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™Small steam turbine operating at low pressure for generating electricity in the Amazon

Pequena turbina a vapor operando em baixa pressão para geração de energia elétrica na Amazônia

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ABSTRACT

In the Amazon, local electrical energy production is very important due to the large number of isolated communities, usually far from the conventional grid. In this context, steam turbines are relevant technologies to be used in the region, since waste biomass is widely available in several communities, besides, where sustainable agricultural activities take place, such as the use of açaí seeds, sugarcane bagasse, among others. Currently, there are not many relevant studies in the literature for small steam turbines operating at low pressure, conditioned to the reality of the Amazon region. Hence, the main goal of this work is to develop an experimental study of a small steam turbine operating at low pressure, in order to apply it to small energy demand, typically found in the Amazon. We developed measurements on the behavior of mechanical and electrical powers in relation to the shaft rotational speed of the small steam turbine, taking into account pressures of 0.1, 0.2 and 0.3 MPa. We concluded that the preliminary experimental survey, made in this work, demonstrates a good mechanical behavior of the small turbine and could be an alternative for electricity generation system to supply small demands in isolated communities in the Amazon, taking advantage of biomass from sustainable agricultural activities.

Keywords: Steam turbine; Boiler; Cyclonic combustor; Magnet permanent generator.

RESUMO

Na Amazônia, a produção local de energia elétrica é muito importante devido ao grande número de comunidades isoladas, geralmente distantes da rede convencional. Nesse contexto, as turbinas a vapor são tecnologias relevantes a serem utilizadas na região, uma vez que a biomassa está amplamente disponível em diversas comunidades, inclusive, onde ocorrem atividades agrícolas sustentáveis como a utilização do caroço do açaí, bagaço de cana, entre outros. Atualmente, não existem muitos estudos relevantes na literatura para pequenas turbinas a vapor operando em baixa pressão, condicionadas à realidade da região amazônica. Assim, o objetivo principal deste trabalho é desenvolver um estudo experimental de uma pequena turbina a vapor operando em baixa pressão, a fim de aplicá-la a pequenas demandas de energia, tipicamente encontradas na região. Desenvolvemos medições do comportamento das potências mecânica e elétrica em relação à velocidade de rotação do eixo da pequena turbina a vapor, levando em consideração as pressões de 0,1, 0,2 e 0,3 MPa. Concluímos que o levantamento experimental preliminar, feito neste trabalho, demonstra um bom comportamento mecânico da pequena turbina e pode ser uma alternativa para o sistema de geração de energia elétrica suprir pequenas demandas em comunidades isoladas na Amazônia, aproveitando a biomassa oriunda de atividades agrícolas sustentáveis.

Palavras-chave: Turbina a vapor; caldeira; combustor ciclônico; gerador magnético permanente.

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1. INTRODUCTION

The Amazon has an enormous biomass potential, representing a significant source to be used in thermal systems for electric power generation. For example, the açaí fruit, which after being consumed by the population, many tons of açaí seed are inappropriately disposed every day on the nature. In addition, considerable parts of the Amazon region still lack access to electricity services, largely due to the long distances needed to be covered, as well as the challenging topography [1–3].

Thus, the combined heat and power systems, which are called as cogeneration power systems, are very effective equipment, which generate both electric power and thermal energy [4]. Furthermore, technologies including biomass-based small thermal system are interesting solutions to improve the Brazilian electrification in remote areas [5]. Simultaneously, they can minimize negative environmental impacts due to residual from agricultural activities. According to SLOUGH *et al.* [6], this type of system contributes for the rural electrification and it would serve the goal of socio-economic development. Improved electricity access can power rural industries, enhance agricultural productivity, and provide households with more productive time for study and work at night.

Specifically, a steam turbine is a mechanical device that converts thermal energy in pressurized steam into useful mechanical work, and they are most popular devices for generating electricity due to the higher thermal efficiency and power-weight ratio in various conventional, nuclear or other power plants [7, 8]. Each turbine section consists of a set of a moving blades attached to rotor and a set of stationary vanes in which steam is accelerated to high velocity [9]. Those turbines have rotational speed suitable for connecting electric generators.

Steam turbines used as process drivers are usually required to operate over a range of speeds in contrast to a turbine used to drive an electric generator, which runs at nearly constant speed [10, 11]. They are also used as a constituent part of combined cycle power plants, in various marine or offshore applications as well as for driving various mechanical power consumers that are not electrical generators [12].

Typically, steam turbine consists of three types, high, medium and low pressure and it can generate from 750 W in small units, up to 1,900 MW in large power plants [7, 13]. In addition, such turbines use renewable sources, contributing to the non-dependence on fossil energy used in most area of the Amazon region, increasing the supply in the country [14, 15].

Several communities in the Amazon have low electricity demand, making small steam turbines important [3] to be utilized, as it operates at low pressure. Some studies have been developed by SÁNCHEZ *et al.* [1], VAN ELS *et al*. [5], PLOVNICK [16] and PINHEIRO *et al.* [17] about electrification in the Amazon. But, only the research of MACÊDO *et al.* [3] presents experimental data of a steam microturbine combined to a vertical boiler with steam capacity of 150 kg per hour and a maximum pressure of 0.98 MPa, using a direct current generator of 12 V and 500 W. In their studies, the tests are carried out on two different days, leading to average results of 565 Wh for power consumption, 207 W for electric power, and 0.34 MPa for boiler pressure. Also, the study showed a high specific biomass consumption, reaching an average value of 706 kg of steam per kWh.

According to MEDICA-VIOLA *et al.* [12], just a few works are available in the literature regarding steam turbines, including its components or other devices, which ensure stable, reliable and efficient operation of the entire power plant. Some of such studies are energy, exergy, economic, or environmental analysis, but none deal with small demand applied to sustainable agriculture in Amazon, mainly using regional biomass.

In this context, more studies to investigate the performance of steam microturbine to generate electricity are needed, in order to meet actual demand of isolated communities, as well as contributing to the sustainability of the Amazon. The efficiency of small steam turbine systems must be improved. The main challenge in the region is that most of the thermal systems used are still thermal-diesel generator, whose fuel is extremely polluting [18]. Therefore, it is necessary to evaluate small thermal systems using biomass, operating at low-pressure and low-rotation condition, allowing cheaper, compact and security generator units.

Then, the experimental investigation carried out in this work is important to the current state-of-the-art, as it fits the needs of isolated regions as in the Amazon. The results, obtained here, are relevant to evaluate the performance of small steam turbines at low pressure for power electric generation in the region, mainly in isolated rural communities. These types of steam turbines can contribute significantly to reusing residual biomass generated in the region, minimizing environmental impacts mainly from small agricultural activities.

Hence, the main goal of this paper is to develop an experimental study of the performance of a small steam turbine at low pressure, coupled to a boiler with a cyclonic combustor using regional biomass. A magnet permanent generator of 1 kW applied to small demands is employed, which is a good contribution for this research because it works at low rotation and high torque. Additionally, the work evaluates the behavior of mechanical and electrical power in relation to the shaft rotational speed of the steam turbine for pressures of 0.1, 0.2 and 0.3 MPa. In this case, a load bank with equivalent resistance of 2.4 Ω is used to simulate the electrical load. As a result, for a working pressure of 0.3 MPa, the turbine provided good stability, being able to generate energy reliably. Besides characterizing the superior specific heat and humidity of the biomass used in this study, also, it investigates the efficiency of the electric generator under test conditions.

2. MATERIALS AND METHODS

To investigate the performance of the small steam turbine operating at low pressure, details of its characteristics is described in this section, as well as the experimental apparatus used in the bench setup. The biomass characterization based on the European Committee for Standardization Solid Biofuels – ECS/SB: CEN/TS 14774-1:2004 is also detailed [19].

2.1. Operational characteristics of the steam turbine

The experimental analysis is carried out on the commercial steam Turbine COPPUS, RLA Type [20], model RL12L, which is manufactured for small systems. It is constituted by a single stage and characterized as a horizontal flow turbine, whose nominal operating condition is of 50 kW of power, angular velocity of 3000 rpm, maximum steam pressure of 0.965 MPa at a temperature of 511 K. Figure 1 illustrates the steam turbine according to its instruction manual, pointing the exhaust flange in the casing, inlet flange and four hand valves on the cover, allowing a flexible and controlled operation [21, 22].

This steam turbine is chosen because it is commonly used in steam systems for generating electricity. However, the biggest issue in to use this type of turbine is the necessity of large boiler to reach high steam pressure, which is usually complex. In this work, the main contribution is the adaptation of this steam turbine to a small and simple cyclonic combustion boiler as described later.

The basic operating principle of the turbine comes from the impulse force from the high-pressure steam jets entering through the flange and passing through four small nozzles inside cover, each one of about 0.01 m as shown Figure 1. Then, the fluid reaches the first series of rotor blades passing through the stator, reversing the flow direction to the second set of moving blades, thus rotating the turbine shaft and exiting the exhaust flange. In front of the rotor, there are 78 blades height of 0.01 m and on the back one, 98 blades with 0.016 m height, both made in concave shape and stainless steel [21].

2.2. Experimental test bench setup and system analysis

The bench setup is placed in the Energy and Environmental Laboratory, in the Department of Mechanical Engineering (LABEM) at the Federal University of Pará (UFPA). Figure 2 illustrates a small steam turbine connected to a cyclonic combustor boiler (Figure 2A) with a permanent magnet electric generator of 1 kW manufactured

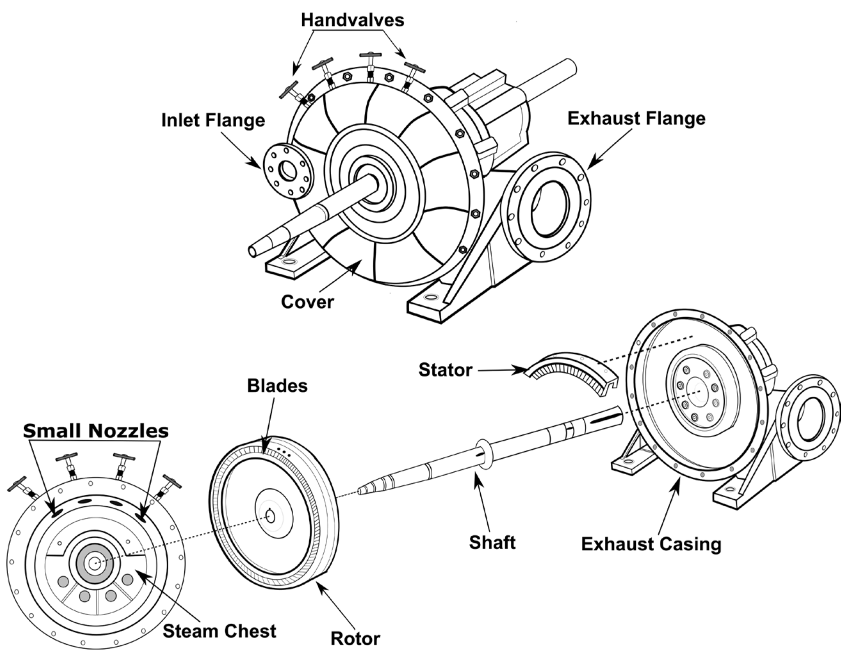

Figure 1: Illustration of the steam turbine adapted from RLA Turbine Instruction Manual [21].

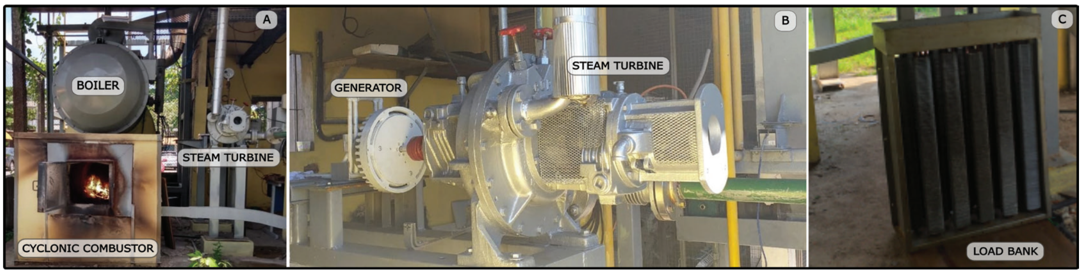

Figure 2: The experimental bench used in the study, cyclonic combustion boiler and steam turbine (A), permanent magnet electric generator and steam turbine (B) and resistive load bank (C).

by ENERSUD Industry (Figure 2B) and a load bank (Figure 2C). This system works in an open cycle without the use of a condenser. The steam wet is eliminated through the turbine exhaust flange direct to the environment, and no environmental impact is made.

The boiler is integrated with the concept of cyclonic combustor, staged together with a more efficient mixture with oxidizer [23]. A cyclonic combustor consists of a rotational flow inside a cylindrical chamber, where the particulate solid fuel in combustion follows a cyclonic motion caused by the tangential air injection from outside of the environment to inside of the combustor through a fan. ZARZYCKI *et al.* [24] and CARNEIRO *et al.* [25] describe the structure of this technology studied with more details. The main difference between the boiler used in this work and the commercial one, is the "water wall". It means that the fuel burn while performing tangential movement in relation to the combustor axis-line, exchanging the heat with water flowing outside the reactor wall. This technology enables a stable flame along the combustion zone with a more efficient mixing of the fuel with the oxidant, reaching high values of combustion efficiency around 98.4% to 99.6% [25].

The electric generator is responsible to produce the electricity from mechanical power, it works using electromagnetic induction [26]. As the present work aims to evaluate a small steam system at low pressure, it has to use a permanent magnet generator, because the most common electric generators require high rotations to produce power [27]. According to FARIAS *et al.* [28] and MOREIRA *et al*. [29] permanent magnet synchronous generators have their advantages over field coils (conventional generators), as they simplify the technology, besides having a smaller volume, lower rotation and higher operational efficiency. The generator used in this study is a three-phase alternator developed and patented by ENERSUD Company, which allows the harnessing of energy under unfavorable conditions to the alternators available in the market, since the permanent magnet generators work at low rotation and high torque [29]. In this paper, the EN2 alternator model from ENERSUD is used. This alternator can generate power up to 1 kW for a nominal output voltage of 48 V.

The basic specification of permanent magnet generator used consists of wire-wound coils with twisted stator, bidirectional axial flow and excitation provided by permanent magnets arranged in rotating disc structures. Each set is distributed in two metal discs, which constitute the rotor of the generator. The main features of this alternator are: low starting resistance, high throughput, mechanical robustness, corrosion resistance, lightweight, and high torque at low rpm. The generator is employed together with a rectifier and a resistive load bank, which is set for 2.4 Ω for electric load simulation. The generator is tested in a bench developed in the laboratory of the Group of Studies and Development of Energy Alternatives (GEDAE) of the UFPA [30]. The methodology used to obtain the generator efficiency curve is the same as described in the study of FARIAS *et al*. [28] due to lack of experimental data on the generator efficiency by the manufacturer. The system consists basically of a three-phase induction motor to simulate the rotation of the turbine rotor, which is mechanically coupled to the permanent magnet electric generator of 1 kW.

The frequency inverter (variable speed drive) controls the variation of the angular velocity of the electric motor. Voltage and current transducers are connected to the rectifier in generator output; a magnetic encoder for speed measurement; a computer for monitoring measurements and controlling the frequency inverter; a data acquisition board, which comes from the measurements made by the transducers; and a resistive load bank with connection to a circuit breaker. The control of the frequency inverter is done through a computational tool developed in LabVIEW environment. For this work, an energy analyzer Fluke 434/series II is used to infer the mechanical torque applied to the generator shaft, as well as its efficiency, as shown in the illustration of Figure 3. Hence, the results of generator efficiency, electric power and mechanical power are calculated and treated using the MATLAB software.

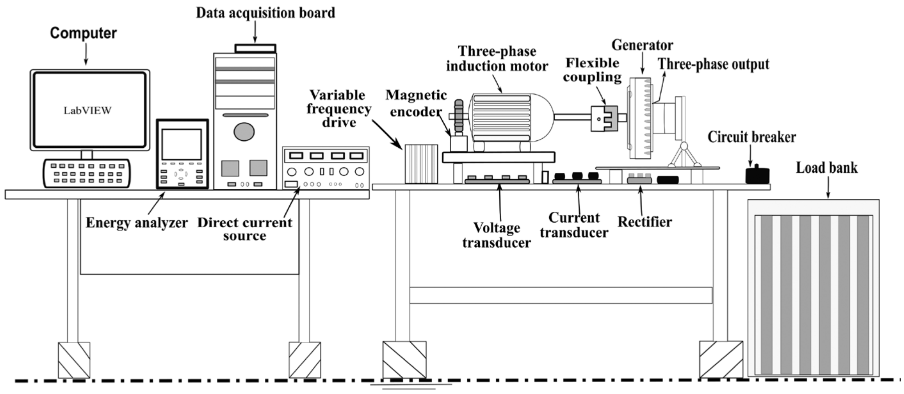

Figure 3: Illustration of the experimental setup for testing the efficiency of the generator.

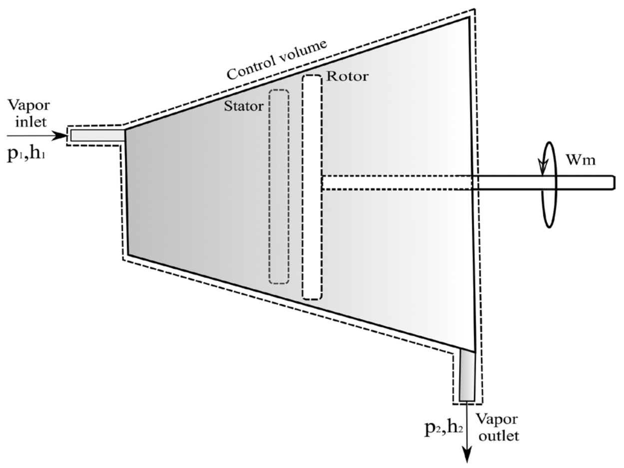

Figure 4: Illustration of the control volume of the steam turbine.

All tests of the generator efficiency are developed for electric load of 2.4 Ω and shaft rotations ($\omega = \pi n/30$), where n is in the range of 90 to 600 rpm. The same values are corresponding to the experimental studies of the steam turbine in operation.

Experimental measurements are performed using the following instruments: a digital photo and contact tachometer: model MDT-2238A Minipa brand, to measure turbine shaft rotational speed (ω). In this work, it is proposed Equation 1 to estimate the generator efficiency, as the manufacturer did not provide the efficiency of the generator. This equation allows a good fit with the experimental data, as shown later, where k_1 and k_2 are parameters determined through regression analysis, in which $k_2 < 2\omega^{1.2}$.

$$\eta_g = k_1 \, 1\text{n}\left(\omega^{1.2} - \frac{k_2}{2}\right) \tag{1}$$

A portable digital oscilloscope of 4 channel: Fluke 190-204 brand for measuring electrical current, voltage and electrical power. Also, a Bourdon manometer is used to measure the outlet pressure of the boiler. Thus, the turbine mechanical power (W_m) is calculated by Equation 2, where W_e is the electrical power and η_g is the generator efficiency.

$$W_m = \frac{W_e}{\eta_g} \tag{2}$$

Considering the control volume of the steam turbine shown in Figure 4, the isentropic efficiency can be calculated. For this, we adopt the following hypotheses:

(1) The state of the fluid being admitted to this turbine and the outlet pressure are fixed for each operating condition;
(2) Heat transfer between the turbine and surroundings, kinetic and potential energy effects are neglected;
(3) Steady-state regime.

Thus, according to DIXON and HALL [31] mass and energy balances are reduced in order to give the work produced per unit of mass passing through the turbine. As the difference between the inlet and outlet kinetic energies are small, the ideal maximum work output $(\dot{W}_m/\dot{m})$ is expressed by Equation 3.

$$\frac{\dot{W}_m}{\dot{m}} = h_1 - h_{2s} \quad (3)$$

The expansion through the turbine leads to $h_2 > h_{2s}$, so less work than the maximum is produced, as described in the *h-s* diagram of Figure 5. In this way, Equation 4 defines the isentropic efficiency of the steam turbine (η_t).

$$\eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}} \quad (4)$$

The main issue to calculate the isentropic efficient is the determination of h_{2s}. In the present work, the expression proposed by DIXON and HALL [31] for a finite change of enthalpy in a constant pressure process is used, which is given by Equation 5.

$$h_2 - h_{2s} \cong T_2(s_2 - s_{2s}) \quad (5)$$

In this case, according to Figure 5, $s_{2s} = s_1$, thus Equation 5 reduces to Equation 6.

$$h_{2s} \cong h_2 - T_2(s_2 - s_1) \quad (6)$$

2.3. Biomass characterization

The characterization process consists of analyzing the biomass in order to discover its chemical composition and the energy contained in its matter. This information is used to qualitatively and quantitatively compare biomasses of different types and conditions, as well as providing information necessary to perform reactor sizing [19, 32]. This process is also performed in LABEM at UFPA, where, first, the biomass is put in a grinder Ika werke A11 basic blade to reduce the size of the material to be analyzed, transforming it into powder, because it must be having a low grain size.

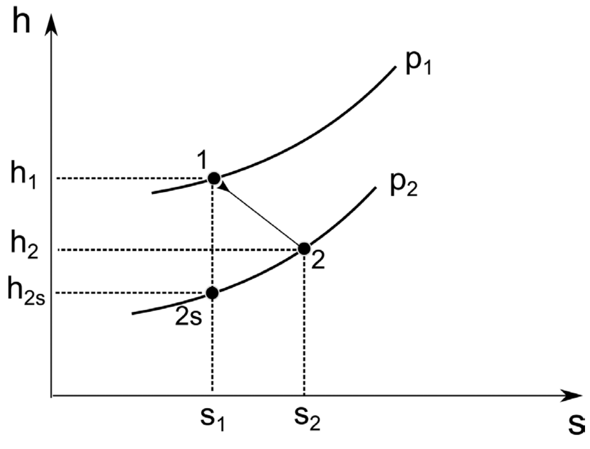

Figure 5: Illustration of the *h-s* diagram for the steam turbine.

The equipment used in the analysis need a small amount of sample only. The biomass is taken to a drying oven (Odontobrás, EL 1.4 model) to remove all superficial moisture from biomass. It is common, in this kind of analyze, the use of dried materials (dry basis). The analysis of moisture rate in percentage (U%) is given by the difference of mass between fresh biomass (before drying oven) and dry biomass (after drying oven). This method consists of placing 0.001 kg of wet biomass sample into a calcined crucible, measuring its mass on a scale, and then put it into the drying oven at 378.15 K. After that, it is necessary to weigh it during 2, 3 and 4 hours. The moisture rate in percentage U(%) is obtained through Equation 7 (based on the European Committee for Standardization Solid Biofuels – ECS/SB: CEN/TS 14774-1:2004 [19]).

$$U(\%) = \frac{m_2 - (m_3 - m_1)}{m_2} \tag{7}$$

where m_1 is the mass of empty crucible; m_2 is the mass of wet sample; m_3 is the mass of empty crucible plus sample after drying oven and U(%) is the original sample moisture rate [19, 32].

Therefore, part of the sample is put in a calorimetric pump, which is an equipment used to obtain the Superior Calorific Power (SCP) of biomass. In the experiments performed in this work, the model C2000 calorimeter pump from the manufacturer Ika Werke is used. The SCP is an intrinsic property of the material which informs the amount of energy contained in the sample, usually expressed in $kJ.kg^{-1}$. In this characterization process, a set of analysis is carried out to quantitatively obtain moisture content values, based on ECS – BS EN 14918:2009. For calculating the SCP of the biomass, triple measurements are performed by inserting quantities of about 5.217×10^{-4} kg, 5.531×10^{-4} kg and 5.319×10^{-4} kg of dry sample into a metal crucible.

This metal casing has been placed in a water container with temperature monitored. The material is activated by an electrode system with a biomass-linked wick inside the crucible. After that, the material has ignited and the oxygen-rich environment causes the material to burn completely. The heat released during the combustion of the material is transferred to the bath, and it quantified by the water temperature difference, then, the equipment calculated automatically the average SCP.

3. RESULTS AND DISCUSSION

3.1. Generator efficiency

For the electric load (2.4 Ω) used during the bench tests, it is noted that the maximum efficiency (42%) of the generator occurs for a shaft rotation (ω) close to 600 rpm, according to the results achieved in the experimental study of the permanent magnet generator with a nominal power of 1 kW shown in Table 1. The values of active electric power and estimated mechanical power of the three-phase motor are measured and calculated. In this way, the results of the generator efficiency are obtained by the quotient of these two quantities, respectively.

The maximum rotational speed possible during the measurements is 600 rpm, due to the high torque applied to the motor shaft to overcome the resistive electric load. As a consequence, the frequency converter stops the motor as a protection. Such a protection occurs always the motor operates under overload current. For this reason, the system is unable to obtain results for shaft rotations higher than 600 rpm. Hence, the electric generator efficiency is adopted between 16 and 42%, taking into account the estimated values presented in Figure 6 to calculate the electric and mechanical powers of the steam turbine. As previously stated, the steam turbine operates with a cyclonic combustion boiler of 44% thermal efficiency [25], allowing it to operate at low pressures.

Table 1: Measurements of the permanent magnet generator for 2.4 Ω.

ESTIMATED MECHANICAL POWER (W)	ACTIVE ELECTRIC POWER (W)	GENERATOR EFFICIENCY (%)
79.3	12.7	16
119.9	34.6	29
179.0	60.2	33
247.6	92.4	37
915.5	370.3	40
1,352.5	567.4	42*

(*) Maximum generator efficiency for test conditions.

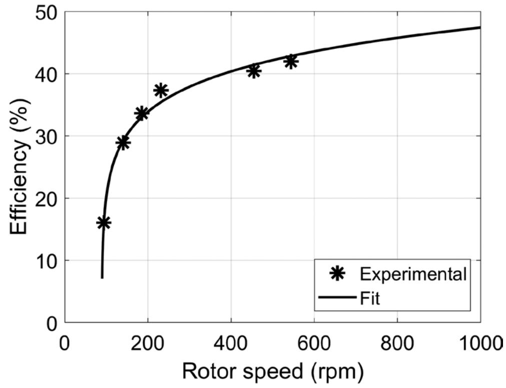

Figure 6: Generator efficiency curve for an electric load of 2.4 Ω.

3.2. The turbine experimental test

In order to assess the behavior of the small steam turbine without electric load, first a constant pressure of 0.2 MPa is set in the steam system. In this case, the turbine starts rotation at 160 rpm for a 12 V (rectifier output voltage) with the inlet valve slightly opened. When the valve is fully opened, the turbine rotation reaches 1200 rpm and 100 V, using 250 kg of biomass.

The second measurement is done considering the 1 kW permanent magnet generator with a 2.4 Ω resistive electric load. The turbine operation is activated by the cyclonic combustion boiler using the biomass popularly called *Andira-uxi*, which is scientifically called *Andira inermis* of the family *fabaceae – W. Wirght DC*. This biomass has phytogeographic domains in the Amazon, Cerrado and Atlantic Forest of Brazil [33–35]. It is collected at UFPA campus and 216 kg of small logs with 33.56% humidity and average SCP of 17404 $kJ.kg^{-1}$ are placed in the boiler furnace.

The boiler spent 3 hours of biomass burning to get the nominal operating pressure to perform the measurements, using the insufflator (boiler fan) at angular velocities of 600 to 1200 rpm. After this period, the system has been worked for 2.5 hours under nominal condition. The valve is gradually opened to increase steam flow for each pressure studied in intervals of 30 s, in which the rotational speed of the turbine for the respective voltage, current and electric power, it is marked.

As shown in Table 2, three tests are performed to study the steam turbine under electric load. In the first one, the boiler operates at a pressure of 0.1 MPa, where the starting rotation of the steam turbine is 82 rpm, reaching a maximum rotation at 290 rpm with the control valve fully opened. The generator reached electrical powers of 6.70 W (minimum) and 119.00 W (maximum), corresponding to the mechanical powers of 39.05 W and 288.00 W, respectively.

After that, the system worked to a pressure of 0.2 MPa. The turbine began to rotate when the valve of boiler is opened. The initial rotational speed is 63 rpm, which is gradually increased up to 368 rpm (valve fully opened), generating mechanical power from 36.50 to 443.24 W. The electric powers generated for this condition are from 3.30 to 197.072 W.

Finally, the turbine is tested for a pressure of 0.3 MPa, where the starting rotational speed is in the range of 110 rpm (minimum) to 586 rpm (maximum). The respectively mechanical powers are in the range of 67.82 to 1396.80 W, generating electric powers between 14.75 and 504.60 W.

In order to show the isentropic efficiency of the steam turbine, Equation 4 is applied only for the maximum values of the mechanical power described in Table 2. All parameters used are presented in Table 3. The isentropic efficiency for each maximum value of the mechanical power is: 25.7, 25.9, and 26.2%, respectively. This result demonstrates that the steam turbine efficiency is small when operating at low pressure. So, it is presumed that this turbine can reach higher efficiency for high pressure. Also, optimization of steam turbine blades is interesting because the turbine rotor can be adapted for real conditions at low pressure, without increase the number of stages, as it can turn the turbine complex and expensive.

Figure 7 shows the electrical (A) and mechanical (B) power trend curves for a pressure of 0.1 MPa plotted for a rotational speed ranging from 80 to 300 rpm, according to the data in Table 2. In the range of 80 to 200 rpm, a small vibration is perceived on the turbine shaft, which promoted a slight instability in the rotation of the turbine when subjected to the electric load, even for the maximum steam flow from the boiler. After 200 rpm, the system has a stable behavior, offering a good thermodynamic performance of the steam turbine, sufficient

Table 2: Experimental results for the steam turbine and the permanent magnet generator for 0.1 MPa, 0.2 MPa, and 0.3 MPa.

ROTOR SPEED (rpm)	ELECTRIC POWER (W)	MECHANICAL POWER (W)
PRESSURE = 0.1 MPa		
82	6.7	39.0
206	56.7	165.2
238	81.3	217.2
244	80.9	213.1
267	104.7	263.2
287	116.9	284.2
290	119.0	288.0
PRESSURE = 0.2 MPa		
63	3.3	36.5
128	21.0	85.8
270	107.0	267.5
357	184.8	417.9
368	197.1	443.2
PRESSURE = 0.3 MPa		
110	14.7	67.8
170	40.0	132.5
216	69.0	195.2
286	118.6	288.7
364	197.1	444.2
451	299.0	675.6
515	399.90	961.1
570	464.8	1236.4
586	504.6	1396.8

Table 3: Parameters used to calculate the isentropic efficiency of the steam turbine for mechanical power 288 W, 443.2 W, and 1396.8 W.

PARAMETER	INLET	OUTLET
MECHANICAL POWER = 288 W		
Temperature (K)	372.7	368.7
Pressure (MPa)	0.1	0.086
Enthalpy (kJ/kg)	2675.5	2669.2
Entropy (kJ/kgK)	7.3594	7.4084
MECHANICAL POWER = 443.2 W		
Temperature (K)	393.3	386.7
Pressure (MPa)	0.2	0.163
Enthalpy (kJ/kg)	2706.7	2697.0
Entropy (kJ/kgK)	7.1271	7.1982
MECHANICAL POWER = 1396.8 W		
Temperature (K)	406.7	385.4
Pressure (MPa)	0.3	0.155
Enthalpy (kJ/kg)	2725.3	2694.9
Entropy (kJ/kgK)	6.9919	7.2137

to generate electricity for really small energy demand at 0.1 MPa. In this case, the maximum electrical power achieved (Figure 7A) did not exceed 119 W for a valve fully opened.

Figure 7B shows the estimated curve with good convergence to the experimental data. On the instability observed, it is mainly due to the very low working pressure imposed on the turbine rotor (0.1 MPa), which is

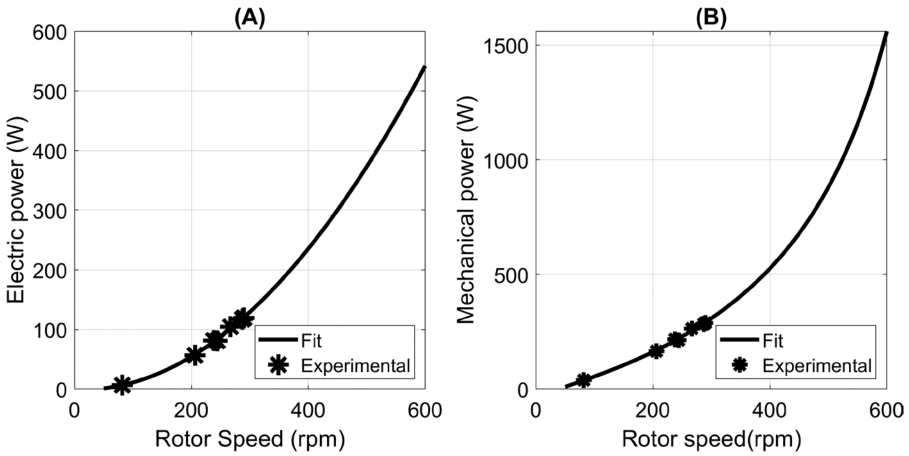

Figure 7: Electric (A) and mechanical powers measured (B) in relation to the rotational speed (rpm) at 0.1 MPa.

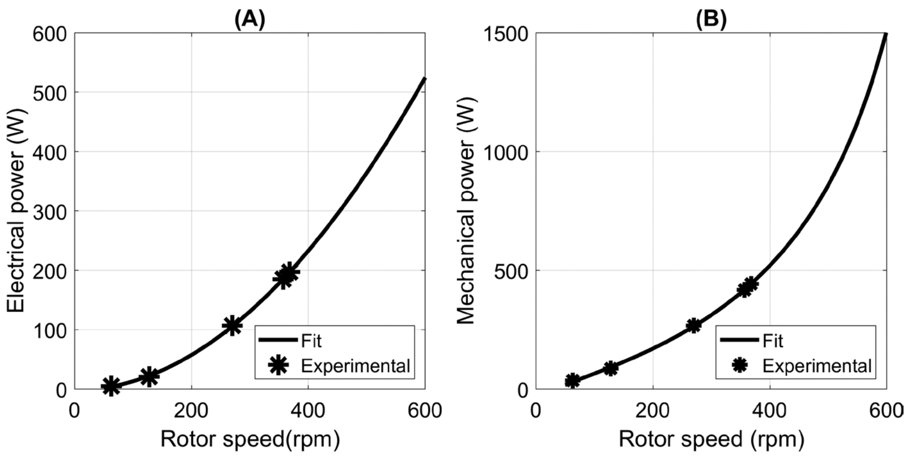

Figure 8: Electric (A) and mechanical powers measured (B) in relation to the rotational speed (rpm) at 0.2 MPa.

insufficient to maintain the hydrodynamic forces on the blades of the rotor. Thus, for the turbine to operate efficiently, it is necessary to increase the working pressure.

Figure 8 shows the behavior of the electrical (A) and mechanical (B) powers in relation to the rotational speed at a steam pressure of 0.2 MPa. In this case, the electrical power did not exceed 200 W (Figure 8A), even with the control valve fully opened. This is because the pressure of 0.2 MPa remains low, and the rotation of the turbine is again unstable. The results of rotational speed, current and voltage vary greatly from such that the portable digital oscilloscope has failed to establish a constant value for a long time. Therefore, this operating condition points out to an unfavorable performance for reliable electric power generation.

In Figure 8B, a good performance of the mechanical power of the steam turbine is observed. The maximum output power had a value of 443.24 W, which represents a good value of mechanical energy for starting at low working pressure. However, in terms of electrical energy, a high-efficiency generator for these operating conditions is necessary in order to get a suitable system for low energy demands with good thermodynamic performance to generate energy in a reliable manner.

Figure 9 shows the behavior of the electrical (A) and mechanical (B) powers as a function of the rotational speed at a steam pressure of 0.3 MPa. In this case, the experimental data are measured for rotations in the range of 100 to 600 rpm (Table 2). The system operates with good performance and in a stable manner even with the system valve fully opened. This stability is due to the fact that for a pressure of 0.3 MPa, the steam flow is sufficient to maintain the stability of the hydrodynamic forces on the rotor blades, leading to an operation with good behavior of the torque generated on the shaft of the turbine. Therefore, the working pressure of 0.3 MPa is the starting pressure in terms of reliable electrical generation of the turbine object of this experimental investigation, showing that for small energy demands, it corresponds to a relevant technology, mainly for using in small scale.

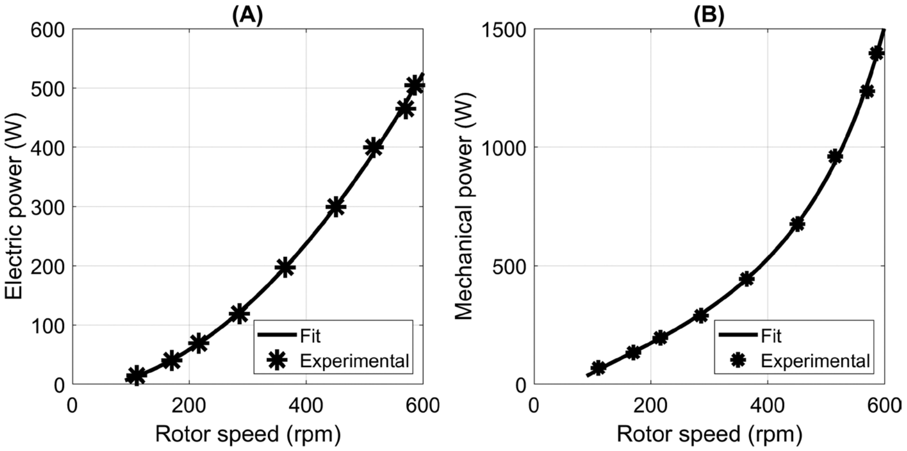

Figure 9: Electric (A) and mechanical powers measured (B) in relation to the rotational speed (rpm) at 0.3 MPa.

For Figures 7, 8 and 9, a regression analysis is done using a second-degree polynomial function. This type of polynomial function is commonly used in turbomachinery to calculate hydraulic power, agreeing well with experimental data, as further described in [36]. Thus, second-degree polynomial function is a good choice for estimating electrical and mechanical powers of a steam turbine. For this case of regression analysis, the coefficients of determination R^2 for 0.1, 0.2, and 0.3 MPa are 0.9969, 0.9998, and 0.9992, respectively. These values for the coefficients of determination are good because they demonstrate that electrical and mechanical powers can be predicted from the shaft rotational speed variable. In this way, this result represents a good performance, demonstrating that such a technology can be used in isolated communities or small sustainable agricultural activities in the Amazon region.

The hypothesis of the study, would be to reach a maximum electrical power of up to 500 W, however, the system exceeded this expectation, maintaining a rotation speed and reliable electrical power to generate electricity in values greater than those achieved.

Regarding the mechanical power of the steam turbine at 0.3 MPa, it is observed, in loco, that the system operated with better confidence to read the results from 100 rpm. As the steam flow is released by the valve, the speed of rotation remained constant for a long time when compared to the pressures of 0.1 and 0.2 MPa. In Figure 9B, it is shown that the scale of the system tested for the mechanical power curve, establishes a good polynomial tendency, similar behavior for all pressures evaluated in the experimental tests.

However, only at 0.3 MPa the turbine shows good stability of its rotation in the range of 100 to 600 rpm, being able to achieve even greater values of mechanical power. Therefore, it is relevant that the present turbine has a good mechanical behavior at 0.3 MPa with a good thermodynamic performance, even the turbine operating in an opened system, which is strongly linked to the reduction of irreversibility. Such an irreversibility is related to the loss of energy in the system to the detriment of a lower quality of steam (superheated steam).

4. CONCLUSIONS

The experimental investigation carried out in this work is important for the Amazon region. The results are relevant to evaluate the performance of small steam turbines at low pressure for electricity generation in the region, mainly in isolated rural communities. These types of steam turbines can contribute significantly to reusing residual biomass generated in the region, minimizing environmental impacts mainly from small agricultural activities. So, the conclusions of this work are:

- The measurements reveal that the turbine has an unstable behavior at pressures of 0.1 and 0.2 MPa. The instability problem can be caused by the hydrodynamic performance of the rotor, which needs to be further investigated at low speeds, since under these conditions the rotor generally operates at low Reynolds numbers (low flow rates). Another possibility of this behavior is the power train of the turbine, which is strongly influenced by the moment of inertia of the system, being necessary to be further investigated;
- For pressures of 0.1 and 0.2 MPa, the turbine achieved small electricity power, mainly due to the use of a low efficiency electric generator when operating at low rotational speeds;
- For a working pressure of 0.3 MPa, the turbine provided good stability, being able to generate energy reliably, even at an isentropic efficiency of 26.2%, considered low for a steam turbine. The results of the most stable

operation at this pressure have become a very positive point of this experimental study that deserves to be highlighted.

Furthermore, detailed research on the quality of low-pressure electricity generation is still needed. Some limitations of the system are:

- Operation in an open cycle without the use of a condenser and with saturated steam;
- There is no back pressure regulator at the turbine inlet, and this could be a limiter to keep the pressure and shaft rotational speed constant at 0.1 and 0.2 MPa, in order to establish the resemblance to a residential load;
- The system did not have a pressure and flow meter, nor temperature sensors in the steam rotor;

For future work, further research on this steam system is suggested, as:

- Performing thermodynamic and computational studies in order to compare with these experimental tests;
- Other tests to perform new measurements at pressures greater than 0.3 MPa (the maximum pressure achieved by the system) are needed, to verify whether the steam turbine's behavior remains stable at higher pressures.

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