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# EXPERIMENTAL STUDY OF FRACTURED PROPELLANT INFLUENCE ON THE IMPULSE ROCKET MOTOR SAFETY

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***Abstract:*** *Impulse rocket motors are group of solid propellant rocket motors, which main characteristic is extremely short operating time. The application of these rocket motors is of particular importance for missile weapons as busters or control thrusters. The total operating time of such rocket motor is in order of ten milliseconds and that complex processes are highly non-stationary. In the anti-tank rockets the impulse motor role is to accelerate the rocket to a certain velocity in a very short time, during the rocket's motion through the launch tube, and to provide the necessary ballistic characteristics (dynamic stability, greater range, shorter flight time to the target and the less dispersion of hits). Reliability of this type of rocket motors is of crucial importance in terms of operation safety. This paper presents an experimental study of how fractured propellant charge affects rocket motor performances and safety.*

***Keywords:*** *impulse rocket motor, propellant, fracture, propulsion, pressure.*

## 1. INTRODUCTION

Rocket missiles are launched by a rocket motor which is an integral part of the projectile. In order for a rocket to accelerate to a certain veocity and to be able to maintain that velocity, overcoming air drag and gravity, it is necessary to generate a force called thrust [1-11].

Thrust is the reaction force that occurs when a certain mass is ejected from the propulsion group. The separation of mass is most often realized through the outflow of gases (gaseous products of combustion) where the direction of the generated thrust force is opposite to the direction of outflow of gases [1-10].

In order to ensure the generation of gases, it is necessary to have a certain source of energy. Chemical energy contained in solid propellant is converted into thermal energy through a propulsion reaction which is accompanied by the release of energy. Propulsion is performed in the propulsion chamber where the chemical energy is transformed into heat, while the thermal energy is converted into kinetic energy through the rocket motor nozzle [1-10].

In the anti-tank weapons, all energy required to solve the ballistic problem is provided by the rocket motor propulsion. The projectile of such a weapon must have a basic impulse rocket motor, which achieves initial velocity at the muzzle. Rocket can also have an additional rocket propulsion system that is activated during flight on the trajectory and improves its ballistic characteristics [12].

This type of weapon is used for shooting at short ranges (200 m to 500 m) by launching from the rocket operator's shoulder, therefore the reliability and safety of such systems must be at a very high level.

As the most common form of propellant for man-portable anti-tank rocket launcher are multiple small diameter thin tubes with. Such a propellant geometry is the most favorable because of:

1. definition and reproducibility of manufacturing

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technology,
2. combustion without significant slivers,
3. elegant solution of propellants integration inside the rocket motor chamber and
4. control benefits [1].

The basic internal – ballistics (IB) parameters of the rocket motor are maximum pressure, mean effective propulsion time and total impulse.

## 2. THEORETICAL BASIS

The rocket motor operating regime calculation can be conducted using IB coefficients that can be calculated theoretically, experimentally or semi-empirically (Figure 1) [1-2].

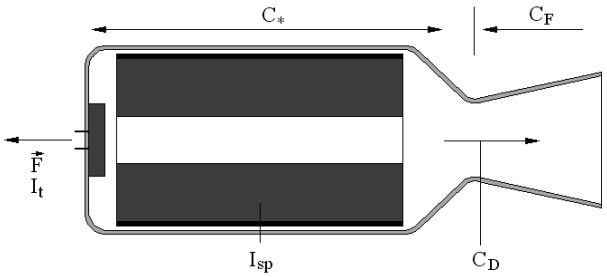



**Figure 1.** Basic model of propulsion product flow through the nozzle and characteristic process parameters [2].

Thrust of the rocket motor can be calculated based on the consideration of the motion of a body of variable mass (Meschersk's equation) and it is determined by the expression:

$$F = \dot{m}v_e + \left(p_e - p_a\right)A_e \tag{1}$$

where are:

$\dot{m}$ - mass flow rate,
$v_e$ - nozzle exit velocity,
$p_e$ – nozzle exit pressure,
$p_a$ – atmospheric pressure and
$A_e$ – nozzle exit area [1-2].

Nozzle exit pressure can be differentiated which depends on the difference ($p_e$ - $p_a$):

- $p_e > p_a$ → under - expanded,
- $p_e = p_a$ → fully - expanded,
- $p_e < p_a$ → over – expanded [1-2].

Total impulse is the integral of thrust curve over the total operating time period τ and it can be calculated according to the equation:

$$I_t = \int_0^{\tau} F(t)dt \tag{2}$$

where is: τ – rocket motor operating time [1-2].

The specific impulse represents the thrust per unit propellants mass. Also, the specific impulse can be expressed as the ratio between the thrust coefficient $c_F$ and the discharge coefficient $c_D$. It can be calculated according to the equation [1-2]:

$$I_{sp} = \frac{F}{\dot{m}} = \frac{I_t}{m} = \frac{C_F}{C_D} \tag{3}$$

The thrust coefficient represents efficiency of thrust generation, regarding nozzle flow efficiency and is dimensionless. It can be calculated according to the form:

$$c_F = \frac{F}{p_c A_t} \tag{4}$$

where are:
$p_c$ – pressure of propulsion products,
$A_t$ – specific nozzle throat area [1-2].

Discharge coefficient defines mass flow rate $\dot{m}$ trough throat area $A_t$, inducted with products pressure energy in chamber. It can be calculated according to the form:

$$c_D = \frac{\dot{m}}{p_c A_t} = \sqrt{\frac{\kappa}{RT_c}\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} \tag{5}$$

where are:
$\kappa$ – heat capacity ratio,
$R$ – gas constant,
$T_c$ – chamber temperature [1-2].

The characteristic flow rate is a function of the propellant characteristics and propulsion chamber design, and it is independent of the nozzle characteristics. It can be calculated according to the equation [1-2]:

$$c^* = \frac{p_c \cdot A_t}{\dot{m}} = \frac{1}{c_D} \tag{6}$$

The output velocity of the propulsion product is calculated according to the equation [1-2]:

$$v_e = \sqrt{\frac{2\kappa}{\kappa-1}RT_c\left(1-\bar{p}_e^{\frac{\kappa-1}{\kappa}}\right)} \tag{7}$$

Propulsion of the solid propellants takes place on the propulsion surface. Propulsion rate $r$ is defined as a distance that crosses the flame front perpendicular to the free charging surface in a unit of time.

Pressure has a dominant influence on the value of propulsion rates and this dependence is expressed in form of Saint – Robert's law:

$$r = bp^n \tag{8}$$

where are: $b$ – initial charge temperature function and $n$ – the propulsion index which is a characteristic of rocket propellant and is always less than 1 [1-2].

Only in the case of propellant with frontal propulsion, the discharge of gases is carried out normally on the propulsion surface. In other cases, the gases move parallel to the propulsion surface, which affects the propulsion rate, which increases with increasing gas velocity along

the propulsion surface. This phenomenon is called erosive propulsion [1-2] [13].

The geometry of the nozzle (flow sections, number of nozzles and their position) is defined within the ballistic calculation of the rocket motor. During the flow of gaseous products through the nozzle, erosion of the nozzle neck can occur, which causes a reduction in the total impulse. Due to the expansion of the nozzle neck caused by erosion, the pressure drops and the operation of the rocket motor is prolonged. The erosion process occurs when the surface temperature of the nozzle neck reaches the melting temperature of the nozzle material. The most intense heat transfer from the propulsion surface to the flow cross-sectional surface is in the nozzle throat, so the melting temperature is reached closest there [1-2] [13].

The degree of expansion *(ε)* of the nozzle is a constant geometric characteristic that depends on the ratio of specific heats of the propellant and the ratio of pressures in the chamber and at the outlet of the nozzle. The calculation of the nozzle strives for the complete expansion of gases, with the aim of achieving the highest energy utilization. This is achieved if the pressure at the nozzle outlet is equal to the ambient pressure. The degree of expansion of the nozzle is determined by the equation [1-2]:

$$\varepsilon = \frac{A_e}{A_t} = \frac{\left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \cdot \left(\frac{p_c}{p_e}\right)^{\frac{1}{\kappa}}}{\left\{\frac{\kappa+1}{\kappa-1} \cdot \left[1-\left(\frac{p_c}{p_e}\right)^{\frac{1-\kappa}{\kappa}}\right]\right\}^{\frac{1}{2}}} \qquad (9)$$

The chamber of the rocket motor is cylindrical shape, made of high-quality steel capable of withstanding the pressure of propulsion gases and their erosive action. The bottom of the rocket motor connects with a warhead over the thread. A stabilizer is set on the rear end of the rocket motor chamber.

## 3. EXPERIMENT

Since the man-portable anti-tank rocket is launched from the operators' shoulder, the rocket motor's operating time must be completed while the motor is in the tube. Such weapons are designed with a maximum rocket motor operation time of around $t_{max} \leq 18$ ms and the total impulse of around $I_t \approx 85$daNs [1]. For this type od weapons factor of safety must be maximum. The aim of this experiments was to show how fractured propellant influence on [5] [14]:

1. safety of the rocket operator,
2. performances of the impulse rocket motor, especially on pressure which is the most important rocket motor parameter in terms of safety.

The impulse rocket motor chamber is designed to have high mechanical properties. The high-strength aluminum alloy chambers usually can withstand pressure values of 1000 bar or more, which has been confirmed by experiments. The maximum pressure of the propulsion products in the rocket motor chamber is between 500 bar and 600 bar, and this is in case when propellant was previously exposed to extremely high temperatures (+50°C) for a period of time. In the case of ambient temperature (+20°C), the maximum pressure of combustion products is around 400 bar.

In this experiment two expected potentially critical failures are examined:

1. Due to the deterioration of the mechanical characteristics of the propellant and mechanical operational loads, different degree of fragmentation of certain number of tubes potentially may occur;
2. The bounded joint of the tubes to the grain holder may fail, which will lead to the ejection of certain number of the tubes through the nozzle.

For purposes of the experiments, two mentioned types of failure are simulated: some of propellant tubes were intentionally fractured or unbounded form the grain holder, in order to simulate propellant material deterioration, protentional damages of the rocket, bad exploitation conditions, etc. Since the propellant fractures cannot be easy detected, the aim of the experiment was to show whether such a flaw could cause a critical increase in pressure gradient [15] and the destruction of the rocket motor chamber, endangering the operator's safety.

Before realization of this experiment, propellant and the pyrotechnic mixture were tested by the method of vacuum stability and compatibility, described elsewhere [16].

The static tests of experimental rocket motors were realized on the test bench. First set of experiments were carried out at ambient temperature of +20°C, with intentionally fractured propellant. Propellant tubes are shredded to pieces 5×10 mm, and are shown in Figure 2. Shredded pieces of tubes are freely poured into chamber.



**Figure 2.** Intentionally fractured propellants tubes.

Second set of experiments are conducted with propellant grains with sertain percent of not bounded tubes, which are freely placed into the chamber as free-standing grains.

All static tests were carried out in experimental rocket motors, which free volume fully corresponds to a flight rocket motor. Changes in the pressure of the combustion products inside the chamber was measured during the

rocket motor operating time.

### Experiment 1. Tube fracture.

In the first experiment, 4 of 37 or around 10% of the total number of propellant tubes were fractured. With such damage to the propellant, it was shown that the maximum pressure of the combustion products reaches over 350 bar, while operating time of the rocket motor is several milliseconds shorter than the projected operating time. Figure 3 shows diagram of the motor chamber pressure-time function.

### Experiment 2. Tube fracture.

In the second experiment, 10 of 37 or around 27% of the total number of propellant tubes were fractured. Maximum pressure of the combustion products reaches 420 bar, while operating time of the rocket motor is similar like in the first experiment.

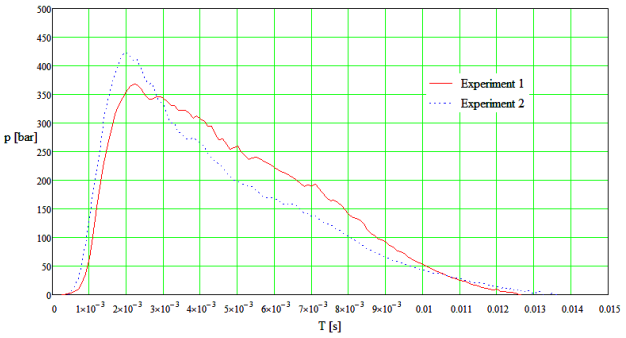



**Figure 3.** The rocket motor chamber pressure-time curves for experiments 1 and 2 with fracture tube.

The pressure-time curves are significantly changed compared to regular tests. The maximum pressure is increased, the pressure integral is reduced due to the ejection of unburned pieces of propellant, and the operating time is extended due to the pressure drop in the last stage.

Based on these two experiments, it can be concluded that a very significant fragmentation of the propellant grain is required in order to achieve a greater increase in pressure in the chamber. This type of propellant grain anomaly can lead to the motor failure only with tubes fragmentation in smaller pieces and a larger percentage of tubes.

### Experiment 3. Joint failure.

In the third experiment, 8 of 37 or around 20% of the total number of propellant tubes were unbounded – free-standing. The maximum pressure of the combustion products reaches 340 bar, while operating time of the rocket motor is extended including significant secondary pressure peek. In this motor configuration complex internal ballistics phenomena are present, including movement of free-standing tubes. Free standing tubes are partially trapped in initial configuration, standing between chamber walls and bounded tubs. During the propellant combustion, products flow cause ejecting force on the free-standing tubes and they can randomly leave the motor partially burned. During the tube's passing through the nozzle, throat choking can occur, which can be explanation for secondary peek in pressure diagram.

### Experiment 4. Joint failure.

In this experiment, 16 of 37 or around 37% of the total number of propellants tubes were unbounded. The maximum pressure of the combustion products reaches 380 bar, while operating time of the rocket motor is stilly extended. In this case two smaller secondary pressure peeks can be noticed. In this configuration free standing tubes are not rigidly confined like in previous experiment, so probably throat choking is less distinct.

### Experiment 5. Joint failure.

In the last experiment, 22 of 37 or around 60% of the total number of propellants tubes were unbounded. The maximum pressure of the combustion products reaches 400 bar, while operating time of the rocket motor is also stilly extended, without secondary pressure peeks.

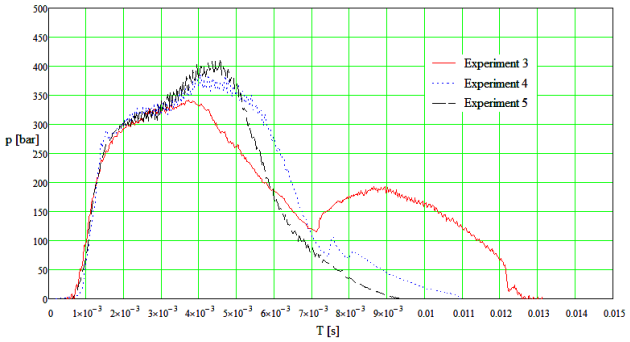



**Figure 4.** The rocket motor chamber pressure-time curves for experiments 3, 4 and 5.

The pressure-time curves are significantly changed in comparison to regular tests. The maximum pressure is increased, the pressure integral is reduced due to the unburned grains ejection. Assuming that every unburned grain ejection is causing some level of throat choking, configuration, type and percentage of ejecting tubes cause pressure increase which differ pressure diagram.

## 5. CONCLUSION

In this paper, an experimental study of fractured propellant influence on the impulse rocket motor safety was performed. From the IB parameters of the impulse rocket motor, the emphasis is placed on the maximum pressure of propulsion products inside the chamber as the most important safety parameter of the motor.

Five static tests were carried out with different amounts of fractured propellant tubes in order to check the safety impact on the rocket operator, as well as to check the changes in the pressure gradient depending of the increase in the propulsion surface.

In all of the five experiments, pressure gradient of the propulsion products was not significantly increased and did not exceed 415 bar (even in the case of severe damage to the propellant tubes - up to 60%), which corresponds to the nominal maximum pressure of the propulsion

products.

The operating regime of the rocket motor was not correct, which affects the operating time and which would potentially affect the flight parameters of the rocket, but the requirements during the desing of the weapon guarantee the safety of the rocket operator even in case of major damage to the propellant.

Nowadays, modern variants of man-portable anti-tank rocket launchers are in use in current warfares. An experimental study of this type provides a clear insight into the importance of safety over functionality in weapon systems that are launched by a rocket operator, in cases of unforeseen failures.

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