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Application of Eight-Shaped Propellant Charge in the Ejection Seat Rocket Motor

Milorad Savković, PhD (Eng)[1)]

In this paper a solution for cylindrical propellant charge with the cross-section in the shape of number eight has been analyzed. A mathematical expression for calculating the burning surface area change as a function of web burned and the charge characteristic values are included. A diagram with a propellant grain perimeter change as a function of the geometric values defining the charge has been included as well. As an example concerning a solution for the eight-shaped propellant charge of the ejection seat rocket motor, an inner-ballistic calculation of thrust is presented. The calculation results have been compared to the thrust measurement results obtained during static testing of an experimental rocket motor. The experimental and calculated thrust values have shown a good agreement.

Key words: **rocket motor, propellant charge, burning surface, thrust, ejection seat, pilot seat.**

Introduction

THE thrust of a solid propellant rocket motor is a vector the intensity of which depends on the pressure inside the rocket chamber and the nozzle characteristics. The change of pressure in time, or a pressure-time function, depends mostly on the change of: $m(t)$ - mass flow of combustion products of the propellant charge, A_t - critical cross-section of the nozzle and C^* - characteristic rate. The mass flow of gas combustion products is a function of change: $A_b(t)$ – burning surface area, $r(t)$ – burning rate and ρ_p density of propellant [1,2,3,4 and 5]. The characteristics of the pressure-time curve depend on the process of the burning surface area change in time, or the web burned $y(t)$, because the web burned is a time function, and in a given moment of time the burning surface area has a specific value $A_b(t)=A_b(y(t))$. Hence the importance of determining dependence of the burning surface area A_b from the web burned y for every analyzed propellant charge.

A high thrust intensity value is achieved in a rocket motor of large mass flow which is possible in propellant charges with large burning surface or in propellant charges with a sufficient burning rate. However, in order to achieve a total required impulse of the rocket motor, it is necessary for thrust to have certain intensity in a given time period, which occurs when a propellant charge has an adequate mass with a big enough thickness of the burning layer, W – web.

Combustion of an eight – shaped hollow cylinder

The special case of combustion of a hollow cylindrical uninhibited charge is a charge with two circular holes at the cross-section (Fig.1). During combustion this charge keeps its shape of number eight until slivers form (Fig.2). A sliver has negligible volume, or mass [6]. This propellant charge generally burns in the radial as well as in the axial direction; however, in a great number of multi-perforated grains the size of the frontal surface is negligible so that this propellant charge is most commonly considered to be a solution with a radial burning pattern. Radial burning has a relatively neutral character of the burning surface area change, and since it is dominant, this charge is said to have neutral burning. The flow of combustion products occurs within and around the propellant charge; therefore, it is necessary to put the mesh on the nozzle intake. The diameters of mesh holes should be smaller than the outer dimensions of the propellant charge at the end of burning, i.e. before slivers form, and for this propellant charge it is $(a + R_1 + R_2)$. In the case of multi-perforated propellant grains in the shape of number eight, a high coefficient of filling the combustion chamber is achieved. As for multi-perforated propellant charge grains, it is not necessary to protect the chamber from hot combustion products since the operational time of the rocket motor is short.

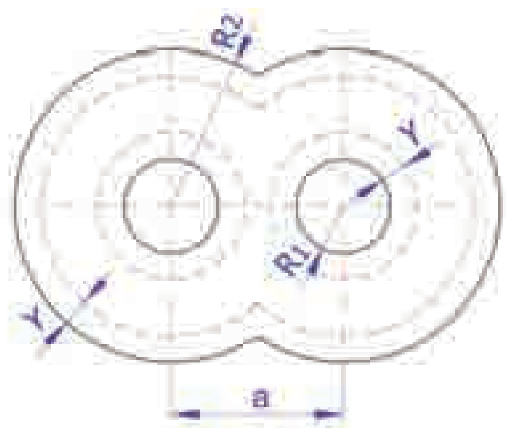

Figure 1. Cross-section of propellant grains in the shape of number eight

A propellant grain with the cross-section in the shape of number eight (Fig.1) is defined by four geometric dimensions as follows:

[1)] Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

- R_1 – inner radius,
- R_2 – outer radius,
- A – channel distance,
- L – propellant grain length.

Production of propellant charge

The final operation in developing double-based propellants, out of which propellant grains are obtained, is extrusion with a press with special tools. Its schematic presentation is given in Fig.2.

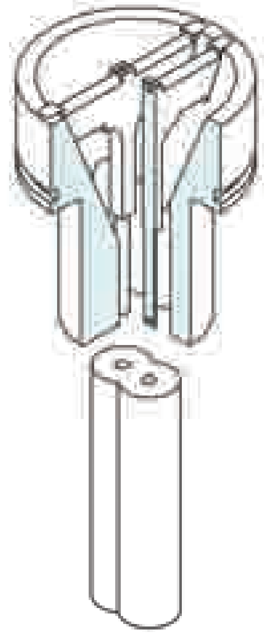

Figure 2. Section of a gunpowder pressure tool

Change of the burning surface area

The burning surface area of propellant grain as a function of the web burned (y) is defined by the following relation:

$$A_b = P_r * (L_0 - 2 * y) + 2 * A,$$

with:
- P_r – perimeter
- A – frontal area and
- L_0 – initial length of propellant grain.

The change of the eight – shaped propellant grain perimeter $P_r(y)$ as a function of the burned fraction (Fig.3) is an increasing or mildly decreasing function depending on the geometric values of the grain cross-section (Fig.4) [6].

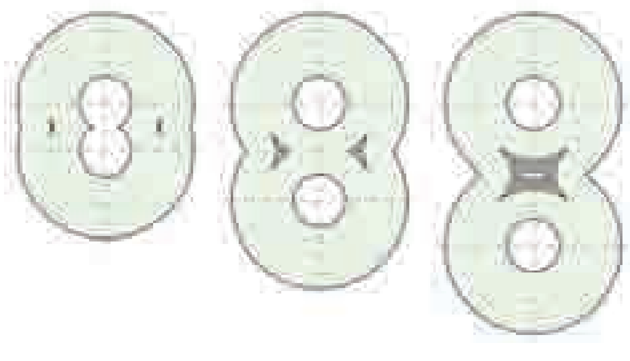

Figure 3. Change of the grain perimeter for different channel distances

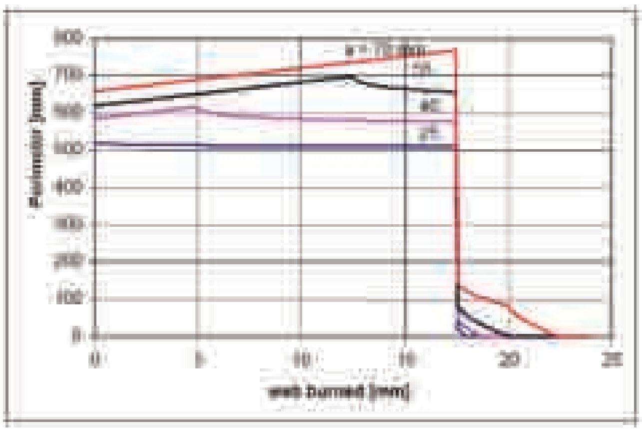

Figure 4. Perimeter of the grain with the cross-section of R_1=15 and R_2=50 mm for different channel distance a values

The change of the burning surface area as a function of the burned arch can be slightly progressive and regressive depending on the relation between the geometric values of the cross-section and the propellant grain length (Fig.5). The burning surface area is directly proportional to the grain length which decreases during burning. This effect occurs more frequently in shorter 8-shaped grains.

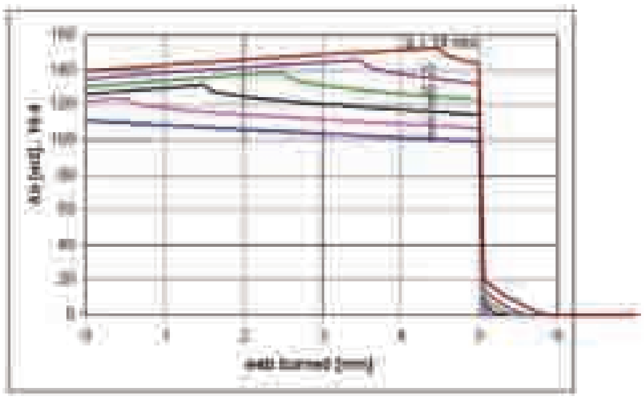

Figure 5. Burning surface area of the grein with the cross-section of R_1=2.5, R_2=12.5 and L_0=100 mm

Characteristics of the rocket motor with the eight-shaped propellant charge

One solution for a rocket motor with a multi-perforated propellant grain in a form of number eight is the rocket motor of the Mig-29 aircraft ejection seat [7]. The experimental rocket motor design in Fig.6 is based on the recorded dimensions of the original solution for the Mig-29 aircraft ejection seat.

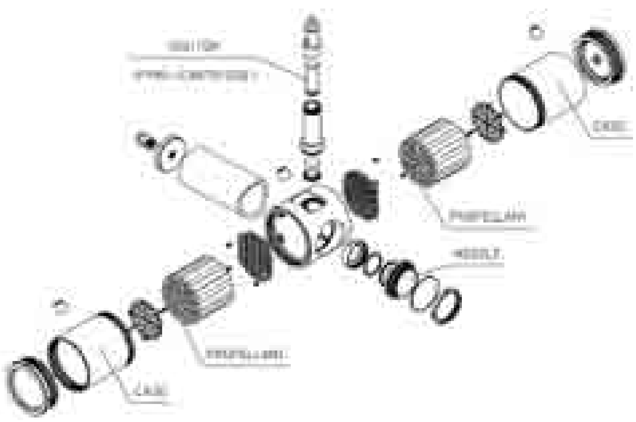

Figure 6. Parts of an experimental rocket motor

A two-chambered experimental motor is a replica of an original solution of the ejection seat rocket motor; it is used in a number of experiments to measure thrust and pressure. Since the analysis of the original solution has shown that thrust occurs under particular angle in space in relation to the motor axis, the thrust measuring location is thus determined to measure the resulting thrust power [7]. The basic characteristics of the rocket motor are given in Tables 1 and 2.

Table 1. Basic dimensions of the rocket motor

Dimensions	∅ 160 x 445 mm
Inner diameter of the chamber	∅ 129 mm
Critical section of the nozzle	∅ 47 mm
Exhaust section of the nozzle	∅ 68 mm
Semi angle of the nozzle divergent part	9°
Chamber free volume	2,32 dm^3
Propellant surface	6 500 cm^2

Table 2. Geometric relations in the rocket motor

Propellant surface– Critical section ratio, coefficient *Kn*	$A_b / A_t = Kn = 375$
Inner channel burning surface area in a single grain – Channel flow section ratio	$Kiu = 117$
Relation between the outer burning surface of the propellant grain and the flow section between the grain and the chamber	$Kis = 94$

The propellant charge used in the rocket motor is a double-perforated propellant grain with the cross-section in the shape of number eight (Fig.7), with the dimensions given in Table 3. The charge consists of 50 grains, with 25 grains in each of two chambers.

Figure 7. Propellant charge grains

Table 3. Mass and dimensions of the propellant charge grains

Length of the grain	$L = 117,5\,\text{mm}$
Outer radius	$R_2 = 8,8\,\text{mm}$
Inner radius	$R_1 = 2,1\,\text{mm}$
Distance between the channels	$a = 6,4\,\text{mm}$
Mass of the propellant charge with 50 grains	$m = 3,73\,\text{kg}$

Theoretical determination of the inner-ballistic characteristics of the rocket motor

Theoretical determination of the inner-ballistic characteristics of the rocket motor with the designed and in-country made eight-shaped propellant grain made out of double-based rocket propellant [8 and 9], is performed on a computer with a modified program from [2] and mathematical expressions for determining the burning surface area in [6], together with new expressions that define the burning surface area and the sliver burning time period. The program includes quasi-stationary combustion while neglecting the influence of erosive burning and flow in the chamber, together with pressure falling on the intake meshes and with decreasing theoretical characteristic burning rate (C^*) and the thrust coefficient (C_F). The thrust $F(t)$ and the chamber pressure $P(t)$ are determined from the following relations:

$$F(t) = \lambda \cdot \eta_F \cdot C_F \cdot A_t \cdot P(t)$$

$$P(t) = \eta_C \cdot C^* \cdot \rho \cdot \frac{A_b(y)}{A_t} \cdot r(t)$$

$$r(t) = a \cdot P(t)^n$$

$$y = y^* + r(t) \cdot \Delta t$$

were:

- y, y^* - web burned of the propellant charge in the given moment (t) and the previous time step (t-Δt) ,
- Δt - time step,
- $r(t)$ – propellant charge burning rate without the influence of erosive burning,
- a, n - constants in the empirical expression for the burning rate (form $a*P^n$). The constants are determined by the Least Squares Method from the experiments with double-based rocket propellant in FLS engines with appropriate *Kn*.
- ρ - density of the propellant charge solid phase, which in this case is 1660 kg/m3,
- $A_b(y)$ - geometric dependence of the burning surface area change from the size of burned arch. The mathematical relations are given in [6],
- A_t - area of critical section of the rocket motor nozzle, given in Table 1,
- C^* - theoretical burning rate for double-based rocket propellant, which is determined on the basis of inner ballistic characteristics of the propellant charge: μ = 23.6 kg/kmol – molecular mass, Tc = 2254,5 K – burning temperature, k = 1.2 specific heat ratio,
- C_F - theoretical value of the thrust coefficient for the rocket motor nozzle; the values for environmental pressure of one normal atmosphere were used for its determination, as well as the pressure on the exhaust nozzle determined by the iterative procedure and based on intake nozzle pressure and the degree of expansion in the divergent part of the nozzle, i.e. the given ratio of the exhaust section and the critical section of the nozzle (A_e/A_t),
- λ - loss coefficient determined by unparallel outflow of combustion gases from the nozzle, given by a value of 0.5 * (1 + cosα), α is a semi angle of the divergent part of the nozzle, with a value of 9° from Table 1,
- η_F, η_C - coefficients of the reduction of theoretical values for thrust coefficient and characteristic rate, with values 0.95 and 0.99, respectively. These values have been determined by experience.

The mass of the propellant charge consisting of 50 propellant grains with 8-shaped cross-section and dimensions given in Table 3 is determined theoretically and it is 3.766 kg with the total impulse of *Itot* = 702 daN*s, which is very similar to the experimentally obtained values. The obtained value for thrust $F(t)$ is presented with experimentally obtained values in the diagram in Fig.8.

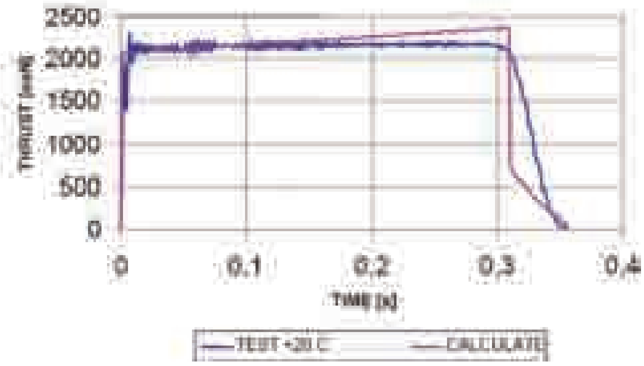

Figure 8. Calculated and experimental dependence $F(t)$ for 8-shaped propellant charge

Conclusion

The tests performed on original samples taken from 8-shaped propellant grains for the rocket motor of the Mig-29 aircraft [7] ejection seat have helped with defining the initial technical requirements for developing in-country produced propellant charge, while the analysis of built-in materials and pyrotechnical elements of the original parts of the ejection seat rocket motor has enabled theoretical calculation, analysis, construction and production of corresponding tools and experimental rocket motors for static experiments with inner-ballistic characteristics. The obtained results of in-country made propellant charges with grains in the shape of number eight in cross-section show that it is possible to produce propellant charges of satisfactory quality [8,9 and 10].

The mass, shape and dimension, as well as physical, mechanical, energy and kinetic properties of propellant charges provide requested ballistic performances of a defined rocket motor, whereby the procedure of production is safe, and the product (propellant charge) is of required quality and reproductibility.

Theoretical thrust determination gives satisfactory results and is in good accordance with experimentally obtained values.

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Primena pogonskog punjenja u obliku osmice u raketnom motoru pilotskog sedišta

U radu je analizirano rešenje cilindričnog pogonskog punjenja sa poprečnim presekom u obliku osmice. Dat je matematički izraz za određivanje promene površine sagorevanja u funkciji sagorelog svoda i karakterističnih veličina koje određuju to punjenje. Prikazan je dijagram promene perimetra barutnog zrna u funkciji geometrijskih veličina koje karakterišu punjenje. Za jedan primer izvedenog rešenja raketnog motora pilotskog sedišta sa pogonskim punjenjem u obliku osmice, predstavljen je unutrašnje balistički proračun potiska. Rezultati proračuna su upoređeni sa rezultatima merenja potiska pri statičkim opitima u eksperimentalnom raketnom motoru. Dobijeno je dobro slaganje eksperimentalnih i proračunatih vrednosti potiska raketnog motora.

Ključne reči: **raketni motor, pogonsko punjenje, površina sagorevanja, potisak, sedište za katapultiranje, pilotsko sedište.**

Применение приводного заряда в виде восмёрки в ракетном двигателе сиденья лётчика

В настоящей работе анализировано решение цилиндрического приводного заряда с поперечным разрезом в виде восмёрки. Здесь показано математическое выражение для предозначения изменения поверхности сгорания в функции сгоревшего свода и характерных величин определяющих этот заряд. Тоже показана и диаграмма изменения периметра боевого заряда в функции геометрических величин характеризирующих заряд. Для одного примера выведённого решения ракетного двигателя сиденья лётчика с приводным

зарядом в виде восмёрки представлено внутренее баллистическое вычисление давления. Результаты вычисления сопоставлены с результатами измерения давления при статическими опытами в экспериментальном ракетном двигателе и получено хорошее согласовывание экспериментальных и вычисленных значений давления ракетного двигателя.

Ключевые слова: ракетный двигатель, приводной заряд, поверхность сгорания, тяга (давление), катапультируемое кресло, сиденье лётчика.

Emploi de la charge propulsive en forme du numéro huit chez le moteur à fusée du siège de pilote

Dans ce papier on a analysé la solution de la charge propulsive cylindrique à l'intersection transversale en forme du numéro huit. L'expression mathématique pour la détermination du changement de la surface de combustion en fonction de la voûte brûlée et les valeurs caractéristiques qui déterminent cette charge ont été données. On a présenté le diagramme du changement du périmètre du grain de poudre en fonction des valeurs géométriques qui caractérisent la charge. Comme exemple de la solution du moteur à fusée du siège de pilote à charge propulsive en forme du numéro huit, on a présenté le calcul balistique intérieur de la poussée. Les résultats de ce calcul ont été comparés aux résultats des mesurages de la poussée pendant les essais statiques chez le moteur à fusée expérimental. On a obtenu un bon accord des valeurs expérimentales et calculées de la poussée du moteur à fusée.

Mots clés: **moteur à fusée, charge propulsive, surface de combustion , poussée, siège catapultable, siège de pilote.**