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STUDY OF A SMALL STEAM TURBINE AT LOW PRESSURE USING A PERMANENT MAGNET GENERATOR

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Abstract. *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. 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. It is used two bench setups. In the first one, a small steam turbine COPPUS, RLA Type is connected to a cyclonic combustor boiler with a permanent magnet electric generator of 1 kW. In this case, a load bank with equivalent resistance of 2.4 Ω is used to simulate the electrical load. In the second setup, the generator efficiency is investigated under pressures of 0.1, 0.2 and 0.3 MPa. The experimental bench for this setup is used to take measurements on the behavior of mechanical and electrical powers in relation to the shaft rotational speed of generator. 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.*

Keywords: *power generation, boiler, cyclonic combustor, magnet permanent generator.*

1. INTRODUCTION

Technologies that include biomass-based system are interesting solutions to improve the Brazilian electrification in remote areas (Els *et al.*, 2012). Steam turbines are the most popular devices for generating electricity due to the higher thermal efficiency and power-weight ratio (Carcasci *et al.*, 2017; Celis *et al.*, 2017). Those turbines have rotational speed suitable for connection of electric generators. Generally, from 750 W for small units and up to 1,900 MW for large power plants (Tanuma 2017). In addition, those turbines use renewable sources, contributing to the non-dependence on fossil energy in most area of the Amazon region, increasing the supply in the country (Gómez & Silveira, 2015).

Some Amazon communities have low electricity demand, making small steam turbines important to be used in biomass electric generation systems (Macêdo *et al.* 2016). Some studies have been developed by Plovnick (2010); Pinheiro *et al.* (2012); Els *et al* (2012) and Sánchez *et al.* (2015) about electrification in the Amazon, but only the research of Macêdo *et al.* (2016) showed 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 electric energy produced, 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.

In this context, more studies are needed to investigate the performance of the steam microturbine operating at low pressure and improve its efficiency using permanent magnet generator systems in the Amazon, in order to meet the actual small demand of local communities. Therefore, it is necessary to evaluate small steam turbines operating at low-pressure conditions, allowing a cheaper steam system. 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. It investigates the efficiency of the electric generator under test conditions.

2. EXPERIMENTAL TEST BENCH SETUP

To investigate the performance of the small steam turbine operating at low pressure and generator efficiency used in the bench setup, the experimental analysis is carried out on the commercial steam Turbine COPPUS, RLA Type (Venkatesh *et al.* 2012), model RL12L, which is manufactured for small systems. It is characterized as single stage and horizontal-radial flow turbine, whose nominal operating condition is of 50 kW, angular velocity of 3,000 rpm, maximum steam pressure of 0.965 MPa at a temperature of 511 K.

The bench setup is in the Energy and Environmental Laboratory in the Department of Mechanical Engineering (LABEM) at Federal University of Pará (UFPA). The small steam turbine (Fig. 1A) is connected to a cyclonic combustor boiler with a permanent magnet electric generator of 1 kW manufactured by *ENERSUD* Industry (Fig. 1B) and a load bank (Fig. 1C). 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.

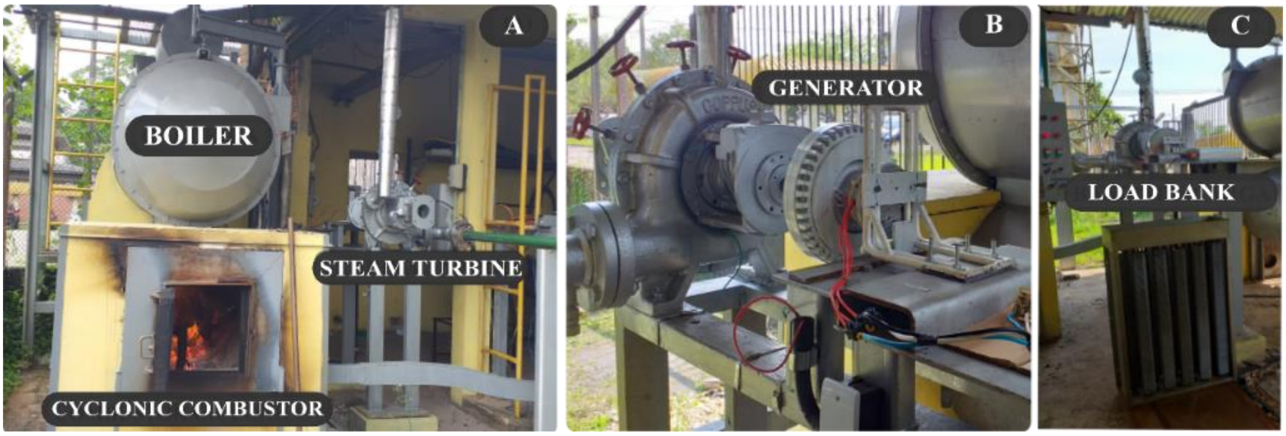

Figure 1. The experimental bench used in the study (A) Cyclonic combustor boiler and steam turbine (B) permanent magnet electric generator (C) Resistive load bank. Available from: Authors

The boiler is integrated with the concept of cyclonic combustor, staged together with a more efficient mixture with oxidizer (Lima *et al.* 2017). Carneiro *et al.* (2017) describe the structure of this technology studied with more details and reports that this combustor 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%. In this work, 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 generator is employed together with a rectifier and a resistive load bank, which is set for 2.4 Ω for electric load simulation. The measurement of generator efficiency is performed in a test bench developed by the Group of Studies and Development of Energy Alternatives (GEDAE) from UFPA (Azevedo *et al.*, 2011) and the methodology used to obtain the generator efficiency curve is the same as described in the study of Farias *et al.* (2019). All tests of the generator efficiency are developed for electric load of 2.4 Ω and shaft rotations in the range of 90 to 600 rpm. The same values are corresponding to the experimental studies of the steam turbine in operation.

Hence, the results of generator efficiency (η_g), electric power and mechanical power are calculated and treated, using the MATLAB software. 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. In this work, it is proposed Eq. (1) to estimate the generator efficiency. This equation allows a good fit with the experimental data, as shown later.

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

Where k_1 and k_2 are parameters determined through regression analysis, in which $k_2 < 2\text{rpm}^{1.2}$. A portable digital oscilloscope of 4 channel: Fluke 190-204 brand for measuring electrical current, voltage and power. Also, a Bourdon manometer is used to measure the outlet pressure of the boiler. Thus, the turbine mechanical power ($\mathbf{W_m}$) is calculated by Eq. (2), where $\mathbf{W_e}$ is the electrical power and $\boldsymbol{\eta_g}$ is the generator efficiency.

$$W_m = \frac{W_e}{\eta_g} \quad (2)$$

3. RESULTS AND DISCUSSION

Table 1 shows the results achieved in the experimental study of the permanent magnet generator with a nominal power of 1 kW. The values of active electric power and estimated mechanical power of the three-phase motor simulating the steam turbine are measured and calculated. In this way, the results of the generator efficiency in Tab. 1 are obtained by the quotient of these two quantities, respectively. 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 close to 600 rpm.

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

ESTIMATED MECHANICAL POWER (W)	ACTIVE POWER (W)	GENERATOR EFFICIENCY (%)
79.30	12.73	16
119.90	34.66	29
179.03	60.22	33
247.65	92.37	37
915.56	370.30	40
1,352.56	567.43	42(1)

(1) Maximum generator efficiency for test conditions.

This is the maximum rotational speed possible during the measurements due to the high torque applied to the motor shaft to overcome the resistive electric load. Therefore, the frequency converter stops the motor as an overcurrent protection. 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%, considering the estimated values presented in Fig. 2 to calculate the electric and mechanical powers of the steam turbine.

Figure 2 shows the results for the generator efficiency curves. Note that the measurements show a logarithmic tendency. Thus, the solid line is the estimation curve calculated through Eq. (1), for k_1 = 5.756 and k_2 = 435.9. For this regression analysis the coefficient of determination R^2 = 0.9876.

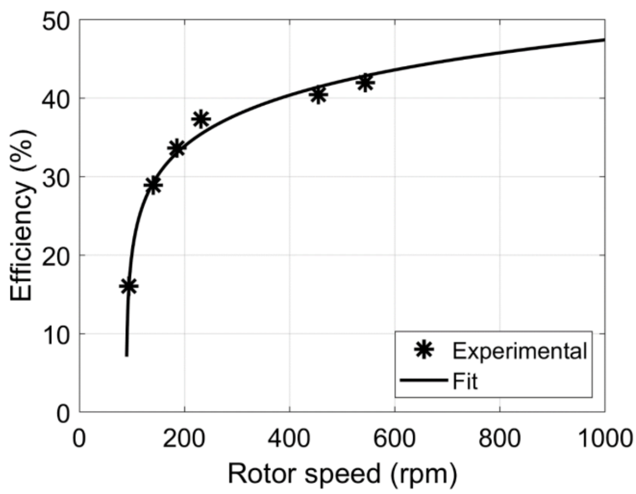

Figure 2. Generator efficiency curve for an electric load of 2.4 Ω. Available from: Authors

As previously stated, the steam turbine operates with a cyclonic combustion boiler of 44% thermal efficiency (Carneiro *et al.* 2017), allowing it to operate at low pressures. In this context, the boiler spent 3 hours of biomass burning to get the nominal operating pressure to perform the measurements. After this period, the system has been worked for 2.5 hours under nominal condition and three tests were performed to study the steam turbine under electric load. 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 are measured. 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. Figure 3 illustrates the behavior of the electrical (A) and mechanical (B) powers in relation to the rotational speed for steam pressures of 0.1 MPa. In the range of 80 to 200 rpm, a small vibration occurred 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 to generate electricity for really small energy demand at 0.1 MPa. In this case, the maximum electrical power achieved (Fig. 3A) did not exceed 119 W for a valve fully opened.

Figure 3B shows the estimated curve with good convergence to the experimental data. The observed instability is mainly due to the very low working pressure imposed on the turbine rotor (0.1 MPa), which is 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.

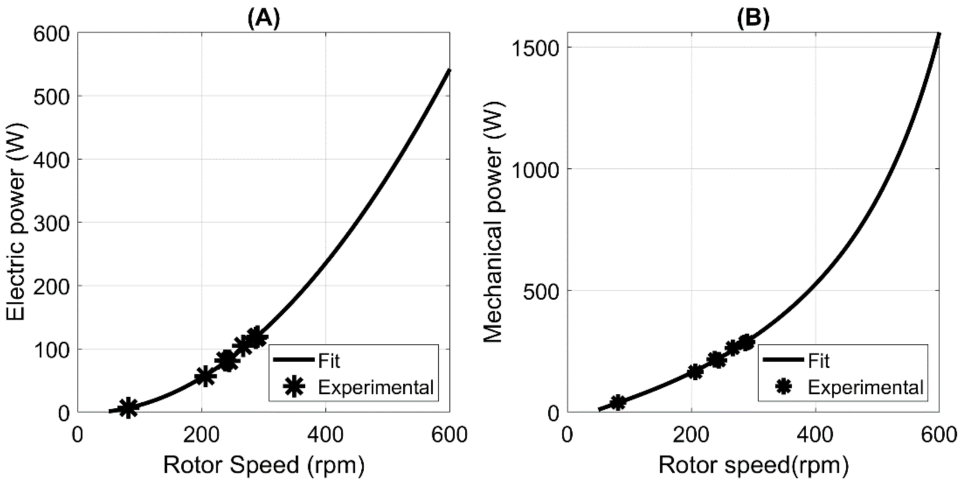

Figure 3. Electric (A) and mechanical powers measured (B) in relation to the rotational speed (rpm) at 0.1 MPa. Available from: Authors

After that, the system worked with 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.

Figure 4 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 (197,072 W), 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.

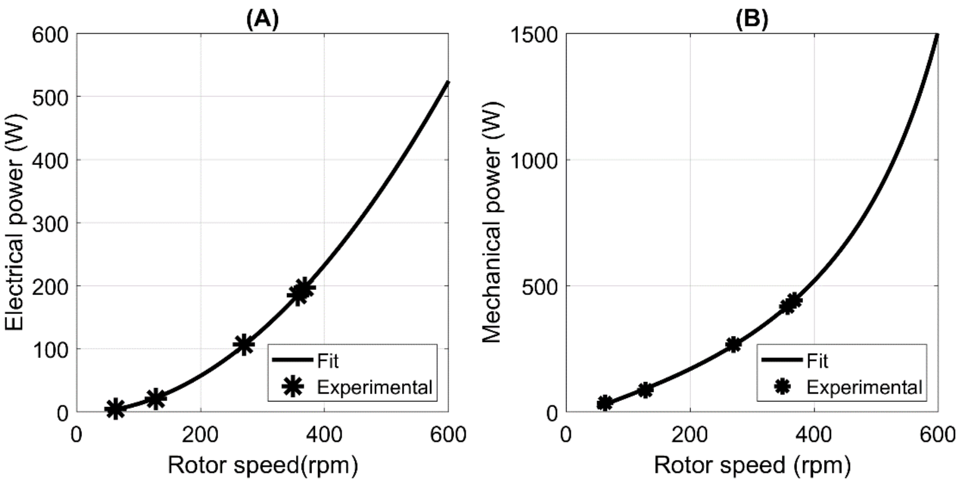

Figure 4. Electric (A) and mechanical powers measured (B) in relation to the rotational speed (rpm) at 0.2 MPa. Available from: Authors

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 Fig. 4B, 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 starts 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.

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 Fig. 5, 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 (Fig 5B).

For all experimental power curves, a regression analysis is done using a second-order 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 Lewis (1996). Thus, this function is a good choice for estimating electrical and mechanical powers of the 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.

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).

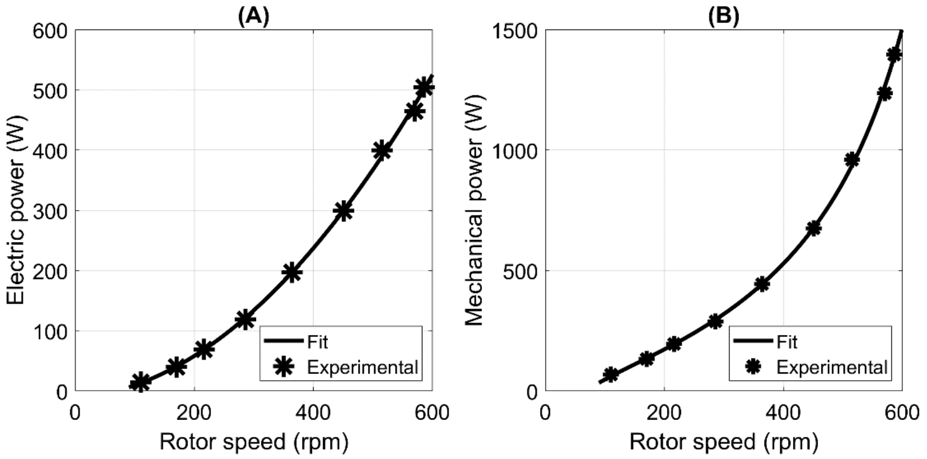

Figure 5. Electric (A) and mechanical powers measured (B) in relation to the rotational speed (rpm) at 0.3 MPa. Available from: Authors

The system also 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 stability 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 small scale.

The hypothesis of the present work, 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 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 longer time when it is compared to the pressures of 0.1 and 0.2 MPa.

4. CONCLUSION

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 using permanent magnet generator systems at low pressure for electricity generation in the region, mainly applied 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 industrial companies.

The measurements reveal that the turbine has an unstable behavior at 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. The instability problem is also due to 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 a working pressure of 0.3 MPa, the turbine provided good stability, being able to generate energy reliably.

The use of permanent magnet generator is essential for 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 because this generator to operate low-rotation and high torque. Furthermore, detailed research on the quality of low-pressure electricity generation is still needed.

Some limitations of the system are as follows: this system operated 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 or industrial load.

In addition, the system did not have a pressure and flow meter, nor temperature sensors in the steam turbine. Thus, further research on this steam system is suggested for future work, 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) to verify that the steam turbine's behavior remains stable at higher pressures are needed.

5. ACKNOWLEDGEMENTS

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