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SELECTION OF MATERIALS FOR COMBUSTION CHAMBER OF LIQUID PROPELLANT ROCKET ENGINE

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Abstract: *The present work aims the analysis of the material and the thickness of the walls of combustion chambers. In this analysis, the geometric characteristics of combustion chamber, the heat flux through wall, the temperature of wall and the material properties of walls will be taken into account. As results, answers for the following questions will be obtained. What is the possibility to cool the wall of inner shell of a combustion chamber? Which material is the best considering the mass minimization criteria? What kind of modifications should be incorporated in the design to afford the combination of reliability and performance?*

Key words: *Combustion chamber, Materials, Heat flow, Regenerative cooling, Liquid propellant rocket engine*

1. INTRODUCTION

The VLS-2 will be a next step in the evolution of the Brazilian launcher vehicle family. According to the “Programa Nacional de Atividades Espaciais” of AEB (Agência Espacial Brasileira), the primary objective of this launch vehicle is to place a satellite into polar Earth orbit, carrying a payload mass of 1000 kg to an altitude of 1000 km. To attain this objective the inclusion of stages with liquid propellant becomes a relevant condition.

As discussed in Niwa and Yoshino, 1997, the technology of liquid propellant rocket engine (LPRE) is completely new in our country and therefore broad fundamental studies are required in this field. Among the subsystems of a LPRE, combustion chamber is one of component that deserves deep studies, due to its critical working conditions, in terms of temperature and pressure.

In this work, a methodological procedure which is based essentially on Russian experience is presented (Ballard, R. O., 1995 and Sergienko, A. and Chervacov, V., 1996), to select the materials and to calculate the thickness of the walls of a combustion chamber of a LPRE. For the analysis, the following information from combustion chamber will be taken into account: the geometric characteristics, the heat flux through the walls, the wall temperature and the load capacity of the structure. Firstly, a short description of combustion chamber problems will be made to allow assessment of the problems and secondly, an analysis procedure will be presented. Finally, a model of combustion chamber, whose the main characteristics are suited for upper stages of VLS-2, will be considered for numerical calculation.

2. CHARACTERIZATION OF COMBUSTION CHAMBER PROBLEMS

2.1. Geometrical configuration

In LPRE, liquid fuel and liquid oxidizer are housed in separated tanks and during engine operation both are introduced into the thrust chamber for burning. The hot gases, resulted from combustion, are accelerated to supersonic velocity in the nozzle to provide the thrust.

The basic elements of a combustion chamber are the injector head, the cylindrical part (main body) of combustion chamber, the expansion nozzle, the ignition device, the propellant inlet and the distribution manifolds.

Both the cylindrical part of combustion chamber and the nozzle usually consist of structure of double shells connected by brazing. In general, the space between shells (cooling jacket) is obtained by means of milling ribs. The material of inner shell can be copper alloy or stainless steel with or without refractory coat, on the hot gas side wall and the material for the outer shell is usually stainless steel.

The fuel passing through the cooling jacket cools down the inner shell of the chamber.

The cylindrical part of combustion chamber serves as an envelope to retain the propellants for a sufficient period (stay time) to ensure complete mixing and combustion. The required stay time, or combustion residence time is a function of the propellant combination, the injected conditions of the propellants, combustion chamber geometry, and injector design.

The customary method of establishing the dimensions of chamber of a new design largely relies on past experience and statistical data with similar propellant and engine size.

For a given required volume, the chamber can have any shape. Nowadays, however, the choice of combustion chamber configuration is limited. A long chamber with a small cross section entails high nonisentropic pressure losses. Long chambers also dictate a longer thrust chamber envelope and impose space limitations on the injector plate. With a short chamber of large cross section, the propellant atomization and vaporization zone occupy a relatively large portion of the chamber volume, while the mixing and combustion zone become too short for efficient combustion. Other factors, such as heat transfer, combustion stability, weight, and ease of manufacturing must also be considered (Huzel and Huang, 1992).

For the expansion nozzle, the following considerations and goals generally influence the selection of its shape (Kessaev, 1997):

- Uniform, parallel, axial gas flow at the nozzle exit for maximum vector momentum;
- Minimum separation and turbulence losses within the nozzle;
- As shortest as possible nozzle length for minimum space envelope, weight, wall friction losses, and cooling requirements;
-Ease of manufacturing.

To fulfil these objectives, one of best solutions is the contoured or bell-shaped nozzle. It employs a fast-expansion section in the initial divergent region, which leads to a uniform, axially directed flow at the nozzle exit. The wall contour is changed gradually to prevent oblique shocks.

2.2. Heat transfer

Because of high combustion temperatures and high heat transfer rates from the hot gases to the chamber wall, thrust chamber cooling will be a major design consideration.

For the chamber analyzed in this work, the following techniques are used for cooling:

- Regenerative cooling: where one propellant (fuel) is fed through passages (cooling jacket) in the chamber wall for cooling, before injecting into the combustion chamber;

- Film cooling: exposed chamber wall surfaces are protected from excessive heat by a thin film of propellant (fuel) introduced through the most external ring of injectors and through orifices placed in the manifold in the chamber wall, at the end of the cylindrical part of chamber. This method has been used in areas of chamber with high heat flux, in combination with regenerative cooling (Kessaev, 1997).

The properties of the thrust chamber materials will profoundly affect the cooling system design. Strength at elevated temperature and thermal conductivity will determine the suitability of a given material for regenerative cooling. For film cooled chambers, high temperature performance materials are desired to decrease film coolant flow rates.

For the complete analysis of chamber-cooling systems it is required the knowledge in the fields: heat transfer, fluid mechanics, thermodynamics, materials and structures.

A first step in the design of a thrust chamber cooling system is the analysis of heat transfer from the combustion gases to the chamber walls, which occurs by forced convection and radiation. Before the gases transfer convective heat to the wall, the heat energy must pass through a layer of stagnant gas along the wall, the boundary layer.

The basic correlation for the convective heat transfer (q_{co}) can be expressed by the following equation (Kessaev, 1997):

$$q_{co} = \left(B \frac{1-\beta^2}{D_{sp}^{\ 1.82}} \right) \frac{(P_{ch})^{0.85}}{(D_{cr})^{0.15}} \cdot \frac{S_o}{(\mathrm{Pr})^{0.58}} \qquad (1)$$

$$B \cong 0.0086 \qquad (2)$$

$$\beta = \sqrt{1 - \frac{2}{2 + M^2.(k-1)}} \qquad (3)$$

$$D_{sp} = \frac{D}{D_{cr}} \qquad (4)$$

Where:

B is a non dimensional coefficient;

β is a non dimensional velocity;

S_o is a complex of thermophysical parameter dependent on the mixture ratio and wall temperature (range: 3000 to 7000 W/m^2);

Pr is the Prandtl number (for gases in the wall layer condition Pr ~ 0.75);

M is the Mach number (range: 0 to 4.5);

k is the adiabatic exponent (range: 1.14 to 1.21);

P_{ch} is the chamber pressure (MPa);

D is the actual section diameter (m);

D_{cr} is the critical diameter (m).

The basic correlation for calculation of the radiactive heat flux (q_{rad}) is:

$$q_{rad} = \varepsilon_{wall} \varepsilon_g \sigma (T_{ch})^4 \varphi \qquad (5)$$

Where:

σ is the Steffan-Bolttzmann coefficient (5.67 . 10^{-8} W/m^{2}K^4);

T_{ch} is the gas temperature at core of combustion chamber (K);

ε_{wall} is the effective emissivity coefficient of wall surface (less than 1);

ε_g is the emissivity coefficient of chamber gases (less than 1);

φ is the absorption coefficient in the wall layer (less than 1).

2.3. Temperature distribution in the walls

Regenerative cooling has several advantages over other cooling systems and some disadvantages. Advantages include small performance loss (thermal energy absorbed by the coolant fuel is returned to the injector), essentially no change in wall contour as a function of time as ablative cooling, long firing duration, and relatively lightweight construction. Disadvantages include limited throttling and high-pressure drops (Huzel and Huang, 1992).

For this chamber, the selected cooling technique is the milling ribs because it is more reliable, of cheap construction and the manufacturing process is the simplest. In milling ribs, the coolant propellant passes through rectangular slots or channels, machined into the chamber liner (inner shell). The machined channels are closed out and the liner is enclosed with the outer shell (structural support of chamber). More information about cooling technique selection is presented in Shimote et al. 1999.

The methodological procedure to evaluate the temperature distribution along the wall of inner shell takes into consideration the efficiency of ribs, thermophysics properties of kerosene and metal, gas temperature distribution in the wall layer and kerosene temperature inside cooling jacket.

There are several recommendations for designing the inner shell, the more important are (Kessaev, 1997):

- The temperature of kerosene inside cooling jacket cannot be more than 450 K to avoid separation of resin and formation of hard sediments in the walls of cooling jacket.
- The material of inner shell must have a high thermal conductivity.
- The thickness of inner shell must be as thin as possible.

The temperature of inner shell wall from gas side ($T_{wall.gas}$) can be expressed by the following equation (Kessaev, 1997):

$$T_{wall.gas} = \frac{\left[\dfrac{T_{\mathrm{ker}}}{\dfrac{\delta_{inner}}{\lambda_{inner}} + \dfrac{1}{\alpha_{\mathrm{ker}}\eta_{rib}}}\right]\dfrac{1}{q_{co}} + \dfrac{q_{rad}}{q_{co}} + \dfrac{T_{gas}}{T_{gas}-1000}}{\dfrac{1}{\left(\dfrac{\delta_{inner}}{\lambda_{inner}} + \dfrac{1}{\alpha_{\mathrm{ker}}\eta_{rib}}\right)}\dfrac{1}{q_{co}} + \dfrac{1}{T_{gas}-1000}} \tag{6}$$

Where:

T_{ker} is the temperature of kerosene in the cooling jacket (range: 300 to 420 K);

λ_{inner} is the thermal conductivity of inner shell material (290 W/mK for copper alloy and 22 W/mK for stainless steel at temperature of 500 K);

α_{ker} is the kerosene heat transfer coefficient (range 1.8.10^5 to 4.1.10^4 W/m^{2}K);

η_{rib} is the efficiency of ribs (range 0.8 to 1.5);

T_{gas} is the temperature of gas in the wall layer.

The temperature of the inner shell wall from liquid side ($T_{wall.liquid}$) can be expressed by the following equation:

$$T_{wall.liquid} = T_{wall.gas} - \frac{\delta_{inner}}{\lambda_{wall}} q_{total} \tag{7}$$

Then, the inner shell temperature is the average between $T_{wall.gas}$ and $T_{wall.liquid.}$

The temperature of the outer shell is estimated by the average between the temperature of kerosene in the cooling jacket and ambient temperature.

2.4. Stress and strain

The load carrying capacity of the chamber case with connected shells is estimated by the value of limiting gas pressure in the combustion chamber. In order to find the limiting gas pressure it is necessary to construct the curve that expresses the relationship between the gas pressure in the combustion chamber and the radial elongation of the chamber under action of combined loading of pressure and temperature (Oliveira, 1998).

The limiting gas pressure is the value of pressure such that a small increment on it corresponds to a large increment on the radial elongation of shells, by development of plastic deformations in both shells of the chamber.

From equations of force balance, it is possible to write the following equations:

$$\sigma_{inner}\delta_{inner} + \sigma_{outer}\delta_{outer} = P_g R \tag{8}$$

$$\varepsilon = \varepsilon_t - \alpha T \tag{9}$$

$$\sigma = \sigma(\varepsilon) \tag{10}$$

$$\varepsilon_t = \frac{\Delta R}{R} \tag{11}$$

Where:

ΔR is the radial elongation;

σ_{inner} and σ_{outer} is the stress for inner and outer shell material respectively for the calculated temperatures;

P_g is the gas pressure;

R is the chamber radius;

ε_t is the total strain;

ε is the mechanical strain.

3. COMBUSTION CHAMBER MODEL

Based in a mathematical algorithm, presented in Almeida, 1998, it is possible to construct a model for combustion chamber, with the main characteristics suited for upper stages of VLS-2 (Niwa and Yoshino, 1997). The more important characteristics of this combustion chamber calculated by this algorithm are shown in Table1 and a tri-dimensional view of the combustion chamber is show in Fig.1.

4. RESULTS AND DISCUSSIONS

With the profile of combustion chamber and data of Table 1, heat flux through walls of the combustion chamber was calculated.

Figure 2 shows a calculation sample for convective and radiactive heat flux along the chamber profile using Eq. (1) and Eq. (5), respectively. In this figure, it is shown the level of the heat flux, near 5.10^7 W/m^2 in the critical section. This value is very high, in result, the temperature of kerosene in the cooling jacket will increase and inner shell temperature, in critical section, will increase too. With the increase of temperature, the fuel can boil and a collapse of regenerative cooling or melting of material of inner shell can occur. Then, it is necessary to decrease the heat flux. This is possible by means of implementation of film cooling.

Table 1 - Characteristics of combustion chamber:

Variable	Value
Thrust	75000 N
Propellant	LOX + Kerosene
Chamber Pressure	6 MPa
Nozzle outlet pressure	7500 Pa
Expansion ratio	800
Propellant ratio	2.42
Temperature	3618 K
Efficiency	0.948
Specific impulse in	3364 m/sec
Vacuum characteristic velocity	1736 m/sec
Chamber diameter	211 mm
Critical diameter	90 mm
Outlet diameter	719 mm
Chamber length	285 mm
Nozzle length	1206 mm
Total length	1491 mm
Oxidizer flow rate	15.6 kg/sec
Fuel flow rate	6.4 kg/sec

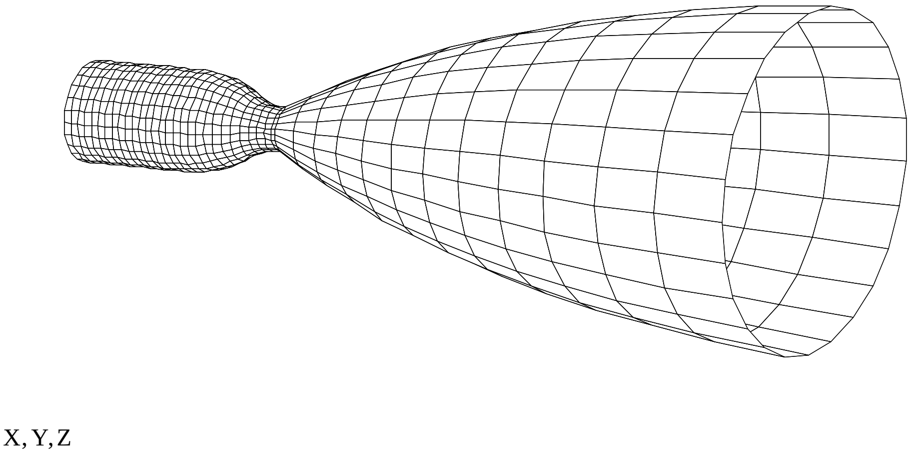

Figure 1 - Tri-dimensional view of combustion chamber.

Figure 3 shows a comparison between total heat flux with and without heat protection by film cooling, calculated by Eq. (1) and Eq. (5). The film cooling is organized using the most external ring of injectors and a manifold of orifices placed at the end of cylindrical part of combustion chamber. The flow of kerosene through the external ring of injectors and manifold of orifices goes to combustion chamber wall. The evaporated kerosene decreases the value of propellant ratio near combustion chamber wall. The gas temperature decrease in the boundary layer and the convective heat flux decreases too.

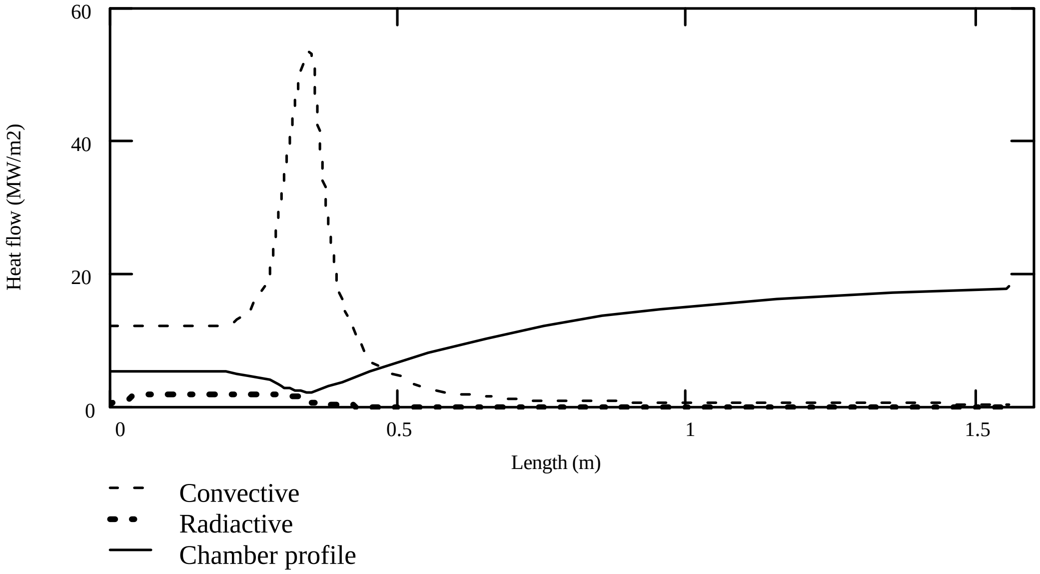

Figure 2 - Convective and radiactive heat flux along the chamber profile.

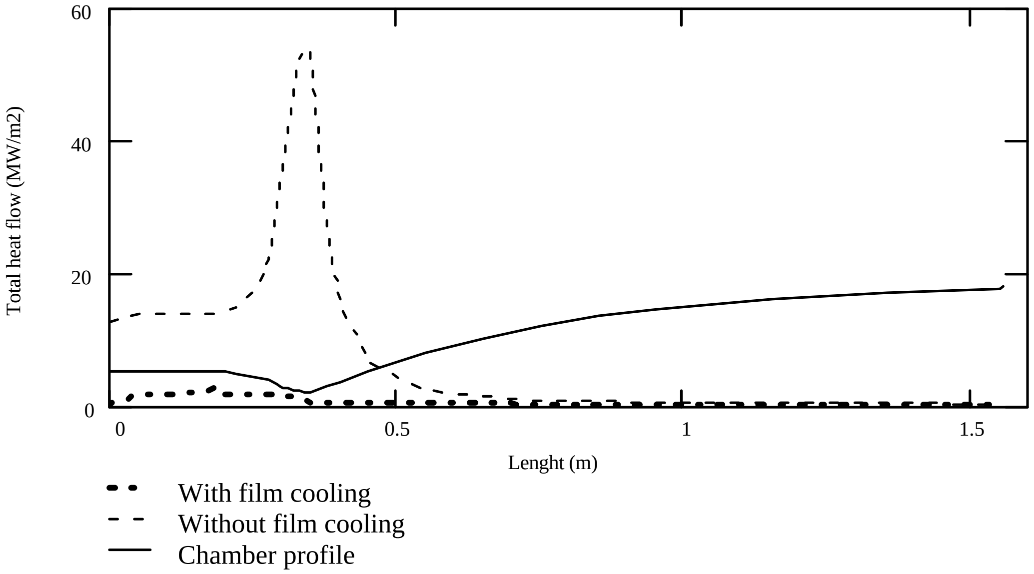

Figure 3 – Heat flux with and without film cooling.

For the model considered here the dimensions of milling ribs (Fig. 4), taking into consideration the limitations of manufacturing processes and efficiency in heat transfer, are:

Thickness of inner shell: $\delta_{\text{inner}} = 1.5$ mm
Thickness of outer shell: $\delta_{\text{outer}} = 2.5$ mm
Width of rib: $\delta_{\text{r}} = 1$ mm

Height of rib: $h_r = 1.5$ mm

Step of rib: $t_N = 3$ to 6 mm

The number of ribs for section of chamber is 100 near the critical section and 400 in the last section of nozzle.

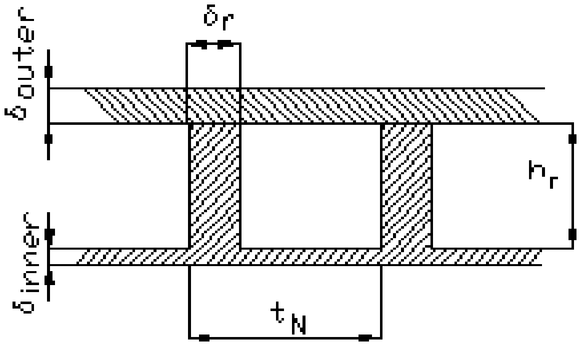

Figure 4 - Cross-section of milling ribs.

The ribs increase the heat flux through the inner shell to coolant liquid by increasing the surface area in contact with liquid. This efficiency is function of geometric parameters of ribs, thermophysics properties of coolant liquid (kerosene) and thermal properties of rib material.

With the results of thermal heat flux and ribs design it is possible to calculate the temperature distribution in the shells of combustion chamber using Eq. (6) and Eq. (7).

Figure 5 shows the inner shell temperature distribution for two materials: copper alloy and stainless steel.

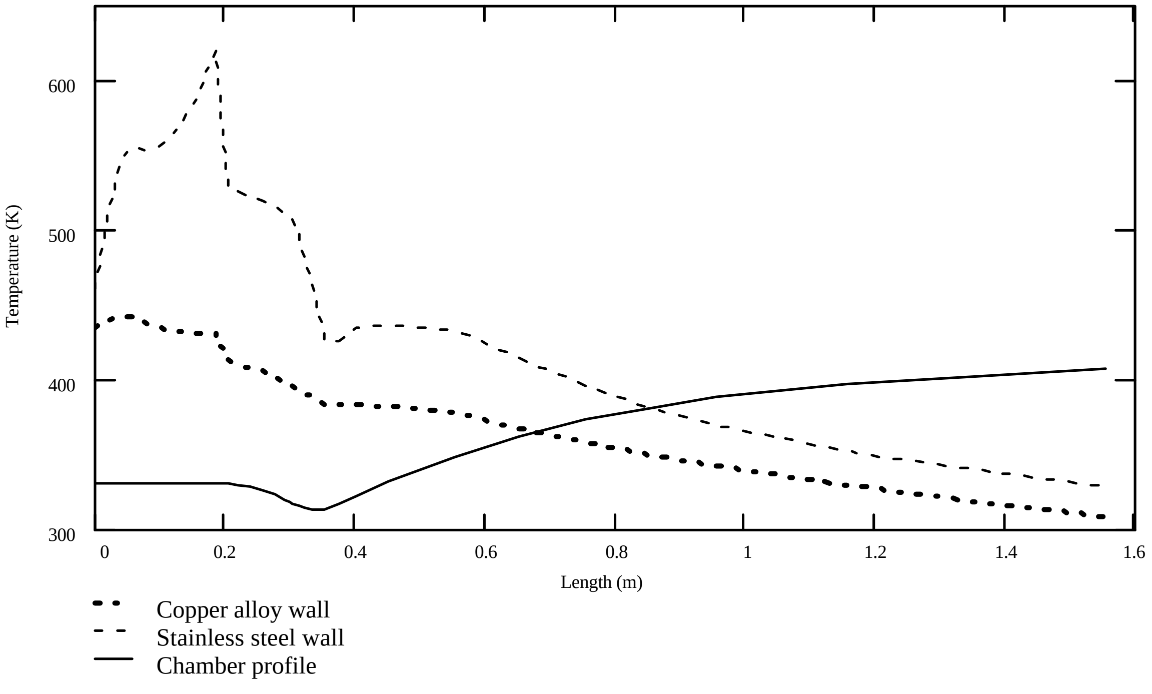

Figure 5 - Inner shell temperature distribution.

Because of the low thermal conductivity of the stainless steel, the inner shell wall temperature of stainless steel is greater than those of copper alloy. Usually, high conductivity is preferred because it reduces the wall temperature for a given heat flux. If the coolant undergoes to nucleate boiling or is subjected to decomposition, however, high wall conductivity may not be advantageous, because of the resulting lower gas side wall temperatures and higher heat flux.

Knowing the material temperature it is possible to determine its strain level, and then, the carrying capacity of the chamber case.

After calculation using Eq. (8) (Almeida, 1998, Santana Junior, 1998), the diagram of relation between gas pressure and radial elongation $P_g = P_g (\Delta R)$, (Fig.6) can be obtained. On these curves it is possible to find the point of working pressure (P_{ch}) and of limiting pressure $p_{g,u}$, and determine the safety factor by the loading carrying capacity of the shells.

It must be point out on curve $P_g = P_g (\Delta R)$ of Fig. 6 the points C_{ss} and C_{ca}, where the straight line drawn from the origin of co-ordinates is tangent to the curve. This point determines the beginning of the large shell deformations, which are dangerous concerning to the change in geometrical shell dimensions, as well as to their strength. The pressure corresponding to point C will be the so-called limit pressure $P_{g,u}$ (Oliveira, 1998).

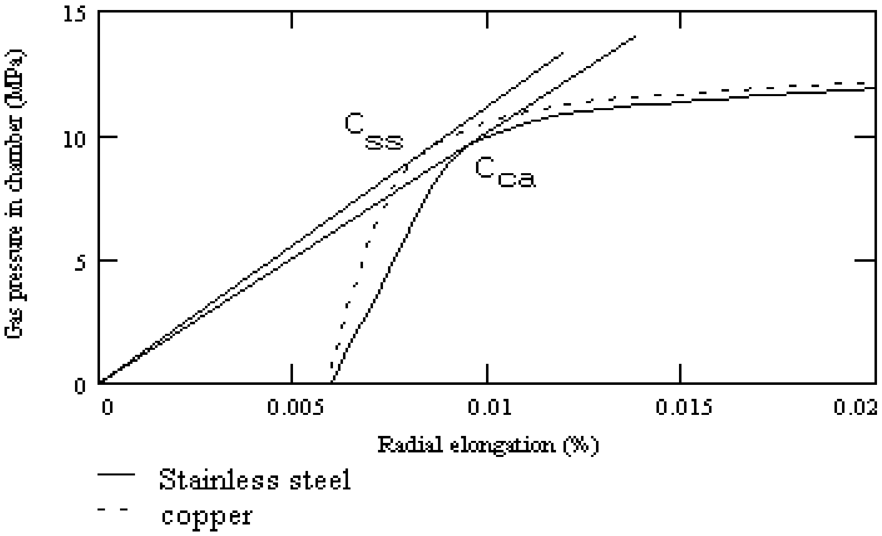

Figure 6 - Gas pressure and shell stress for inner shell made of stainless steel and copper alloy.

The safety factor by the load carrying capacity of shells is the ratio of the limit gas pressure $P_{g,u}$ to the working pressure P_{ch}.

Usually it is adopted a value of safety factor on load carrying capacity within the range n=1.2 to 1.5. In case of unsatisfactory strength it is necessary to change the thickness or the material of outer shell (Oliveira, 1998).

In this work, it was considered two materials for inner shell: copper alloy with Russian designation bpX0,8 equivalent to UNS – C18200 (Cu plus 0.4 to 0.7 of Cr) and stainless steel with Russian designation 12X18H9T equivalent to AISI/SAE 304 (C=0.12, Si=0.8-1.0, Mn=1-2, Cr=17-19, Ni=8.0-9.5) (Zintchouk, 1997).

These materials are the most usual for construction of this type of combustion chamber in Russia, because all properties of these materials are known, they are cheap and they have good mechanical properties.

The methodological procedure developed here could be applied for different combinations of materials.

Table 2 shows the summary of calculation results for cylindrical part of combustion chamber, using copper alloy or stainless steel for inner shell. The geometric characteristics of construction of combustion chamber, in both cases, are the same for good comparison. With these analysis it is possible to choose the best material for the inner shell wall taking into consideration the safety factor and specific mass.

Despite copper alloy has high thermal conductivity and the inner shell made with this material has lower temperature, the inner shell made of stainless steel has a little more value of safety margin. For the same dimensions, the combustion chamber made of stainless steel has lower mass than copper alloy, one important factor for construction of aerospace components. The increase of the fuel temperature in cooling jacket is approximately the same in both cases.

Table 2. Calculation results summary

Material	Average temp. of inner shell (K)	Average temp. of outer shell (K)	δ_{inner} (mm)	Δ_{outer} (mm)	ΔTemp. fuel	Specific mass (g/cm^3)	λ_{inner} (W/mK)	Safety factor
Copper	396	340	1.5	2.5	128	8.9	290	1.5
Steel	478	338	1.5	2.5	125	7.9	22	1.6

7. CONCLUSION

The methodological procedure presented in this work shows a way to calculate the heat flux and organize the heat protection of the inner shell of a combustion chamber.

With this procedure, it is possible to calculate the wall temperature distribution, important information for calculation of the load capacity of the structure. Based on load capacity calculation it is possible to select the best material for shells taking into consideration the safety factor and specific mass minimization criteria.

In a numerical example it was shown the advantages of stainless steel over copper alloy for construction of the inner shell wall for this type of combustion chamber.

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