2017 International Nuclear Atlantic Conference - INAC 2017
Belo Horizonte, MG, Brazil, October 22-27, 2017
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN

Agencia Brasileira do ISBN
ISBN 978-85-99141-07-6

DESIGN OF A RANKINE CYCLE OPERATING WITH A PASSIVE TURBINE MULTI FLUID

Guilherme M. Placco, [1], Lamartine N. F. Guimarães, guimarae@ieav.cta.br[2], Gabriela S. B. Santos[3]

[1]Instituto Tecnológico de Aeronáutica
Praça Marechal Eduardo Gomes, 50 - Vila das Acacias, São José dos Campos - SP, 12228-900
guilhermeplacco@gmail.com

[2] Instituto de Estudo Avançados
Trevo Coronel Aviador José Alberto Albano do Amarante, 01 - Putim, São José dos Campos - SP, 12228-001
guimarae@ieav.cta.br

[3]Universidade Paulista - UNIP
Campus São José dos Campos
Rod. Presidente Dutra, km 157,5 - Pista Sul, São José dos Campos - SP, 12240-420
siqueira.gsb@gmail.com

ABSTRACT

The Institute of Advanced Studies - IEAv, has been conducting a project called TERRA - Fast Advanced Reactors Technology,"which aims to study the effects on the working of a Rankine cycle operating with a Multi Fluid Passive Turbine - TPMF. This turbine has the main characteristic operate bladeless using discs arranged in parallel along a rotating axis. After a thorough literature search, we have not found a previous operating Rankine cycle with this kind of turbine. Thus, the work presented here, began its development with few guidelines to follow. It will be presented, of a sucint way, of the design of the parts that makes up a Rankine cycle; the boundary conditions of the cycle; Data acquisition system; the development schedule; assembly of the components; some associated costs and project management. Experimental results thermal conduction through the cycle; the results of net power generated by the turbine and a comparison between thermal energy to mechanical energy in the turbine (efficiency curve).

1. INTRODUCTION

The project TERRA - Advanced Rapid Reactor Technology (Guimarães et al, 2007), conducted by the Division of Nuclear Energy (ENU) of the Institute of Advanced Studies (IEAv), aims to acquire capacity and develop technology to design And build fast microreactors to generate heat and electrical energy for the purpose of heating and powering space vehicle equipment. As an important option is also the production of propulsion effect (Houts et al, 2013).
The specific short-term objectives of the TERRA project are stated as follows:

1. To develop and construct a Brayton type gas thermal circuit in order to evaluate the thermal cycling technology for the conversion of heat to electric energy, heat extraction from hot source, heat rejection to cold source and control processes , With the purpose of generating electrical energy for space systems.

2. Identify by computational analysis the types of nuclear fuels, enrichments and geometric forms of fast micro-reactor cores of interest, specifying materials and their properties of interest.

3. Identify the R & D needs of an electrical generation system based on a fast micro-reactor to dominate and nationalize the entire development process, identifying technologies of potential use in the spatial application.

4. Construct heat pipe systems in order to evaluate their performance depending on the technology used and their arrangements, such as passive core heat extraction system and application in residual heat rejection.

5. Couple to the Brayton thermal cycle an array of heat pipes, suitably adapted to understand their performance and technology limitations.

The work that was developed is inserted in the third item of the specific objectives of the TERRA project, and as part of the R & D needs, research is done on the operation of turbo-compressor equipment and other thermal cycles of interest.

The objective of this work is to characterize a model of a tesla turbine, which is a multi-fluid passive turbine, which was developed in the IEAv, called TT-2, operating in a Rankine type thermal plant (Potter et al., 2007) . The working fluid, in this case, is water vapor. A series of experiments was carried out to analyze the performance of the turbine operating in a heated gas cycle, and to generate the technological knowledge for the adaptation of the necessary items for this experiment.

1.1. Subsection Title: First Character of Each Non-trivial Word is Uppercase

A Passive Multi-Fluid Turbine is characterized by being a bladeless turbine that draws energy from fluids through the viscous actions that occur between the disc walls and the fluid. At Figure 1 shows a schematic of the original model made by Tesla (Tesla, 1913). The fluid enters the inlet nozzles, passing through the discs depositing part of their kinetic energy. In addition to the central hole in the disc so that it can be fixed to the shaft, there are other holes near the center that allow the passage of low energy fluid. This fluid flows out of the turbine through the side openings of the turbine. The energy that the fluid transferred to the disks is directed to the shaft generating useful power. In the original Tesla model, the turbine could work in two directions, clockwise and counterclockwise, due to the insertion of an additional nozzle for the fluid inlet. If the rotation has to be counterclockwise the right nozzle (from the bottom image) is closed, interrupting the flow. With this, the fluid enters only through the left entrance generating a counterclockwise rotation. The inverse occurs when the left input is interrupted and it is released from the right.

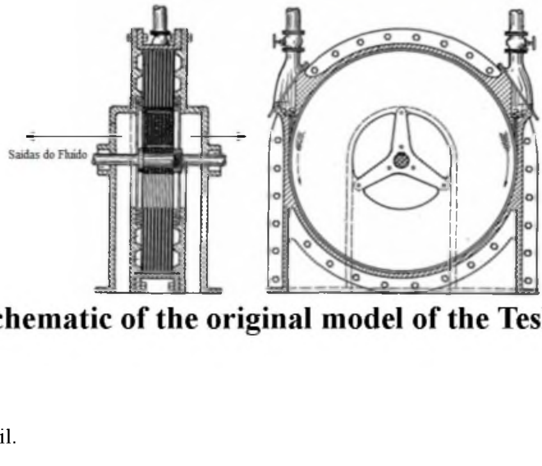

Figure 1. Schematic of the original model of the Tesla turbine.

2. RANKINE CYCLE DEVELOPED

To carry out the tests with the TT-2 developed a closed thermal cycle of the Rankine type. Figure 2 shows a schematic model of the initial design of the developed cycle. The cycle developed in the IEAv aims to characterize the Tesla turbine operating in a closed cycle, so efficiency improvements or cycle operating methods were not considered.

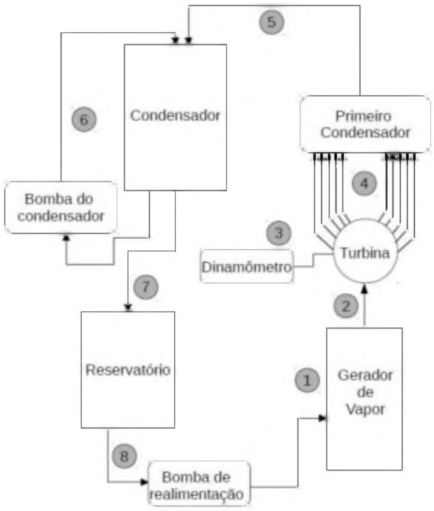

Figure 2. Schematic of the developed cycle.

The water present in the steam generator (1) is heated by the combustion of gases (LPG) making a mixture of water and steam saturated. Due to the effect of gravity, the liquid part is concentrated in the lower part of the steam generator and the vapor saturated in the upper part, where the vapor release valve for the TT-2 (2) is located. The steam directed to the turbine generates work by rotating the turbine axis which is measured by the dynamometer (3). The steam is then passed through a pipe assembly until it reaches the first condenser (4). Within this first condenser there is no complete change of vapor state, generating a mixture of liquid and vapor. This mixture continues through a tube, which then traverses a copper coil which is immersed in running water at atmospheric pressure, forming a condenser (5) where the mixture of liquid and vapor is cooled. There is a hydraulic pump (6) circulating the condenser water to increase heat dissipation. The condensed steam is then passed through a pipe until it reaches the reservoir (7) having a volume capacity of 13.3 liters, which value is greater than that of the steam generator, which has a capacity of 12 liters. Finally, the water in the liquid phase goes to the pump (8), where it is compressed and returns to the steam generator restarting the cycle.

The Figure 3 shows a photo of the developed Rankine closed thermal cycle. In the initial design, a hydraulic pump (6) was used to circulate the condenser water. However, this was not enough, after a certain period of operation of the cycle the water temperature starts to rise, compromising the efficiency of the condenser. To solve the problem the hydraulic pump was dispensed with and a hose (9) was connected, feeding the condenser with water from the laboratory's hydraulic system, and excess water is dispensed into the drain (10).

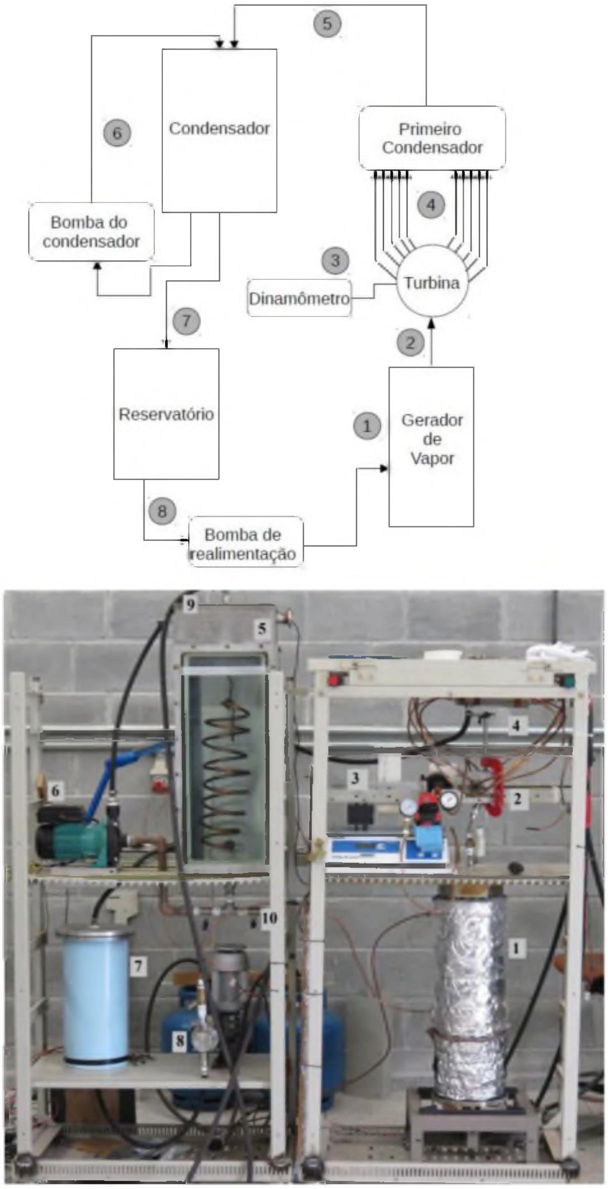

Figure 3. Image of the projected cycle and photo of the developed cycle.

The operation of this cycle is monitored by a data acquisition system that was developed in Arduino [Arduino, 2015] and controlled by LabVIEW software [LabVIEW, 2015] in order to monitor temperature and pressure at various points in the cycle. This monitoring system is currently being modified to become an active control system, which will allow to control the cycle in an autonomous and remote way.

Figure 4 shows a model of the cycle made in CATIA V5R19 CAD software. The whole cycle was designed in real scale in order to facilitate the spatial visualization of the cycle occupying a reserved space within the Laboratory of Thermal Systems (LST) of the Division of Nuclear Energy.

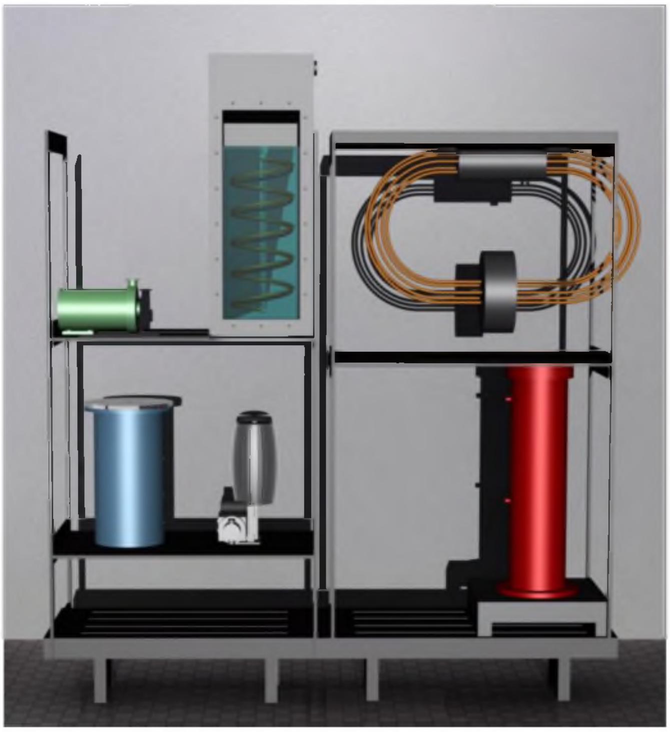

Figure 4. CAD model of the built cycle.

2.1 Dynamometer

A dynamometer was developed to measure the torque and the rotation of the turbine. The concept of this dynamometer is based on the dynamometers used in the automobile industry where a brake disc is connected to the main axis of the engine, in this case in the axis of the turbine, a force is applied in the direction opposite of the rotation (brake) through a rod Fixed at a point (seesaw type), and a mass of known weight which rests on a scale, as the brake force applied on the disc increases, reading the mass of this weight decreases in the balance. In Figure 5 shows the Tesla turbine near the number 1, the brake disk represented by the number 2, the brake pads appear next to the number 3, the fixed point of the lever is next to the number 4, The counterweight next to the Number 5, the balance next to number 6 and the tachometer (rotation meter) next to number 7.

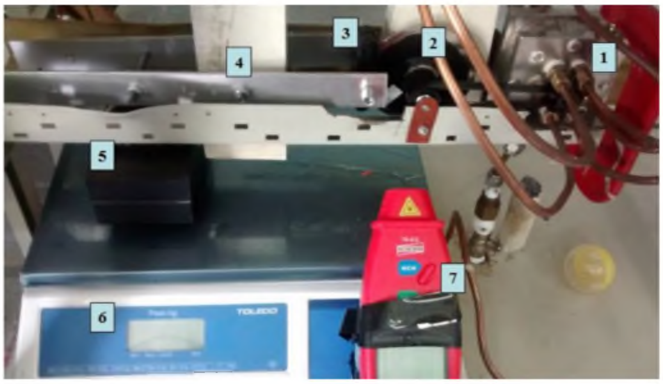

Figure 5. Dynamometer developed.

Next, the data obtained in the experiments and the results of the isentropic efficiency analysis will be discussed.

3. RESULTS

The results of TT-2 power in a range of 300 to 700 kPa transient in increments of 10 kPa totaling 40 points in the power curve by pressure will be presented below. In the following graphs, results will be presented as a function of the input power, since this one was the direct responsible in the variation of the behavior of the turbine. It was not possible to validate the results, given the fact that the study of a Tesla turbine running in a closed thermal cycle has no information available for bibliographic queries. Therefore, there are no parameters for comparison. The analysis was done under an expected estimate for turbine behavior in closed thermal cycles. Figure 6 shows the behavior for the 18 experiments performed.

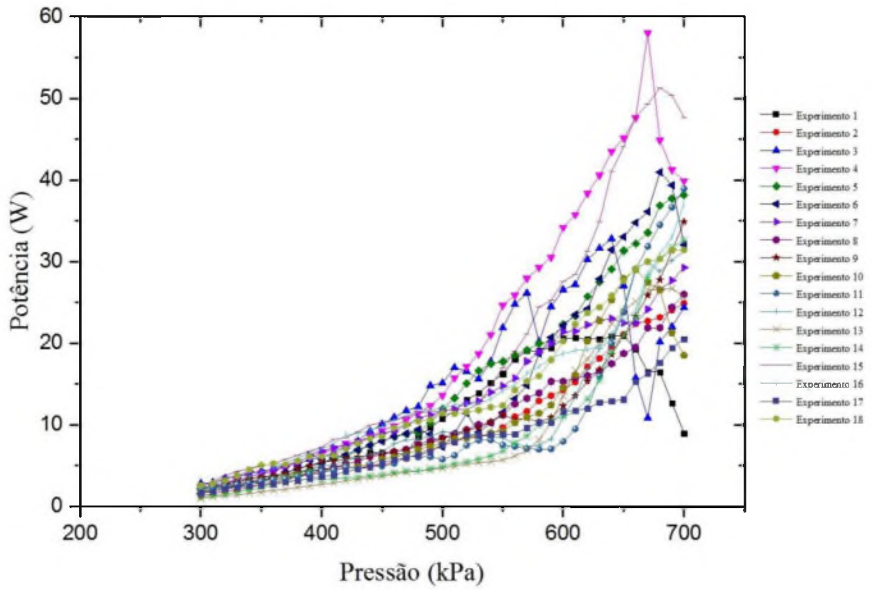

Figure 6. Mechanical power.

It was expected to observe an increase in power with increasing pressure, more precisely, with increasing pressure variation. Although the results presented demonstrate a more dispersed behavior at pressures close to 700 kPa, in calculating the mean and standard deviation it was noticed that the expected behavior was obtained. In the graphs shown in Figure 7 and Figure 8 it is possible to observe this expected behavior. Figure 7 shows the average power curve with the standard deviation bar, σ, as a function of pressure. The standard deviation was high for high pressure values because this region was the accommodation region of the experiment. The temporal reading of these graphs are from right to left, as discussed in the methodology chapter. Among the factors that may explain the greater dispersion in the readings with values close to 700 kPa, are:

- Turbine temperature less than steam: when steam enters the turbine initially at room temperature, there is a decrease in the volume of steam resulting from the loss of thermal energy to the turbine. In thermodynamic tables (Nist, 2015) it is found that for saturated steam at a pressure of 5 kPa the vapor temperature is 100.98 °C, a procedure was done in which it was tried to stabilize thermally by injecting steam into the turbine before Start the tests. However, the equilibrium temperature was not reached.

- Vibrations: high pressure values imply higher turbine rotation, which generates greater vibrations due to possible imbalances. Vibrations are directly related to losses, but are phenomena whose influences are hardly isolated.
- Shaft seal: this part was observed to have leakage at high pressures (> 800 kPa), this leakage may have occurred intermittently during the tests but were not observed due to high operating noise and the sensors were not adequate to identify this Type of leak.
- Lubrication: The turbine is currently operating with a lubrication system that is not ideal for steam systems. This can generate greater resistance to shaft rotation.

Figure 7 shows the curve of the mean value presented in the graph of Figure 6. Although the standard deviation shown is high for the highest pressure values, the standard deviation of the mean, shown in Figure 8 shows that the deviation is lower. Recall that in the standard deviation of the mean the error is estimated in the mean of the values (Farber, 2007), and can be calculated by equation 1. The meaning of the standard deviation of the mean of a given set of n measures is that the mean value has 68 % Probability of being within the range of the deviation around the true value and 95% of being in the range of twice the standard deviation of the mean, as shown in Figure 9.

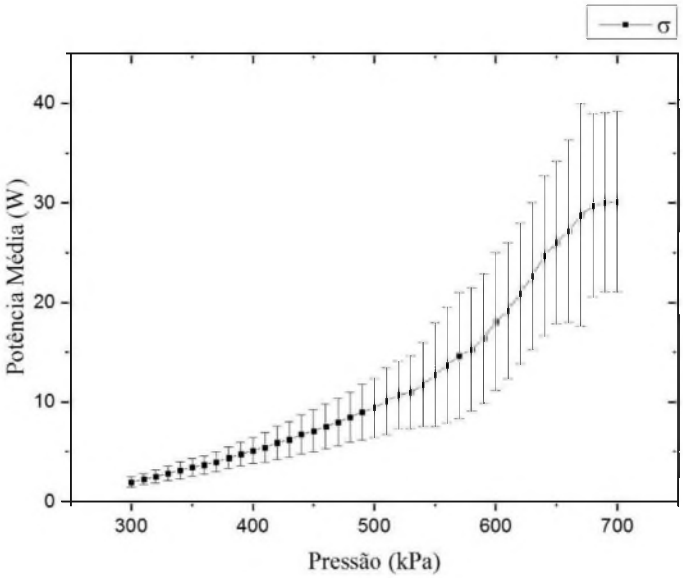

Figure 7. Average power.

$$\bar{\sigma} = \frac{\sigma}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^{n} (\delta x_i)^2}{n(n-1)}} \qquad (1)$$

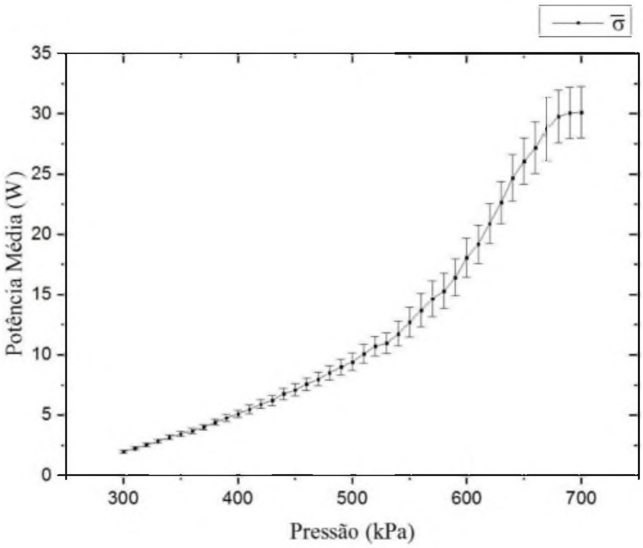

Figure 8. Mean Standard Deviation (68% probability of events occurring in the interval).

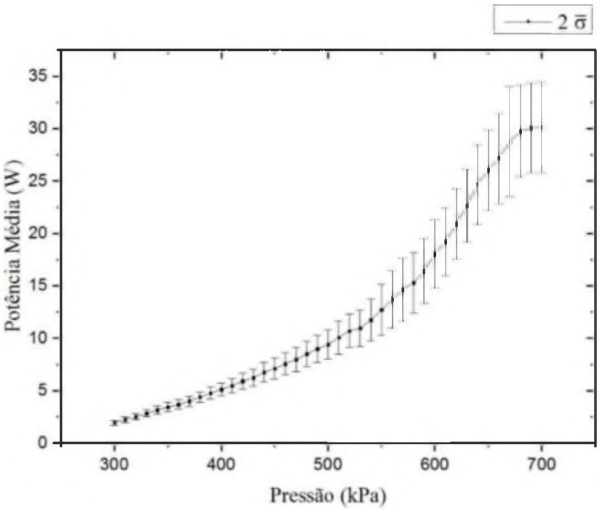

Figure 9. Double the standard deviation of the mean (95% probability that the events occur in the interval).

The graphs shown in Figure 10 and Figure 11 show a comparison of the vapor pressure behavior at the turbine inlet and outlet. It is noted from Figure 10 that for pressures greater than 525 kPa there is a perturbation in linearity as a response to the outlet pressure. This behavior was discussed earlier in this section. Future trials should be done to accurately identify this phenomenon.

From the graph of Figure 11 it is possible to observe the loss of load in the turbine. A percentage decrease in the loss is observed for values close to 700 kPa, that is, the higher the pressure, the lower the pressure drop for the pressure range studied. This decrease is due to viscous actions of the fluid with the inner walls of the turbine. The percentage relative to the loss is observed in numerical form in Table 1. The value of 700 kPa was the one that presented the biggest error, 2.4 percentage points for more for less.

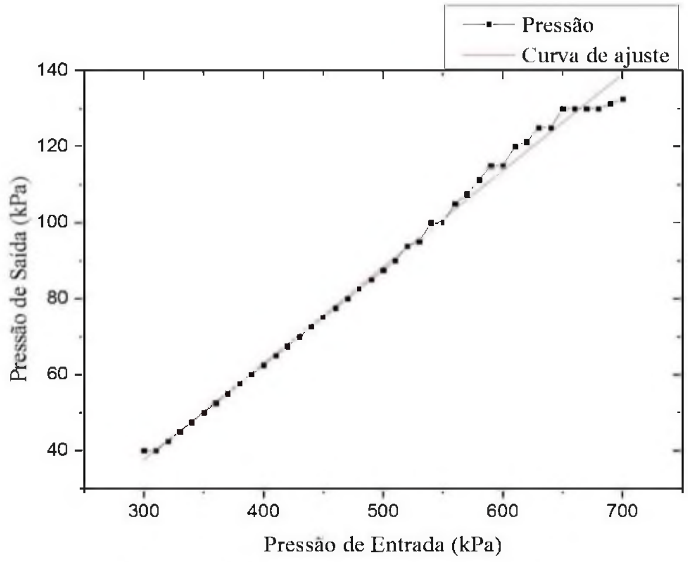

Figure 10. Inlet and outlet pressure.

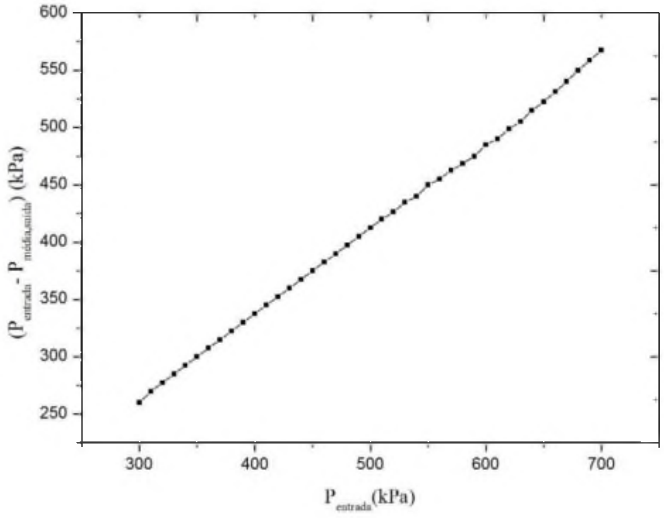

Figure 11. Pressure drop.

Table 1. Percentage on pressure drop.

Inlet Pressure (kPa)	Outlet Pressure (kPa)	%	Error Margin
700,00	132,50	81,07	2,40
600,00	115,00	80,83	0,81
500,00	87,50	82,50	0,43
400,00	62,50	84,37	0,52
300,00	40,00	86,67	0,40

For a turbine operating at steady state, the inlet state of the working fluid and the outlet pressure are fixed. So the ideal process of a turbine is when the process between the inlet state and the discharge pressure is isentropic. The turbine will perform best the closer the actual process follows the idealized isentropic process. The deviation between the actual processes and the corresponding idealized processes of the turbine is measured by the isentropic efficiency. Although the experiments have occurred in a transient regime, the sampling rate can be considered in steady state since the response of the turbine power measurement system is such that it is not influenced by the phenomena observed in the transient regime. The effects that deviate from ideality follow a trend that depends on this transient, so it is vital that further studies are done to identify the influence of transient on non-ideal TT-2 behaviors.
Measurements were made for a range of 300 to 700 kPa at the turbine inlet. Below is shown how the isentropic efficiency of the turbine is calculated at a given point in that range, for example, P = 700 kPa.

The conditions in the turbine inlet and outlet states are respectively:

State 3: P3 = 700 kPa, h3 = 2768.3 kJ / kg and s3 = 6.6616 J / kgK.

State 4r: P4r = 1.35 kPa, T4r = 125.38 °C and h4r = 2713.6kJ / kg.

Where state 3 refers to the input state and 4r to the actual output state of the turbine.

The enthalpy of vapor output to the isentropic process h4s is determined from the condition that the entropy of the vapor must remain constant (s4s = s3).

For the state corresponding to the isentropic case:

State 4s: P4s = 1.35 kPa, s4ls = 1.5857 J / kgK, s4vs = 7.0731 J / kgK, h4ls = 526.71 J / kgK and h4vs = 2713.6 J / kgK. In that ls refers to the liquid phase and vs refers to the vapor.

Since s4ls <s4s <s4vs, at the end of the isentropic process it is concluded that the result is a mixture of liquid-vapor. Thus, it is first necessary to find the title in state 4s:

$$s_{4s} = x_{4s} \times s_{4vs} + (1 - x_{4s}) \times s_{4ls} \tag{2}$$

$$x_{4s} = \frac{s_{4s} - s_{4ls}}{s_{4vs} - s_{4ls}} = 0{,}925 \tag{3}$$

then,

$$h_{4s} = h_{4ls} + x_{4s}(h_{4vs} - h_{4ls}) = 2549{,}6 \, {}^{kJ}\!/_{kg} \tag{4}$$

Substituting the enthalpy values in the equation and describing in percentage the isentropic efficiency of the turbine:

The isentropic efficiency of the turbine for the 300 and 700 kPa range is shown graphically in Figure 12. A decrease in efficiency is noted with increasing inlet pressure. This phenomenon is the opposite of what was expected. As shown in the literature, the increase in efficiency is expected as the pressure increases. But the fact that the turbine is not in thermal equilibrium, causes some of the energy of the steam to be transferred to the heating of the turbine, reducing the efficiency of the system.

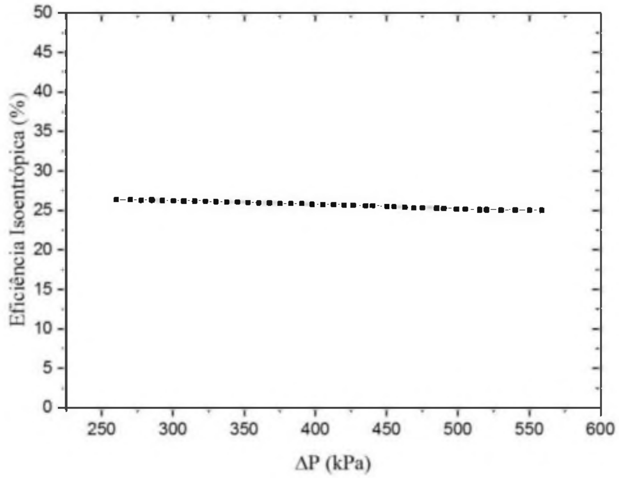

Figure 12. Isentropic efficiency graph.

3. CONCLUSIONS

In this work we present the preliminary results of a Tesla turbine operating with steam in a closed thermal cycle. The results presented raise interest in continuing the project, since even in the preliminary phase, for demonstration of concept, the system demonstrated significant maximum power outputs, around mechanical 30 W, sufficient power to power a small satellite. With some improvements and the implementation of TPMF this value should be even higher.

With an isentropic efficiency of around 25%, still far from that of small steam engines used in industry (about 70%), Tesla's turbine proved to be promising as it has not yet undergone improvements that will increase that efficiency . Remembering that for space applications efficiency is not the only criterion for a project. Other factors such as durability, low maintenance, high reliability in operation, weight, resistance to shocks, are taken into consideration.

The main contribution of this work to the TERRA project was the opening of a new research front that will make it possible to acquire the knowledge of a new model of turbine running in a closed thermal cycle. Future work will show more accurately the characteristics of this turbine's operation, so the TERRA project team will be able to study the feasibility of implementing this new system as an auxiliary or main power unit.

ACKNOWLEDGMENTS

I thank the Institute for Advanced Studies and the Aeronautical Command for the infrastructure and financial support provided.

REFERENCES

Arduino Mega 2560. Disponível em: http://arduino.cc/en/Main/ArduinoBoardMega2560. Acesso em: 16 de junho de 2015.

BEER, F.P.; JR. JOHNSTON, E.R; CORNWEEL, P.J. *Mecânica Vetorial para Engenheiros: Dinâmica*. 7ª. edição. Rio de Janeiro: McGraw Hill, 2006.

BORGNAKKE, C.; SONNTAG, R.E. *Fundamentos da termodinâmica*. São Paulo: Blucher, 2009.

FARBER, B.; LARSON, R. *Estatística Aplicada*. 2ª edição. São Paulo: Pearson Prentice Hall, 2007.

GUIMARÃES, L.N.F., NASCIMENTO, J.A., BORGES, E.M., CALDEIRA, A.D.; DIAS, A.F., Atividades da ENU na área de tecnologia nuclear avançada: previsão de recursos necessários para a primeira fase do projeto TERRA, IEAv-ENU/012/2007, 2007, São José dos Campos, SP, Brasil.

HOUTS, M.G.; BOROWSKI, S.K.; GEORGE, J.A.; KIM, T.; EMRICH, W.J.; HICKMAN, R.R.; BROADWAY, J.W.; GERRISH, H.P.; ADAMS, R.B. Nuclear Thermal Propulsion for Advanced Space Exploration, NASA Marshall Sppace Flight Center, MSFC, AL 35812, NASA Glenn Research Center, Cleveland OH, 44135, NASA Johnson Space Center, Houston, TX, 77058.

LabVIEW. Disponível em: http://www.ni.com/pdf/manuals/373427h.pdf. Acesso em: 16 de junho de 2015.

NIST Livro de Química na web. Diposnível em: http://webbook.nist.gov/chemistry/. Acesso em: 16 de junho de 2015.

POTTER, M.C.; SCOTT, E.P. *Ciências térmicas: termodinâmica, mecânica dos fluidos e transmissão de calor*. São Paulo: Thomson Learning, 2007.

Tesla, N., “Turbine” Estados Unidos Patente nº. 1061206, 6 Maio, 1913.