$: Steam mass flow rate (kg/s);
V: Volume registered from water meter (m³);
t: Time between replenishment cycles (s);
v: specific volume (m³/kg);

The furnace fuel supply system is composed of a silo with a screw and an air blower, Fig. 3. The rotations of the screw and the blower are controlled by frequency inverters and enable the control of the mass flow of air and fuel.

The monitoring system is done by Daqfactory software, it has two pressure transducers, and three thermocouples distributed on the main steam line, calorimeter and exhaustion of combustion product gases, see Fig. 4. Using the software is possible to measure the state of the steam, which is important due the phase transformation to superheated steam from saturated steam during the operation.

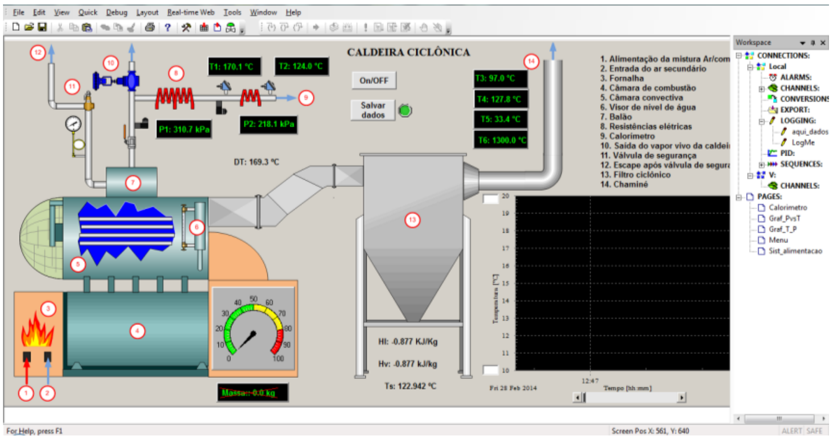

Figure 4. Monitoring screen from Daqfactory software

The combustion gases treatment system comprises a cyclone, ashtray and a chimney, shown in Figure 3. After heat exchange, the exhaust gases enter the cyclone setting the heavier particulate material in the ashtray, only exhausting the combustion gases and lighter particles. The analysis of the collected material from ashtray allows estimate combustion efficiency, which is based on the energy and mass conservation law, as well as the CO mol fraction obtained at the exhaust gases using the gas analyzer Tempest 100 manufactured by Telegan. Equation (2) shows how the combustion efficiency was calculated.

$$n_{comb} = \left\{1 - \frac{[m_a.LHV' + (n_{CO} * \bar{h}_{CO})]}{m_f.LHV}\right\} x100 \tag{2}$$

Where:
n_{comb}: Combustion thermal efficiency (%);
m_f: Mass fuel ratio (kg);
LHV: Fuel lower heating value (kJ/kg);
m_a: Ash biomass mass (kg);
LHV': Ash biomass lower heating value (kJ/kg);
n_{CO}: Molar concentration of CO in the exhausted gases (kmol)
$\bar{h}_{CO}$: Molar enthalpy of CO at measure temperature (kJ/kmol)

After the pressure in the boiler hits the operation value, the monitoring system is activated just before the opening the main boiler valve at steam accumulator. The system was set to work at setpoint shown in Tab.1.

Table 1. System setpoint.

Variables	**Values**
Work Pressure	450 kPa
Sawdust flow	54 kg/h
Air flow	562 kg/h
Equivalence Ratio	0.46
Thermal Power	0.22 MW

The characterization of the Cedrela Fissilis biomass and unburned biomass for the LHV determinations purpose was made through proximate analyses, ultimate analyses and HHV determination (Nogueira, 2008). Proximate analyses follow the Brazilian standards (ABNT) for coal or follow the ASTM standard for wood. Ultimate analyses was made using Elementar Analyzer (Perkim Elmer 2400) and HHV were determined using a calorimeter bomb (IKA C2000). Table 2 shows the results of the analysis.

Table 2: Cedrela Fissilis Analysis

Proximate Analysis				
Carbon (%)	**Hydrogen (%)**	**Nitrogen (%)**	**Sulfur (%)**	**Oxygen (%)**
46.49	5.96	1.89	0.67	44.99
Ultimate Analysis				
Moisture content (wt%)	**Volatile matter (wt %)**	**Fixed carbono (wt %)**	**Ash (wt %)**	
12.59	72.10	14.47	0.84	
HHV (kJ/kg)		**LHV (kJ/kg)**		
18,627		14,829		

The determination of thermal efficiency for the direct method is shown in Eq. (3).

$$n = \frac{\dot{m}_s.(h_g - h_f)}{\dot{m}_f.LHV} x100 \tag{3}$$

Where:
n: Thermal efficiency (%);
$\dot{m}_s$: Steam mass flow rate (kg/s);
h_g: steam enthalpy at main line (kJ/kg);
h_f: Water of replenishment enthalpy (kJ/kg);
$\dot{m}_f$: Fuel mass flow (kg/s);
LHV: Fuel lower heating value (kJ/kg);

3. RESULTS AND DISCUSSIONS

The cyclonic boiler operation results in producing saturated steam at the main steam line and superheated in the extraction calorimeter. Figure 4 shows the cyclonic behavior of the flow in the furnace in a test using only air injection tangentially and hot solid residues in the reactor.

Figure 4. Cyclonic Behavior

During the data measurement, was observed the existence of operational transient points due the water inlet and calorimeter turn on. To overcome these facts the system was modeled as a control volume on a steady-state condition, making possible to apply the First Law of Thermodynamics along with the thermodynamic concepts. Fluid properties were obtained, but for this work, the main results is the thermal efficiency and the steam quality. Figure 5 shows a graph with the variation of the superheated steam temperature, along the calorimeter, during operation time of the boiler.

In the graph it is possible to observe the sudden increasing on temperature due to steam flow. The reading stabilizes at around 100 °C, which point fits the calorimeter to obtain superheated steam, which then passes to assume values of approximately 140 °C. Each temperature fall in this chart corresponds to the water replenishment system. The range between the two full lines is a complete cycle of replenishment used to estimate the steam mass flow. The other interval, between the dashed lines, is the steady-state region, where the superheated steam comes out from calorimeter and is the chosen steady-state region to acquisition data for steam quality.

The elapsed time during the replenishment and the total time during the measurement are shown in the Tab.3. The thermodynamics parameters measured by the calorimeter are on the Tab. 4.

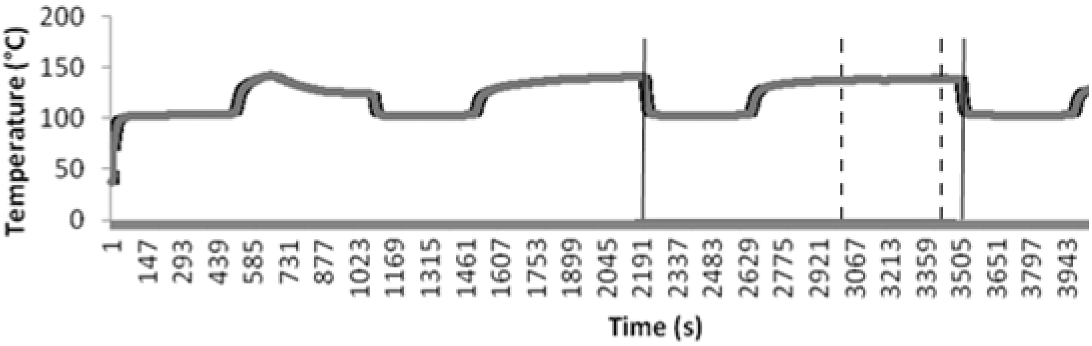

Figure 5. Calorimetric Steam Temperature at calorimetric first termocouple.

Table 3. Measurement Duration
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Measurement	
Total time elapsed	1h
Replainshed cycle time	20min:26s

Table 4. Calorimeter Measured Parameters.

Thermodynamic Proprieties	Entalpy (kJ/kg)	Steam Quality
Values	2,310	0.80

The record of water flow meter showed a variation of 0.05 m^3 every refueling. Table 5 shows the properties of feed water. The mass flow rate of steam, worth 165.6 kg/h, and was determined from the Eq. (1).

Table 5. Properties of Feed Water.

Water	
Temperature	302 K
Enthalpy	121.7 kJ/kg
Specific Volume	0.001004 m³/kg

Having all the parameters related to the Eq.1 was possible assemble on tab 6, which contain these values, as well the efficiency of the cyclonic boiler presented.

Table 6: System output data for efficiency determination

System output data	
Steam mass flow rate	0.046 kg/s
Steam enthalpy at main line	2,310 kJ/kg
Water of replenishment enthalpy	121.7 kJ/kg
Biomass flow rate	54 kg/h
Fuel lower heating value	14,829 kJ/kg
Thermal efficiency	38.54 %

Table 7 and 8 shows the CO emissions taken with tempest 100 analyser and the parameters used in Eq. 2 to calculation of combustion efficience, respectively.

Table 6. CO Emissions – Tempest 100 Measurement

Chemical Element	Sampling	1	2	3	4	5
CO (ppm) At 200ºC		115	151	126	147	**158**

Table 7. Biomass burning and emissions informations

Total fuel mass	60 kg
Ash fuel mass	1.63 kg
Ash heating value	11,237 kJ/kg
CO Mol quantity	0,008631 kmol
CO Mol Entalphy	113,376 kJ/kmol
Combustion efficiency	98,10 %

4. FINAL COMMENTS

Highlights for the cyclone combustor are the short time it requisite to came from rest to operational condition together with short combustion length and consumption of most part of the fuel (from 60 kg, 1.6 kg of ash was produced). It is of simple construction and provide best area for heat transfer to the water.

The calorimeter prove itself to be of easy operation and able to measure steam quality for a large range of values (from 0.8 to 1.0). It is easy to be constructed, have a very low cost and easy maintenance.

The measured thermal efficiency was 38,54%. It is a fair efficiency considering the low water pressure adopted (450 kPa) and the low equivalence ratio adopted (Φ=0.46). Skopec (2014) obtained 59%when burning rape plant straw pellets and 71% for wood pellets using a higher water pressure. The obtained combustion efficiency, 98.1% indicates that the combustion was completed inside the reactor. This conclusion is reinforced with Skopec results. He obtained with a fluid bed combustion boiler 165 ppm of CO and this work found 139 ppm indicating a better combustion in the cyclone than in the fluid bed.

5. ACKNOWLEDGMENTS

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