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PROJECT AND BUILDING OF A SMALL STEAM GENERATOR FOR A RANKINE THERMAL CYCLE WITH A TESLA TYPE

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Abstract. *This work shows the project and building of a steam generator that is a subproject of TERRA project developed in IEAv (Institute for Advances Studies). This subproject has a purpose to build a Rankine thermal cycle to test a Tesla type turbine. The paper presents the equations for calculating cover thickness, cylindrical hull thickness and the amount of bolts necessary to sustain the force and pressure exercised inside the generator. In the equations, the weld coefficient and allowable stress were considered. The stress-strain diagram was obtained through the tensile test on the sample material. The generator has a small volume (12 liters) compared with others found in literature, making it more difficult to find the necessary specifications. Through the calculations it was proved that adding some tubes within the generator improves the efficiency. After the project dimensions were determined, the graphic designs was made in the software CATIA V5R19 with the objective of illustrating the design, for use in machining projects and for the knowledge of final the dimensions of the cycle.*

Keywords: *Rankine, Tesla type turbine, generator*

1. INTRODUCTION

TERRA project (Advanced Technology Quick reactors) is a strategic project of the Air Force Command conducted by IEAv (Institute for Advanced Studies) (Guimarães, L.N.F., Nascimento, J.A., Borges, E.M., Caldeira, A.D. and Dias, A.F, 2007). This project aims to develop technologies for building and designing micro-reactors in order to electrically heat up feed and equipment in space vehicles. Otherwise, can be used micro-reactors for energy in isolated. With the development of the TERRA project, Brazil is among the countries that own and develop nuclear technology in space.

The work presented here is to design and build a steam generator with realimentation, which should ensure a satisfactory autonomy steam supply, security system, realimentation system and heating system.

2. PROJECT AND BUILDING OF A SMALL STEAM GENERATOR

One of the TERRA project activities is to building a thermal cycle closed Rankine type in order to test a Tesla turbine.

In the Rankine cycle (Çengel Y. A., Michael A. Boles, 2006) steam produced in the steam generator is directed to the Tesla turbine. The kinetic energy of the steam is transferred to the rotation axis. Then, the steam passes through the tubing to reach the first condenser. Inside it there isn't complete change of state thereby continues the gaseous fluid and another part liquid. This mixture will continue through a pipe which goes to a copper serpentine. The copper serpentine is inside of a container of water which serves to cool the mixture of steam and water. Again, water vapor and pass through a tube until it reaches the second condenser. Then the liquid goes to the water pump. The water returns to the steam generator restarting again the cycle.

1.1 Graphic designs

All graphic designs related to the project of the steam generator were performed in software CATIA (CATIA V5 R19, "Documentation"). The designs were developed for: illustration, design and machining projects to final dimensions to know about the cycle.

2.1 Calculation of cylindrical hull thickness

To calculate the minimum thickness (*e*) of the cylindrical shell, in millimeters, (Pedro C. Silva Telles, "Vasos de Pressão", 1996) the following parameters are analyzed:

R = internal cylinder radius in millimeters,
P = internal project pressure in megapascals,
S = Basic allowable stress of the material according to the project temperature of the vessel in megapascals,
E = efficiency coefficient of the solder.

According to paragraph UW-12 and Table-12 UW ASM code according to the type and degree of welding inspection adopted, for seamless cylinders, the coefficient of solder (*E*) must be equal to 1,0. These coefficients must to compensate for the smallest possible resistance in the solder region, relative to the whole sheet of the same thickness due to the existence of defects in the solder.

It was observed the appearance of variable *S* (allowable tension) (ASM International Handbook Committee, 1990) two formulas for calculating the thickness. Allowable tension are the maximum tension adopted for the purpose of calculation and design of various parts of a pressure vessel. The allowable tension must be less than the limits of elasticity and breaking the material at a certain temperature. The relation between the limits of resistance and elasticity and allowable stress is the safety factor adopted.

The allowable tension for pressurized parts of the vessels are values set by project standards for each case and each material. As the strength of materials decreases with increasing temperature, the allowable tension are also increasingly smaller as the working temperature of the part until the temperature rises limit of practical use of the material. Project standards provide design standards with the allowable stresses of each material as a function of temperature.

For non-pressurized parts of pressure vessels (brackets, internal parts, external structures, etc.) it is customary to adopt the usual allowable tension for steel structures in general, correcting, when necessary, the effect of reducing the material's resistance with temperature.

Taking into account the maximum and minimum temperature (ASM International Handbook Committee, 1990) and the type of material used in the project (304 stainless steel), for the allowable tension was found the value of 215MPa.

The formula for calculating the hulls of small thickness cylinders is directly derived from the theoretical expression of the maximum circumferential stress of a membrane cylinder and is expressed by:

$$e = \frac{P \cdot R}{S \cdot E - 0{,}6 \cdot P} \cdot \beta \tag{1}$$

The equation is multiplied by a safety factor *β*, in this case, were use the factor 3.

Using the equation shown above, calculates the thickness of that particular steam generator. The hull design is considered small thickness because $e < 1/2R$.

Putting the values obtained in the formula:

$$e = \frac{2 \cdot 85}{215 \cdot 1 - 0{,}6 \cdot 2} \cdot 3$$

The final result will be:

$$e = 2{,}38\ mm$$

Therefore the thickness of 3 *mm* was used due to stock available in IEAv.

2.2 Calculation of the thickness of the lid

A variety of lid tops used for pressure vessels is too big. The ASME code, Seção VIII, Divisão 1, shows the “Fig. 1” as an example of a type permitted by setting it formulas and calculations coefficients in accordance with the format, the fastening system details solder.

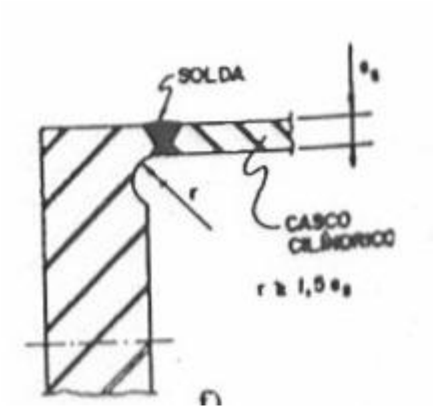

Figure 1. This type of lid used in the steam generator with the particular type of solder

The lid project is used in the "Fig 1 ", and to calculate the thickness of the top plan to weld the following parameters should be taken into consideration:

e: minimum thickness in millimeters of the lid,
d: diameter in milimeters,
N: dimensionless factor dependent on the type of cover and fastening system hull,
P: internal project pressure in megapascals,
S: allowable tension in megapascals.
The formula used is as follows:

$$e = d \cdot \sqrt{\frac{N \cdot P}{S}} \cdot \beta \quad (2)$$

The equation is multiplied by a safety factor β, in the case, according to the ASME code, you must use the factor 2. The dimensionless factor used in the project will amount to 0.17 because the top is the type used forged solder..
Under the demonstration calculations through the equation:

$$e = 0{,}268\sqrt{\frac{0{,}17 \cdot 2}{215}} \cdot 2$$

The final result will be:

$$e = 10{,}72 \cdot 2 = 21{,}44\ mm$$

2.3 Diagram of tension-strain

To perform the stress-strain diagram (Beer, F. P., Johnson, E. R. Jr., 2008), usually it makes a tensile test on a sample of the material. In this test is use a specimen from which to make two marks with a distance L_o. The specimen is brought to the test machine, this applies a load centered *P*. With the increasing value of *P*, distance *L* also increases. A measure indicates the distance *L*, and the elongation $\delta = L - L_o$ is noted for each value of *P*. Another measurer is used to record changes in the diameter of the specimen. For each pair of values read from *P* e δ, the tension is calculated σ and the formule is above:

$$\sigma = \frac{P}{Ao} \quad (3)$$

Ao = initial transverse section of the specimen in square meter.
It is also estimated deformation specific ε wich the formule is:

$$\varepsilon = \frac{\delta}{Lo} \quad (4)$$

Obtain, that way, the diagram of tension-strain indicating ε in the axis x and σ (MPa) in the axis y (Alberto, 1997).

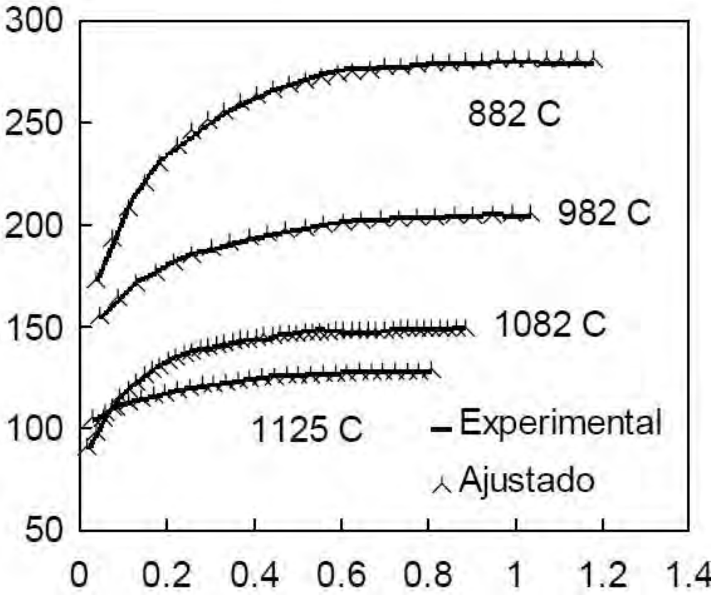

Figure 2. Graphic showing the tension-strain tests performed on samples of 304 stainless steel

2.4 Calculation of amount of screws

According of Per ISO 898, part 1, the pression can be exerted on a screw M8 – 10.9 é de 830 MPa (Figure 3).

Mechanical Properties Per ISO 898-1 (Externally Threaded Fasteners)

Metric Property Class	Material	Size Range	Min. Proof Strength MPa	Min. Tensile Strength MPa	Core Hardness Rockwell Min.	Core Hardness Rockwell Max.	Min. Yield Strength MPa	Grade Identification Marking
4.6	Low or medium carbon steel	M5 - M39	225	400 (58,000 PSI)	B67	B99.5	240	4.6
8.8	Medium carbon steel: quenched & tempered	M5 - M16	580	800 (116,000 PSI)	C22	C32	640	8.8
		M18 - M39	600	830 (120,000 PSI)	C23	C34	660	
10.9	Alloy steel: quenched & tempered	M5 - M39	830	1040 (150,800 PSI)	C32	C39	940	10.9
12.9	Alloy steel: quenched & tempered	M1.6 - M39	970	1220 (177,000 PSI)	C39	C44	1100	12.9

Figure 3. Pression exerted in each screw type

To perform the calculation of the amount of bolts (FEDS, 2009) first the lateral area must to be calculated steam generator:

$$Al = 2 \cdot \pi \cdot r \cdot h \qquad (5)$$

$$Al = 2 \cdot 3{,}14 \cdot 82 \cdot 530 = 272928{,}8\ mm^2$$

Al: area lateral of steam generator (272928 mm^2);
R: internal radius of the steam generator (82 *mm*);
H: height (530 *mm*).

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The next step is to calculate the force that supports the generator to their proper pressure:

$$F = P \cdot A \tag{6}$$

$$F = 2 \cdot 10^6 \cdot 272928{,}8 \cdot 10^{-6} = 545857{,}6\ N$$

F: force supported by the steam generator (545857,6 *N*);
P: maximum internal pressure (2 *MPa*);
A: area lateral of steam generator (272928,8 mm^2).
Calculus of area of each screw M8:

$$A_{M8} = \pi \cdot r^2 \tag{7}$$

$$A_{M8} = 3{,}14 \cdot (3{,}5)^2 = 38{,}465\ mm^2$$

A_{M8}: area of the head of each screw M8 (38,465 mm^2);
R: radius (3,5 *mm*).
Making equation of all these formulas, reach the ultimate goal, there is, calculate how many screws are needed to hold this amount of force and pressure:

$$A_{M8} \cdot N = \frac{F}{P} \tag{8}$$

$$N = \frac{545857{,}6}{830 \cdot 10^6 \cdot 38{,}465 \cdot 10^{-6}}$$

$$N = 17{,}09\ screws$$

N: amount of screw;
A_{M8}: area of the head of each screw M8 (38,465 mm^2);
F: force supported by the steam generator (545857,6 *N*);
P: maximum pressure for each screw (830 *MPa*).
As the factor of safety is already included in the value of the pressure supplied by Per ISO 898, part 1, used 18 screws M8.

1.2 Instrumentations and materials

After done the project of the generator was started acquisition step materials via CNPq design for the construction of the steam generator. Amoung the materials include: pressure gauge (used to measure the pressure within the generator), relief valve, check valve (for the steam generator does not return to the pump, making a path of movement contrary to the cycle), control valve output, copper tube ¼ ", etc.

3. CONCLUSION AND FINAL REMARKS

For data collection were performed calibration tests. Among these are the propagation of temperature, hydrostatic and validation of sensors.

The hydrostatic test is done by pressurizing the water and is intended for the detection of possible defects, failures or leaks when the pressure is 20 bar. This ensures state integrity and ability to withstand normal operating conditions.

Sensor validation was done by sampling temperature. Initially, the temperature is measured by an external thermometer which performs an initial measurement was compared with the measurement made by the sensor. If there are discrepancies, the sensor was adjusted to the reference temperature.

The propagation test temperature was made by thermocouples placed along the steam generator. When the top temperature was added below the generator, the temperature gradient was found, namely the time it takes to become equal temperature from the first to the last thermocouple.

Equating was carried out to find ways on the steam generator. The thickness of the lid was found to be 21.44 mm, since the thickness of the cylindrical hull is 3 mm, this difference is due to be topped up and welded to the hull. Below is the Fig.4 showing the graphic design of the hood and Figure 5 showing the hull.

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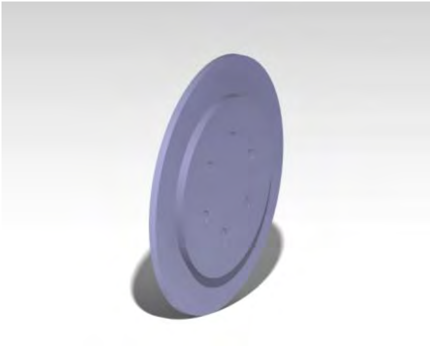

Figure 4. Graphical representation of the bottom head of the steam generator

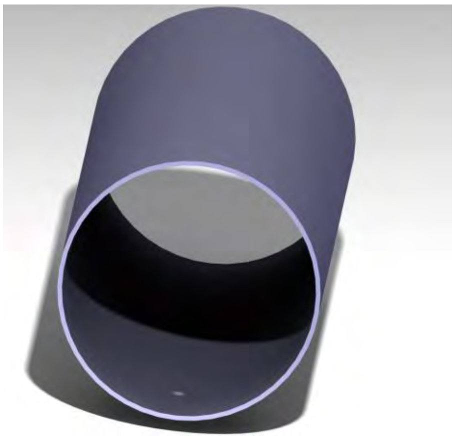

Figure 5. Graphic representation of the hull cylindrical steam generator

For the dissipation of heat in steam generator tubes were made with small holes. Figure 6 illustrates these tubes and where it is.

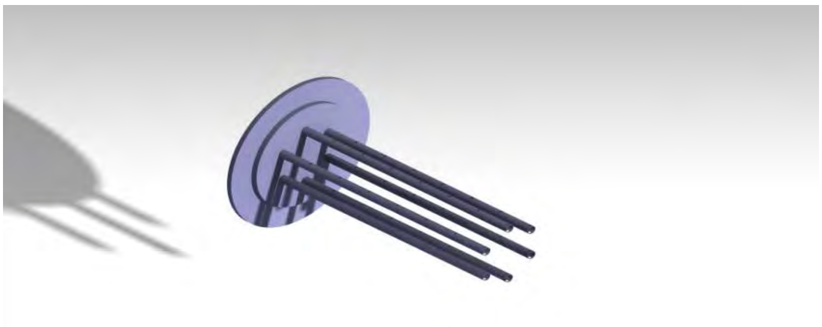

Figure 6. Graphical representation of heat dissipation tubes fixed to the bottom head of the steam generator

By the results on the size of the generator, the graphic design was made of it. Figure 7 shows the final result:

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Figure 7. Steam generator mounted

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