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TURBINE AND BOILER EFFICIENCY EVALUATION OF STEAM CYCLE MICRO THERMAL POWER PLANT USING BIOMASS

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Abstract. *Tthe potential of the biomass as energy resources in Amazon can only be evaluated if the electric efficiency of small plants is properly konwn. This work evaluated the system losses and the efficiency of the boiler and turbine of and experimental 5kW power plant installed at the University of Pará (UFPA). The data were gathered maintaining the boiler work pressure at the at circa 6 bar, that resulted in a turbine's efficiency of around 2,26% (of a maximum expected 3%). The efficiency of the set boiler-furnace was approximately 22%. Steam mass flow, steam temperatures and steam pressures were measured and the data were correlated to infer the turbine, boiler and overall efficiencies.*

Keywords*: Biomass Energy, Experimental Biomass Power Plant, Energy Generation, Steam Cycle, Efficiency.*

1. INTRODUCTION

There are several villages in the Amazon region that use diesel engines to generate electricity, most of them with power less than 200kW. In Amazon region there is a considerable amount of biomass residues such as sawmill and other natural residues that can be used as solid fuel in steam power plants. These residues are mainly açaí seeds (*Euterpe oleracea*), Brazilian nut shells and several palm seeds. Despite the fact that the efficiency of power plants smaller than 1MW is too low, it is still feasible to use biomass as fuel for small power plants in Amazon due to the availability of residues. However, in order to evaluate the energy generation potential of Amazonian communities, it is necessary to estimate the efficiency of steam power plants with less than 200kW.

Marialva et al. (2008) calculated the efficiency of the system boiler-furnace trough the measurements of the global electric efficiency of a 5kW pilot power plant with Rankine steam cycle and fuelled with biomass, located at University of Pará (UFPA) – Brazil. A data acquisition system was used to collect and store the data of biomass consumption, electric power, temperatures and pressures at several points of the power plant. The authors estimated that the losses were 4%, the turbine efficiency 2.3% and the boiler efficiency was 21.8%.

The present work correlated the measured data of biomass consumption, pressures, temperatures and steam mass flow to determine the losses, turbine efficiency and boiler-furnace efficiency.

2. THE EXPERIMENTAL POWER PLANT

The experimental plant is located in the Mechanical Engineering Laboratory of UFPA and uses water vapor as the Rankine cycle working fluid. The plant is comprised of a 12 bar (work pressure) fire-tube boiler, a 5kW steam turbine, condenser, a gear reduction transmission, an electric generator, pumping system, condensate tank, cooling tower, blowing fan and multiple cyclones for air pollution control. The plant is monitored with sensors enabling the data acquisition of the biomass consumption, the steam flow, the generator speed, the voltage and power at each phase, pressure and temperature at the turbine inlet and outlet, pressure and temperature at the boiler inlet and outlet. Analog-to-Digital (A/D) converters with resolution of 16 bits were used for the data acquisition. For measurement of electrical parameters (electric power, current, voltage and power factor) the equipment "SAGA 4500" manufactured by the ESB was used.

3. PROPERTIES MEASURED

The experiment was conducted during 51 days between 7:00 and 18:00, totalizing 194.75 hours of operation. The steam turbine work pressure was chosen above 6 bar. Eleven types of Amazonian biomass fed the boiler-furnace at a frequency of 45 to 50 minutes, weighted and disposed in sets between 80 kg and 100 kg. That sustained a constant consumption of biomass of 240 kg/h. A digital weighing scale with accuracy of 0.1 g connected to the data acquisition system was used to control the feeding of biomass into the boiler-furnace.

The electric power generated was measured by an equipment manufactured by ESB, SAGA 4500, which was also connected to the data acquisition system. Electrical power, electrical current, voltage and power factor.

1.1. Biomass properties

Table (1) shows the 11 different types of Amazonian biomass used as fuel during the experiment. A small amount of biomass was sampled before feeding the boiler-furnace and laboratory tests were performed in order to evaluate the Higher Heating Value (HHV), Lower Heating Value (LHV), moisture content, fixed carbon, volatiles matter and ashes. The electric efficiency was determined based on the electric power measured (W), the amount of biomass (m_{bio}) that fed the boiler-furnace and mean LHV of those biomass used:

$$\eta_{electric} = \frac{W \times Time}{LHV \times m_{bio}} \tag{1}$$

Table1: Biomass properties

Biomass	**HHV (kJ/kg)**	**LHV (kJ/kg)**	**Fixed Carbon (%)**	**Volatile matter (%)**	**Ash (%)**	**Moisture (%)**
Angelim	17514.77	11669.03	15.13	70.01	14.86	26.36
Açaí	19158.80	11466.81	19.45	79.44	1.11	35.00
Angelim pedra	19842.92	10977.66	17.15	81.56	1.30	41.25
Angelim vermelho	4881.00	20435.77	20.35	79.61	0.05	18.48
Casca de dendê	16551.17	10870.98	19.59	76.21	4.20	26.57
Cumaru	20139.76	13988.52	13.29	86.65	0.07	25.11
Jatobá	19412.52	15899.33	19.99	79.63	0.38	13.30
Maçaranduba	20114.77	13070.23	17.36	82.44	0.20	29.87
Muiracatiara	20208.01	14949.81	58.58	41.14	0.28	20.65
Serragem de tauarí	19869.72	17321.93	16.75	82.56	0.69	9.15
Tauari	19869.72	17321.93	16.75	82.56	0.69	9.15

1.2. Temperature and work pressure

Fig. (1) shows the pressure measured at the boiler outlet of at the turbine inlet, in numbers of events along the nearly 195 hours of operation. It can be observed that the resulting pressures (boiler outlet and turbine inlet) were controlled to maintain the turbine work pressure above 6 bars. The difference between the boiler outlet pressure and turbine inlet pressure was around 1.4 bar because the head losses, so the losses could be evaluated.

Table (2) shows the statistical results of the pressure measured comparing the boiler outlet and turbine inlet. For almost 195 hours of operation the mean turbine inlet pressure was 6.97 ± 0.1 bars, while the mean boiler outlet pressure was 8.4 ± 0092 bar with 95% of Confidence Level.

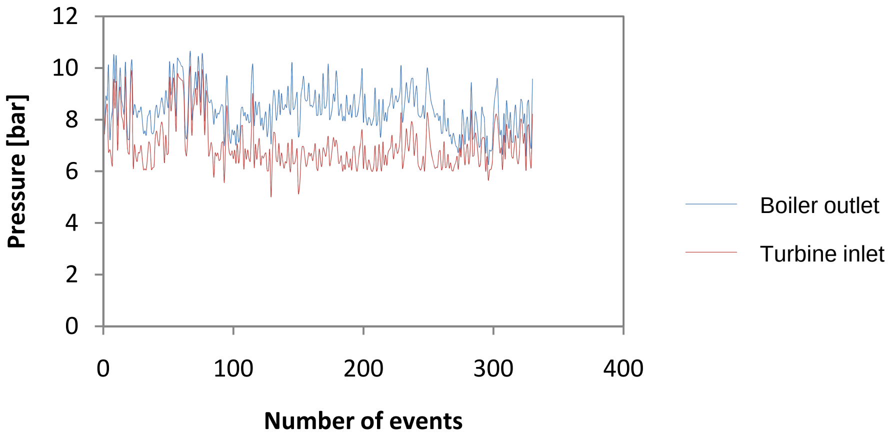

Figure 1- Graph of boiler-turbine steam pressure in numbers of events

Table 2 – Statistics of the measured pressure

	Boiler (bar)	*Turbine (bar)*
Mean	8.40±0.09	6.97±0.102
Standard deviation	0.84	0.94
Minimum value	6.27	5.01
Maximum value	10.59	10
Expanded Uncertainty	0.092	0.102

As for the pressures measurements showed above, the steam temperatures were also measured. Figure (2) shows the temperature measured at the boiler outlet and turbine inlet. Table (3) shows that the mean temperature of the steam leaving the boiler was 232.6 °C ± 2.6 °C and the mean temperature of the steam at the turbine inlet was 170 °C ± 1.4 °C, for a confidence level of 95%.

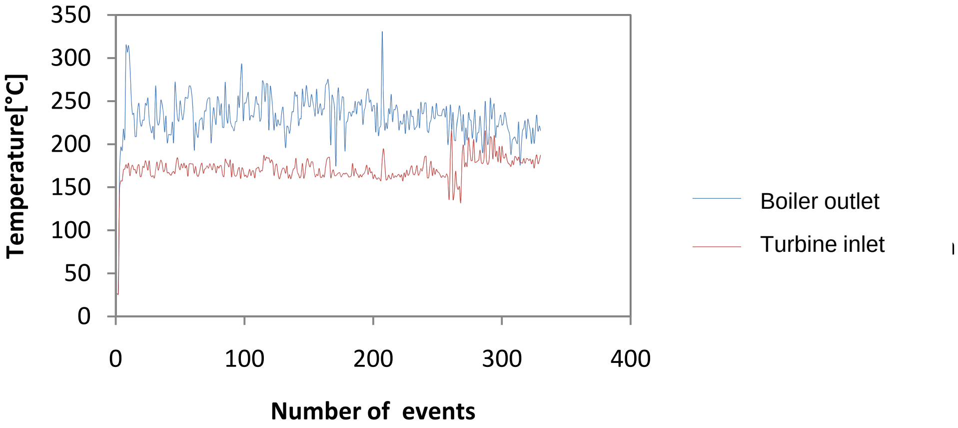

Figure 2- Graph of steam boiler-turbine temperature as a function of numbers of events

Table 3 – Statistics of the measured temperature

	Boiler (ºC)	*Turbine (ºC)*
Mean	232.63±2.63	171.55±1.47
Standard deviation	24.27	13.61
Minimum value	26.38	25.83
Maximum value	330.5	215.82
Expanded Uncertainty	2.63	1.47

1.3. Steam enthalpy

With the pressures and temperatures measured as showed in Figure (1) and Figure (2) the steam enthalpy could be determined through the pair pressure-temperature at the boiler outlet and turbine inlet. Figure (3) shows the resulting enthalpy of the steam at the boiler outlet and turbine inlet.

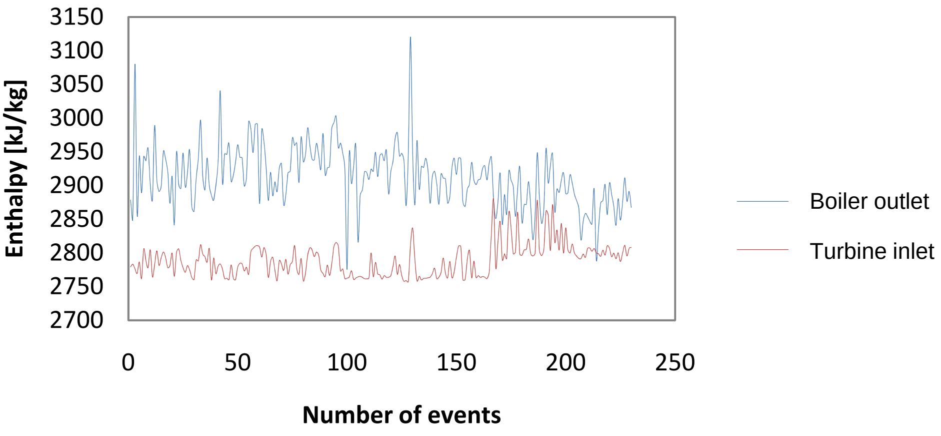

Figure 3- Graph of steam boiler-turbine enthalpy as a function of numbers of events

1.4. Steam consumption

Steam flow at the turbine inlet was measured using an orifice plate with orifice diameter of 14.39 mm. The pressure drop of the orifice plate was connected to the data acquisition system, and the calculated steam flow values were directly correlated to the steam consumption of the turbine (in kg/h) showed in Figure (4). Also shown in Figure (4) when the steam consumption of the turbine is divided by the measured electric power (to be seen in the next item) the specific consumption of the turbine (in kg/kWh) could be determined.

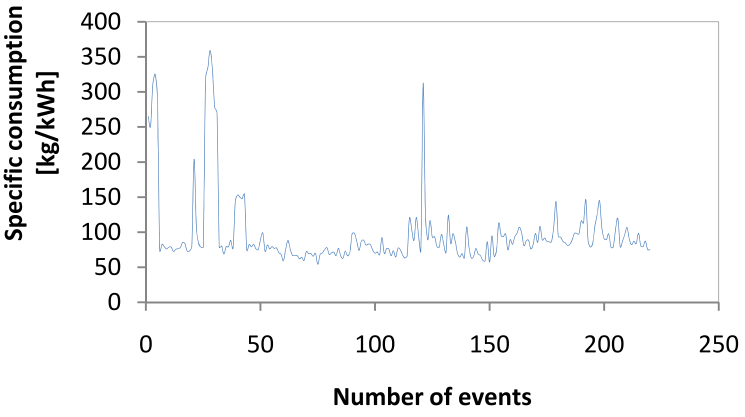

Figure 4 – Graph of the specific consumption and steam mass flow in numbers of events

1.5. Electric Power Generated

The Figure 5 shows the electric power measured along the nearly 195 hours of operation, in number of events. Marialva et al. (2008) showed that for an average value of 6.97 bar of the boiler work pressure (Table 2) the expected electric power output was 2.3 kW. However, Figure (5) and Table (4) show that the average power generated by the plant was 1.93 ± 0.19 kW, which is 16% less than the expected power.

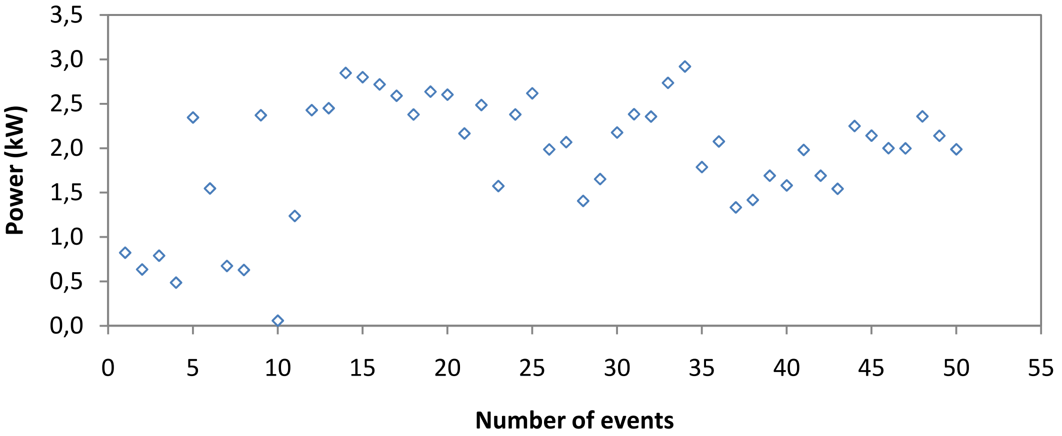

Figure 5 – Graph of the measured electric power in number of events.

Table 4 – Statistics of the measured power

	W (kW)
Mean	1.92±0.1932
Standard deviation	0.6871
Minimum value	0.0593
Maximum value	2.9209
Expanded Uncertainty	0.1932

1.6. Electrical efficiency measure

The overall electrical efficiency was determined by Equation (1), where biomass consumption was 240kg/h and mean LHV was 17321.93 kJ/kg Table (1). Figure (6) and Table (5) show that the mean efficiency of the plant was 0.46 ± 0.08% with 95% of Confidence level.

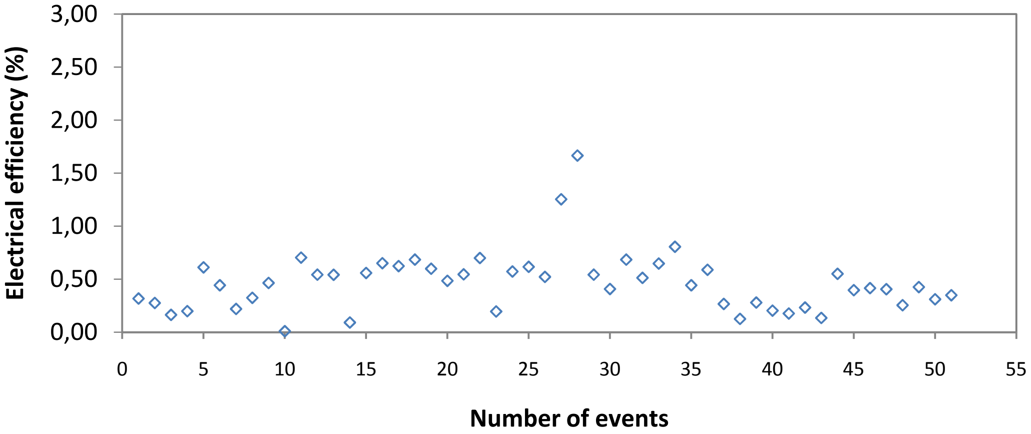

Figure 6 – Graph of the electrical efficiency measured according of numbers of events.

Table 5 – Statistics of the electrical efficiency

	η_e *(%)*
Mean	0.4648±0.0789
Standard deviation	0.2805
Minimum value	0.009
Maximum value	1.665
Expanded Uncertainty	0.0789

2. RESULTS AND CONCLUSIONS

As described in the introduction of this work, the boiler-furnace efficiency calculated by Marialva et al. (2008) was 21.8%, based on estimated losses of 4% and estimated turbine efficiency of 2.3%. With the data gathered by the acquisition system the steam consumption of the turbine could be determined allowing the calculation of turbine efficiency, boiler-furnace efficiency and losses.

2.1. Losses

Figure 3 showed the steam enthalpy calculated from the values measured of the pair pressure-temperature at the boiler outlet and at the turbine inlet, and Figure (4) showed the steam consumption of the turbine. Those two figures combined provided the losses as shown in Figure (7) below. The losses were calculated by the enthalpy difference between of the boiler and turbine multiplied by the steam mass flow. Table (6) shows that the mean losses are 4.6% ± 0.23% with a confidence level of 95%. This value is 15% higher than the losses estimated by Marialva et al. (2008).

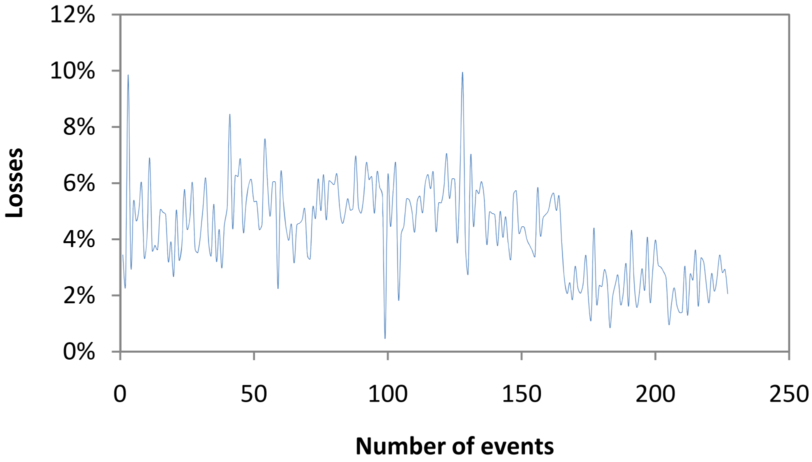

Figure 7- Graph of the calculated losses in numbers of events

Table 6 – Statistics of the calculated losses

	Losses (%)
Mean	4.29±0.23
Standard deviation	0.0162
Minimum value	0.46
Maximum value	9.90
Expanded Uncertainty	0.23

2.2. Boiler efficiency

The boiler-furnace efficiency was determined by the Equation (2) bellow using the values previously presented of steam consumption (Figure 4), the steam enthalpy at the boiler outlet (Figure 3), biomass consumption (240kg/h) and mean LHV (Table 1). The resulting boiler-furnace efficiencies are shown in Figure (8) and statistics in Table (7). The mean efficiency of the boiler-furnace was 21.48% ± 0.23% with 95% of Confidence level. Marialva et al. (2008) estimated an efficiency of 21.8% which is 1.49% higher than the actual value.

$$\eta_{boiler} = \frac{Consumption\ of\ Steam \times Enthalpy}{LHV \times m_{bio}} \tag{2}$$

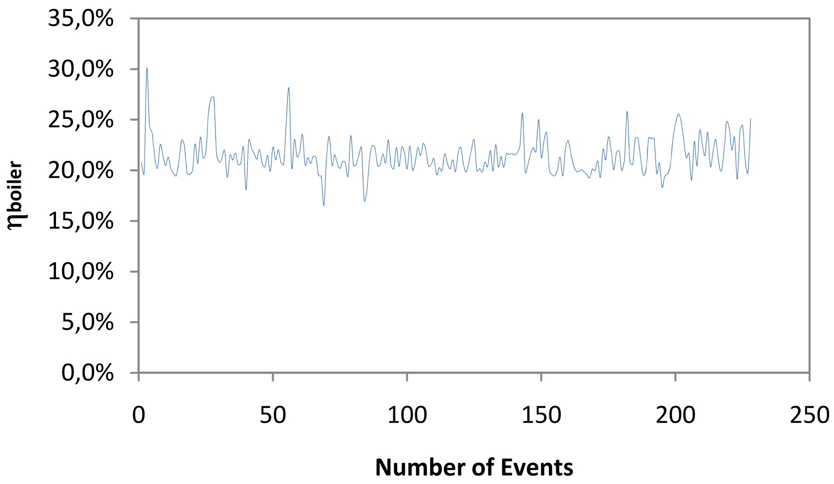

Figure 8 – Graph of the boiler-furnace efficiency according to the numbers of events

Table 7 - Statistics of the calculated boiler-furnace efficiency

	η_{boiler} (%)
Mean	21.48±0.23
Standard deviation	1.79
Minimum value	16.53
Maximum value	30.06
Expanded Uncertainty	0.23

2.3. Turbine efficiency

The turbine efficiency was determined by the Equation (3) bellow using the generator efficiency ($\eta_{generator}$), the gear reduction transmission efficiency (η_{gear}),, electric power generated (W), steam consumption ($\dot{m}_{steam}$) of the turbine and steam enthalpy (h) at the turbine inlet. Figure (9) shows the resulting turbine efficiency and statistics are presented in Table (8). The mean turbine efficiency was 1.45% ± 0.05% with 95% of Confidence. The turbine efficiency of 2.26% estimated by Marivalva et al. (2008) overestimated in 55.8% the actual value.

$$\eta_{turbine} = \frac{3600 \times \eta_{generator} \times \eta_{gear} \times W}{\dot{m}_{steam} \times h} \tag{3}$$

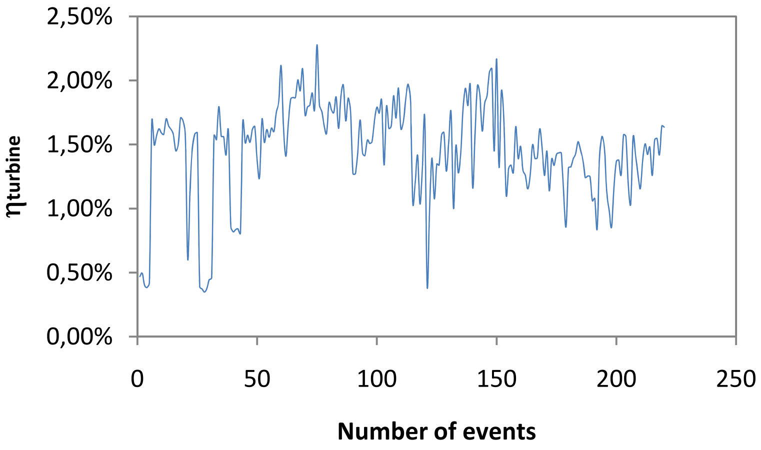

Figure 9 – Graph of the turbine efficiency in of numbers of events

Table 8 - Statistics of the calculated turbine efficiency

	$\eta_{turbine}$ (%)
Mean	1.45±0.05
Standard deviation	0.3786
Minimum value	0.35
Maximum value	2.28
Expanded Uncertainty	0.05

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