USE OF COMPOSITE MATERIALS TO DESIGN A REUSABLE COMBUSTION CHAMBER STRUCTURE

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Abstract. *This paper examines a combination of materials in order to obtain a composite structure with high strength and low weight, capable of withstanding high temperatures and pressures during the combustion of a rocket motor. These qualities allow its reuse in other launches. In a medium-size rocket motor, the pressure inside the combustion chamber can reach more than 10MPa, so it is necessary to use materials with high yielding tensile strength, which are usually heavy or economically impracticable. One solution is to combine less resistant materials that, acting as one, can withstand the thermal and mechanical stress, providing lower cost without degrading the rocket's performance due to the weight. Combining PVC (polyvinyl chloride) and phenolite tubes, the resulting structure is able to resist the required yield stress, leaving only the high temperatures problem left, because thermal and structural effects don´t interfere on each other – provided that the absence of gaps in the assembly and the efficiency of the thermal protection are guaranteed. In order to solve the temperature problem, it is necessary to add heat resistant inner layers, such as cork, or guarantee that they do not reach temperatures that could damage the structural layers, such as PVC and epoxy, in the combustion process. Pressure tests assure the structural integrity, while for the analysis of temperature resistance the propellant combustion in conditions of high pressure, due to the raise of burning rate and, consequently, of the temperature. This paper verifies the maximum tensile strength of the assembly to be validated, PVC-phenolite-PVC, through destructive hydrostatic pressure tests which showed a resistance of 13,9MPa. With these tests performed, the combustion checked the best combination of materials to avoid damage in the structural layers with two layers of cork. Thus, it´s possible to design a simple, light and economically accessible rocket motor combustion chamber with the acquired data.*

Keywords*: composite materials; rocket combustion chamber; hydrostatic pressure test*

1. INTRODUCTION

This paper objective is the analysis of the structure components of the combustion chamber of a solid propellant rocket motor. The combustion chamber is a pressure vessel with a single opening, where the speed increases due to the convergent/divergent nozzle, as shown in Fig. 1. The combustion generates high temperature and pressure gas that is expelled through the nozzle.

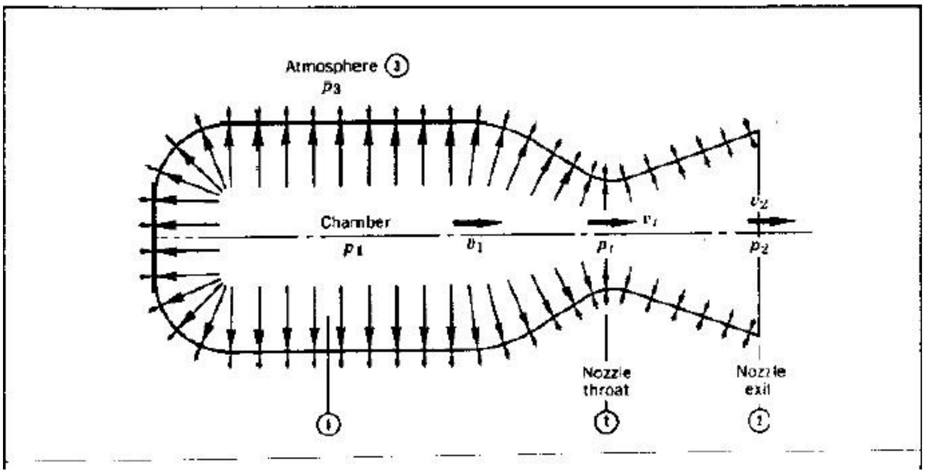

Figure 1. Combustion Chamber, (Nakka, 1984)

The chamber size depends on the propellant type. In liquid propellant rockets only the combustion happens in the combustion chamber, the fuel and the oxidant are stored in separated and isolated tanks. In hybrid and solid propellant rockets, the chamber also stores the propellant or part of it that will be burned.

Combustion chambers of solid propellant rocket motors, due to be submitted to high pressures and temperature, are normally built using materials like:

•Alloys: alloys are the most used materials in aerospace structures because of their great structural resistance and malleability. In order to increase their efficiency, others elements like nickel, cobalt, molybdenum and chrome are added to them. However, this procedure makes the alloy expensive and, consequently, hard to obtain, (Dergamo et al., 2003).

•Composite Materials: composites consist of a reinforcing material suspended in a “matrix” material that stabilizes the reinforcing material and bonds it to adjacent reinforcing materials, (Raymer, 1999). Their application is a reality at aerospace structures, seeing that has high structural performance and low inertia. However, it is expensive, especially in large scales.

•Ceramic Materials: ceramic materials are used in aerospace structures members because their high potential thermal containment ability. Nevertheless, their reduced ductility and consequently high fragility, reduces the intensity range of the material uses.

In rocket engine there is a heat shield between the envelope and the propellant engine consisted of a thin layer of rubber and an adhesive called "liner" in order not to allow the high temperature of the propellant rocket damage the structure (Sciamareli, Jairo et al., 2002). In order to avoid a negative influence of the temperature on the chamber structure, a heat shield was attached to the chamber and tested in conjunction.

Through the analysis of available materials on the market, it is nearly impossible to obtain a single material that is resistant, weightless and affordable and that supports the extreme conditions in a combustion chamber of a rocket engine. This material would allow a practical development of rocket motors using its properties as a single material to proof theories.

Therefore, this paper seeks an alternative structure consisted of weightless and resistant materials, but affordable to rockets engine developers, in order to be used in combustion chamber of medium-size rocket motor. The authors design a structure consisted of three concentric cylinders: a PVC tube in the outer and inner side and a phenolite tube in the middle of them. This structure withstands pressures greater than 12MPa and combustion temperatures for more than 20s.

2. EXPERIMENTAL ANALYSIS

Destructive tests by hydrostatic pressure were performed for the structural analysis. Fluid was injected inside the tube in order to increase internal pressure. This process simulates the pressure increase in a combustion chamber of a rocket engine. Since on this experiment the heat effect cannot be analyzed, thermal tests were also performed.

Several destructive hydrostatic pressure tests were proposed to analyze the maximum stress in the tubes due to sudden increase in pressure and the effects of loading and unloading or malfunction. In one of these tests the fluid was injected in the tubes with different speeds, and each speed created lines with different slopes in a pressure versus time graph. In other test the fluid was cyclically injected in order to obtain the elastic limit of the material.

For these tests, the authors made sixteen composite tubes, which consist of two concentric PVC tubes with phenolite sandwich between them. Two types of PVC were used: the common PVC, brown in color, used for cold water and, as a result, does not resist high temperatures; and the CPVC (chlorinated polyvinyl chloride), green in color, used for hot water and, therefore, resists high temperatures. The tubes have a length of 400mm, an external diameter of 60mm and an internal diameter of 43mm. The CPVC pipes of dimensions 43mm x 3,5mm and 55mm x 2,5mm have a nominal pressure of 750kPa@20°C. The phenolite tubes dimensions are 50mm x 2,5mm. The tubes were machined on a precision lathe and got a gap of 0,5mm between adjacent tubes. The epoxy resin fills the gaps and attaches structures members, so that the stress applied to the inner tube is transmitted to the outer tubes.

Each test used three tubes in order to obtain data for a statistical analysis, divided into five different tests:

1. Tubes under an instantaneous pressure of 15Mpa;
2. Tubes under a pressure of 10MPa that increased 1MPa every 4 minutes;
3. Tubes under a pressure of 10MPa that increased 1MPa every 8 minutes;
4. Tubes under a pressure of 10MPa that increased 1MPa every 12 minutes;
5. And tubes that underwent five cycles of pressure that increased from 0MPa to 6MPa instantly.

An additional tube was made in order to replace any tube that could present defects during testing, as was necessary.

Table 1 shows the mass of each tube.

Table 1. Mass of each tube

Tube	Mass (kg)	Tube	Mass (kg)
1	0.665	9	0.660
2	0.656	10	0.664
3	0.634	11	0.668
4	0.642	12	0.652
5	0.645	13	0.653
6	0.656	14	0.650
7	0.668	15	0.641
8	0.664	16	0.631

Thermal tests were conducted in order to obtain the effect of high temperature on resistance of structural members. The used tube consists of three concentric tubes: a phenolite tube on the outer side, a PVC tube on the middle and a layer of cork in the inner side. The inner side material selection was due to the fact that the cork has a low thermal conductivity.

For these tests, the used propellant was the KNSU that consists of sucrose (sugar) fuel with potassium nitrate as the oxidizer. The oxidizer/fuel ratio is chosen on the basis of which ratio gives the greatest overall performance for a given propellant grain design, (Nakka, 1984).

The solid propellant was ignited in phenolite-PVC-cork tube that has a dimension of 0.2 m length, using CPVC for hot water or PVC for cold water, with one or two layers of cork. The cork is resined with epoxy resin on the inner side. It serves as a thermal barrier, retaining some heat released in the reaction, performing no structural performance. The durability analyses of the tubes were provided by successive combustions. Also it was observed after every firing the possibility of reusing the tubes. Under ambient pressure, the combustion is slower, so the exit area is changed in order to enable the tube behavior analysis in a faster and hotter combustion.

The tubes tested are smaller than the ones used in destructive hydrostatic pressure tests. The phenolite tube dimensions are 25mm of length and 29mm of diameter. The brown PVC, for cold water, dimensions are 21.6mm of length and 25mm of diameter. The green CPVC, for hot water, dimensions are 16.6mm of length and 25mm of diameter. Cork sheets are 1mm thickness. The organization of the tests is in Tab. 2.

Table 2. Type of PVC, number of cork layers, number of combustions and kind of combustion

Tube	Type of PVC	Number of cork layers	Number of combustions	Kind of combustion
1	CPVC	1	1	Not pressured
2	CPVC	1	5	Not pressured
3	PVC	0	1	Not pressured
4	PVC	1	5	Not pressured
5	CPVC	1	3	Not pressured
6	PVC	1	3	Not pressured
7	PVC	2	3	Not pressured
8	PVC	2	1	Not pressured
9	CPVC	1	5	Not pressured
10	PVC	2	1	Not pressured
11	CPVC	1	1	Not pressured
12	CPVC	1	1	Not pressured
13	PVC	2	5	Not pressured
14	PVC	1	1	Pressured (½ of the exit area)
15	PVC	1	1	Pressured (½ of the exit area)
16	PVC	2	1	Pressured (½ of the exit area)
17	PVC	2	1	Pressured (¼ of the exit area)
18	PVC	2	1	Pressured (¼ of the exit area)
19	PVC	1	1	Pressured (¼ of the exit area)
20	PVC	1	1	Pressured (¼ of the exit area)

3. EXPERIMENTAL RESULTS

The experiments involving the structural analysis of PVC-phenolite-PVC tubes showed consistent values as expected, as shown in Tab. 3.

Table 3. Shear stress of the PVC-phenolite-PVC tubes

Tube	Rupture Pressure (MPa)	Initial Pressure (MPa)	Pressure Increment (MPa)	Final Condition
1	15.0	0	until rupture	Did not rupture
2	12.4	0	until rupture	Ruptured
3	14.7	0	until rupture	Ruptured
4	13.6	10	1 every 12 minutes	Ruptured
5	14.0	10	1 every 12 minutes	Ruptured
6	15.0	10	1 every 12 minutes	Ruptured
7	13.9	10	1 every 8 minutes	Ruptured
8	15.0	10	1 every 8 minutes	Did not rupture
9	10.0	10	1 every 8 minutes	Ruptured
10	14.0	10	1 every 4 minutes	Ruptured
11	14.0	10	1 every 4 minutes	Ruptured
12	15.0	10	1 every 4 minutes	Ruptured
13	Not Essayed	-	-	-
14	6.0	0	0-6 (instantaneous)/5 times	Did not rupture
15	6.0	0	0-6 (instantaneous)/ 5 times	Did not rupture
16	3.5	-	0-6 (instantaneous)/ 1 time	Ruptured

The tubes number 1 and 8 have behaved as defective elements, since there is no explanation to their not disruption as they were made identically to all of the other tubes. The tube number 13 showed fractures during its placing in the test machine because of a manipulation mistake done by the lab technicians. In order to replace number 13, the tube number 16 was used, but its results has shown that were also a mistake during its manipulation since there is a difference between its results and numbers 14´s and 15´s results.

However, the authors have observed that the material structural ability is proven, seeing the regularly of average rupture pressures of the tubes, that is equal to 13,88MPa.

Besides the structural resistance, the materials behavior could be verified facing the pressure variation during different periods of time. Also the fatigue in the tubes could be analyzed. Figure 2 shows the results of the destructive tests of hydrostatic pressure in each proposed case.

Figure 2. From left to tight: case 1, case 2, case 3, case 4 and case 5

Relating to the elements submitted to the local ambient pressure combustion, with no strangulation through the expelled gases way, the data of the structure mass, the used propellant mass and the combustion time are shown in Tab. 4:

Table 4. Structure mass, propellant mass and combustion duration

Tube	Combustion	PVC Type	Number of Cork Layers	Structural Mass (kg)	Propellant Mass (kg)	Combustion Duration (s)
1	1st	Green	1	0.085	0.059	69

2	1st	Green	1	0.087	0.054	56
2	2nd	Green	1	0.090	0.046	32
2	3rd	Green	1	0.091	0.061	51
2	4th	Green	1	0.092	0.049	48
2	5th	Green	1	0.094	0.041	82
3	1st	Brown	0	0.075	0.105	37
4	1st	Brown	1	0.080	0.092	56
4	2nd	Brown	1	0.079	0.080	42
4	3rd	Brown	1	0.078	0.071	42
4	4th	Brown	1	0.079	0.075	52
4	5th	Brown	1	0.081	0.079	66
5	1st	Green	1	0.086	0.055	63
5	2nd	Green	1	0.088	0.044	43
5	3rd	Green	1	0.091	0.054	68
6	1st	Brown	1	0.079	0.096	80
6	2nd	Brown	1	0.075	0.087	58
6	3rd	Brown	1	0.070	0.088	60
7	1st	Brown	2	0.089	0.073	103
7	2nd	Brown	2	0.086	0.058	65
7	3rd	Brown	2	0.088	0.055	56
8	1st	Brown	2	0.089	0.063	74
9	1st	Green	1	0.087	0.051	34
9	2nd	Green	1	0.089	0.045	44
9	3rd	Green	1	0.088	0.054	55
9	4th	Green	1	0.089	0.048	47
9	5th	Green	1	0.088	0.053	56
10	1st	Brown	1	0.089	0.067	46
13	1st	Brown	2	0.086	0.076	89
13	2nd	Brown	2	0.085	0.072	59
13	3rd	Brown	2	0.083	0.065	41
13	4th	Brown	2	0.083	0.062	35
13	5th	Brown	2	0.084	0.066	47

Besides the high duration of the combustion and the high temperature reached (700K), the cork worked as a great thermal barrier, avoiding the main part of the exhausted heat reach the PVC and phenolite layers, as shown in Fig. 3 and Fig. 4 that correspond to the tubes after the combustion.

Figure 3. From left to right: tube 3, tube 10, tube 6, tube 4 and tube 8

Figure 4. From left to right: tube 1, tube 5 and tube 2

About the elements submitted to the pressurized combustion, the data of the structure mass, the used propellant mass and the combustion time are shown in Tab. 5:

Table 5. Data corresponding to the pressurized combustion tubes

Tube	Combustion	PVC Type	Funnel Type	Number of Cork Layers	Structural Mass (kg)	Propellant Mass (kg)	Combustion Duration (s)
14	1st	Brown	1/2 of Area	1	0.076	0.100	50
15	1st	Brown	1/2 of Area	1	0.081	0.096	48
16	1st	Brown	1/2 of Area	2	0.086	0.058	58
17	1st	Brown	1/2 of Area	2	0.089	0.064	63
18	1st	Brown	1/4 of Area	2	0.091	0.064	64
19	1st	Brown	1/4 of Area	2	0.094	0.072	75
20	1st	Brown	1/4 of Area	1	0.081	0.089	38
21	1st	Brown	1/4 of Area	1	0.082	0.105	3

In an experiment of a low period of combustion where an increment of the temperature (1000K) happened inside the tube, the cork layer worked as a great thermal barrier avoiding the most part of the heat exhausted during the combustion reach the PVC and phenolite layers.

The pressurized combustion results are exposed as shown in Fig. 5:

Figure 5. From left to right: tube 15, tube 19, tube 20 and tube 21

4. CONCLUSION AND FUTURE WORKS

After the proposed tests ending and the final results analysis, the structural element design resulted in a satisfactory conclusion.

The object of study has shown expressive resistance to stress taking into accounting reduced mass composition. Even if non-linear curve points were found, because of the rough handling during the tests and the manufacturing defects in material and composites, the statistical analysis showed a pressure resistance of 13,88 ± 2,00MPa for a tube mass average of 0,653 ± 0,0005kg.

That fact, therefore, ratifies the composite´s validity as an alternative material to be used in medium-size rocket motors. Although it does not have a performance similar to steel, it is a resistant composite with high structure efficiency. Also it is simple to manufacture and is composed by environmental non-degrading materials.

Besides the structural resistance factor, the resistance ability to successive fatigues was analyzed. Although the irregular curve point, caused by rough handling of the tubes, the tests proved that plastic deformation border of the material is substantial and that it was not exceeded inside the exposure limit of the tube pressure. Thus, this resistance test guarantees the reuse of the tubes after a real essay.

As regards to thermal analysis, the cork uses as a thermal insulating supplemented the inner PVC layer, which gives structural resistance and assists as a thermal protector to the phenolite layer. With a thermal conductivity of 0,074 W/mK, the cork absorbed most part of the released combustion heat, in the unrestricted and restricted combustion, deforming in small scale the inner PVC layer without damage the phenolite.

As cited, tubes with one and two cork layers of 1mm thickness were tested. The use of cork has produced satisfactory results, since, after five combustions, the tubes resisted to high temperature exposure without damaging themselves neither making them unusable. However, with two layers of cork there is a safety factor that guarantees the completely material integrity, without visible damage as the thermal deformation showed in the previous case.

Thus, the desirable structure at the end of the experiments is composed of interspersed pipes of PVC and phenolite following the sequence PVC-Phenolite-PVC, with two layers of cork inside. This structure is able to resist the required effort within the limits and objectives of the project, in this case, the size of the rocket and the quantity fuel used. In order not to have its resistance impaired by the temperature increase, a double layer of cork is able to prevent the transfer of heat through the structural layers, absorbing mass of the heat expelled.

Thus, the structural element reuse is possible because of the thermal layer effectiveness, the only component changeable during the successive combustion. As a result, an element made by the composition of these thermal and structure layers can be used as a structure of a medium-size rocket motor, with possibility of reuse after fatigued.

As future projects, the authors have as objective to do mathematics and computational analysis of the researched structures. Similar results are hoped to de found between those analyses in order to proof, one more time, the material efficiency when used as a combustion chamber in a rocket. Besides those studies, the authors long to test the main structure attached to a real motor to verify its structural ability in a real flight essay.

5. ACKNOWLEDGEMENTS

The authors give thanks to the lab technicians Fábio Gallo and José Cláudio Pinto de Azevedo of the Department of Aeronautical Engineering at University of São Paulo for the assistance at the construction of the analyzed elements as at the development of the used instrumentals for this article.

Thanks are also extended to MSc. José Donato Ambrósio and to the lab technician Robson of the Centre for Development and Characterization of Materials at Federal University of São Carlos who were willing to do the destructive hydrostatic pressure tests in favor of the conclusion of this paper.

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