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COMPARATIVE STUDY OF AN ADDITIONAL OXIDIZER CHARGE EFFECT ON SELECTED OPERATIONAL CHARACTERISTICS OF A SOLID-FUEL ROCKET ENGINE

BADANIA PORÓWNAWCZE WPŁYWU ŁADUNKU DODATKOWEGO UTLENIACZA NA WYBRANE PARAMETRY PRACY SILNIKA RAKIETOWEGO NA PALIWO STAŁE

A b s t r a c t

This paper describes a part of research related to the elimination of adverse phenomenon involving the occurrence of a negative oxygen balance of combustion products of missile engines during their firing from aircrafts. It also presents the results of comparative tests of rocket engines equipped with an additional oxidizer charge.

Keywords: oxygen balance, rocket engine, aircraft, oxidizer charge

S t r e s z c z e n i e

Artykuł opisuje fragment badań związanych z eliminowaniem niekorzystnego zjawiska polegającego na występowaniu ujemnego bilansu tlenowego produktów spalania silników pocisków rakietowych podczas ich odpalania ze statków powietrznych. Przedstawiono również wyniki porównawcze badań silników rakietowych wyposażonych w dodatkowy ładunek utleniacza.

Słowa kluczowe: bilans tlenowy, silnik rakietowy, statek powietrzny, utleniacz

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1. Introduction

Intensive development of air force weapons technology forces the integration of the newly formed systems with the systems already used on aircrafts. This involves conducting a series of tests designed to confirm the efficiency and safety of use of a given armament system [15].

One of the many tested aircraft characteristics of missiles is their impact on the carrier. It is required that fired missiles do not hinder the flight of the aircraft which carries them and do not negatively affect the work of other on-board systems [5, 8, 9]. One of the cases of adverse effects of the fired rocket on the carrier is the impact of the powder gas stream of the rocket engine on the operation of aircraft turbine engines, which can lead to, among others, the engine's compressor stall [4, 13].

This phenomenon was encountered in the case of rockets with engines powered with high--energy solid fuel with a negative oxygen balance. The products of such fuels combustion are rich in unburned carbon and hydrogen molecules. Moreover, their temperature is around 1200 K [3]. The result is their immediate secondary burning out in the atmosphere behind an engine jet, which causes the lack of oxygen behind the flying rocket [2]. In the case of the firing of missiles series in flight, a zone of heated air deprived of oxygen propagates. Its effect on the aircraft may cause compressor stall, which may lead to the carrier's engine stall [6, 14].

In order to prevent the compressor stall, works on the engine missile modification were undertaken. However, due to economic reasons, minor design changes that would not alter significantly aerodynamic and ballistic characteristics of the missile were allowed. Therefore, it was decided to undertake works aimed at changing the oxygen balance of powder gases of the rocket engine without modifications to the powder pulp composition.

2. Theoretical analysis

The introduction of the oxidizer charge into the combustion chamber changes the oxygen balance of rocket fuel products. This method allows for changing the energy characteristics of the rocket engine combustion products (mainly temperature) without modifying the structure of the essential engine units and components like a chamber, a jet, an igniter and does not substantially modify the characteristics of internal ballistics (operating pressure and unit pulse).

The comparison of the after-combustion reaction using an oxygen from the air, without an additional oxidizer

$$2CO + 3H_2 + 2OH + 2\left(O_2 + \frac{0.79}{0.21}N_2\right) \Rightarrow 2CO_2 + 4H_2O + 2\frac{0.79}{0.21}N_2 \qquad (1)$$

with the after-combustion reaction using the additional oxidiser in a form of the salt charge K_2SO_4

$$K_2SO_4 + 2CO + 3H_2 + 2OH + 2\left(O_2 + \frac{0.79}{0.21}N\right) \Rightarrow$$
$$2CO_2 + 3H_2O + H_2S + K_2O + 2O_2 + 2\frac{0.79}{0.21}N_2 \qquad (2)$$

gives a qualitative picture of the oxygen balance improvement for rocket engine after--combustion reaction products. These stoichiometric dependencies do not reflect the entire complexity of the actual combustion with after-combustion reaction but they enable conducting the qualitative analysis.

Taking into account the characteristics of nitro-polymer fuel used in the rocket engine, potassium salts were analyzed as an oxidizer charge material since they are inhibitors of spontaneous ignition initiation of hot hydrocarbons formed from mixing with the atmospheric air. Decomposition reactions of potassium salts are endothermic, which makes it possible to use them as after-combustion flame dampers. In practice, these salts may be introduced into the composition of the fuel charge as an additive or as a separate, external charge placed in the rocket engine's combustion chamber. The literature data show that the use of the oxidizer additive as a component of the rocket engine fuel will completely extinguish the after-combustion flame for the entire engine operation time, using potassium nitrate in an amount of 1.14% of fuel weight or 4% of potassium sulphate charge.

Fig. 1. Comparison of thermograms with corresponding moments of engine operation with the K_2SO_4 oxidiser charge (above) and without one (below)

In the case when an oxidant was used as the external load placed in the combustion chamber, the effect of complete extinguishment lasts for a time comprising 20% of the rocket engine's total operation time. In this latter solution, the much shorter extinguishment time is due to the fact that it is placed in front of the fuel combustion zone, where the temperature of gases is about 2700 K, which is much higher than the K_2SO_4 decomposition temperature (1962 K acc. to [1]). Under such conditions, this distribution can be very intense and its duration will be a function of the radial thickness of the potassium sulphate charge. The comparison of the fuel charge thickness to the thickness of K_2SO_4 charge ratio amounting to 2.75 shows that the rate of movement of the K_2SO_4 charge combustion front is higher than the fuel burning rate [12].

Figure 1 shows the effect of the developed after-combustion flame damper of the operating rocket engine for the same times from the moment of starting the engine [16].

3. Materials and methods

The research conducted by the authors involved determining:
- ballistic characteristics of rocket engines; it was conducted on a horizontal dynamometer (Fig. 2);
- changes in the exhaust gas temperature of the engines using the FLIR SC6000 HSDR thermographic system;
- changes in the initial and maximum speed on a flight path using a Doppler radar.

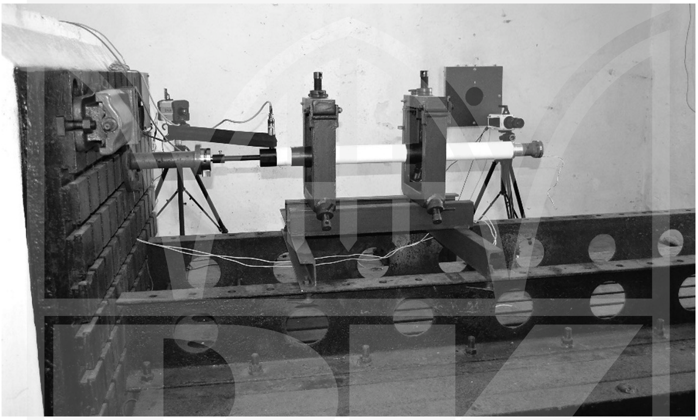

Fig. 2. Test stand with a mounted powder charge

The salts of potassium sulphate (K_2SO_4) were selected for ballistic characteristics tests and the process of their execution was developed [17]. In the developed process, the potassium sulphate charge is a glue of mouldings in the form of bushings embedded on a stainless steel rod. The mouldings were made of granulate, in which potassium sulphate grains were coated with a binding substance. The granulate structure was developed on the basis of trials. At the same time, minimizing the content of binding agents and obtaining appropriate physical properties of the moulding were aimed at [10]. In the course of comparative tests, two types of charges and various engine powder charge grindings were used, which aimed at reducing the maximum pressure in the combustion chamber by increasing its volume.

The placement of the K_2SO_4 charge in the rocket engine is shown in Fig. 3. The exact configuration of five rocket engines for tests is as follows:

a) powder charge no. 1: batch of 2015, grinding 3.50, K_2SO_4 rod weight: 133.39 g;
b) powder charge no. 2: batch of 2015, grinding 3.50, K_2SO_4 rod weight: 133.75 g;

c) powder charge no. 3: batch of 2009, grinding 3.50, K_2SO_4 rod weight: 133.70 g;
d) powder charge no. 4: batch of 2015, grinding 100, K_2SO_4 rod weight: 74.58 g;
e) powder charge no. 5: batch of 2015, grinding 60, K_2SO_4 rod weight: 74.42 g.

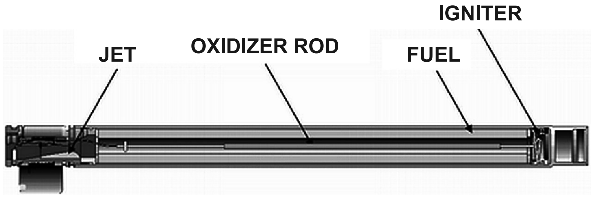

Fig. 3. Cross-section of the rocket engine with the K_2SO_4 charge

During measurements, the following parameters were studied:
- $P_{(t)}$ [MPa] – pressure course in time;
- $R_{(t)}$ [kN] – *R* draught force course in a function of time;
- t_p [s] – product operation time;
- I_c [kNs] – total draught force impulse;
- $R_{śr}$ [N] – average draught force;
- $\Delta R/R_m$ – draught force moment deviation;
- T_g [°C] – exhaust gases temperature;
- t_g [s] – K_2SO_4 rod operation time.

The results of tests of powder charges' ballistic parameters are shown in Table 1.

Table 1

Ballistic parameters tests results (source: [7])

Item	P_{max}	I_c	$R_{śr}$	t_p	Ratio *R*	Ratio *t*	Comments
	[MPa]	[kNs]	[KN]	[s]			
	15.5	min. 6.7	6 ± 0.25 kN	min. 0.9	min. 1.1	min. 1.1	Values required in TC
1	11.22	5.6	5.30	0.97	1.87	0.95	Chamber's tear
2	11.79	6.8	6.61	1.00	1.74	1.10	
3	11.18	6.8	6.07	1.05	1.67	1.17	
4	12.96	7.0	6.86	0.97	1.87	1.08	
5	11.58	7.0	6.83	1.00	1.85	1.10	

The results, except for the first case when the engine chamber was torn, are consistent with the values specified in the Technical Conditions. However, it is clear that the ballistic characteristics of the engines equipped with K_2SO_4 charges with lower mass are better. This is because, in order to eliminate the occurrence of maximum pressures above permissible values in the case of K_2SO_4 charges with higher mass, a flow cross sectional area was enlarged by greater graining of an engine charge in the jet area. At the same time, greater engine charge mass decrease occurred.

Thermal-imaging tests results show that the exhaust gas temperatures at an outlet cone zone are virtually identical for each engine and are 500°C–600°C (Fig. 4), while the exhaust gas temperatures during operation of the inhibitor for the engines 1, 2, 3 are similar and oscillate about the temperature of 600°C for 0.3 sec, then rise to 900°C.

For the engines 4 and 5 (both of reduced rod mass), inhibitor working time (temperature 600°C) is shorter and is 0.18 sec (Fig. 5).

During the ground field tests, two missiles equipped with the K_2SO_4 charges with greater mass were fired. The tests, during which the Doppler radar was used, showed that the

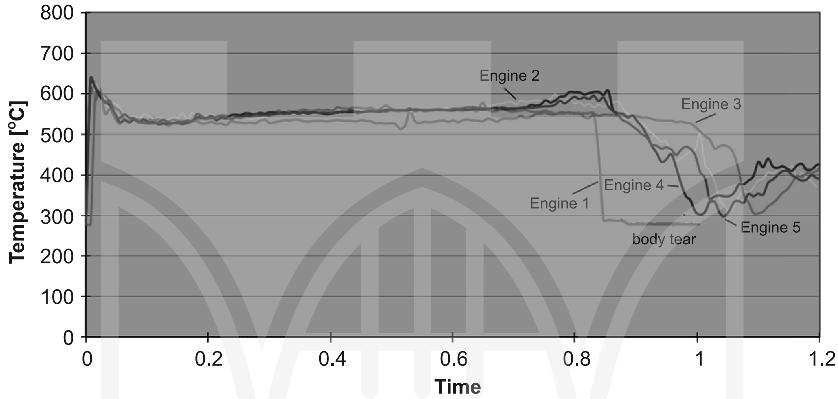

Fig. 4. Exhaust gas temperature changes course in the outlet cone zone

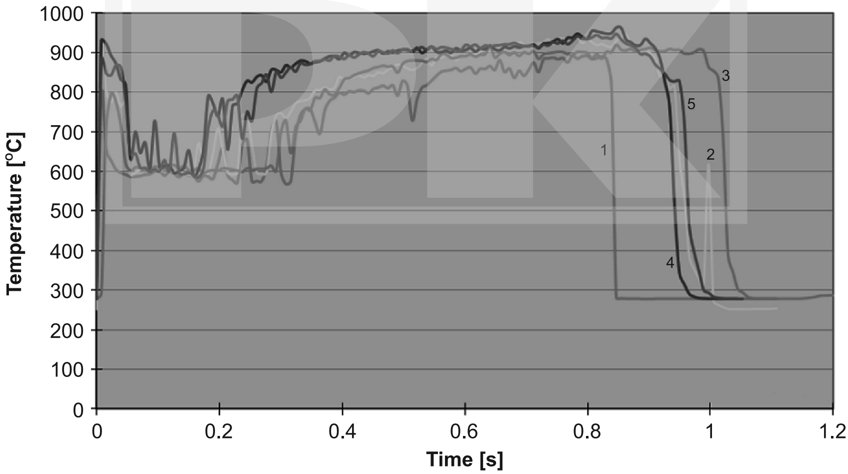

Fig. 5. Exhaust gas temperature changes course in the secondary flame zone: 1 – Engine 1 (grinding 3.5°); 2 – Engine 2 (grinding 3.5°); 3 – Engine 3 (grinding 3.5°); 4 – Engine 4 (grinding 10°); 5 – Engine 5 (grinding 6°)

missile's required initial velocity of not less than 45 m/s decreased to 39.1 and 34.7 m/s, while the maximum velocity of the required value of 650 m/s decreased to the value of 634.1 and 637.8 m/s when using potassium salt charges.

4. Conclusions

The experience gained during the operation of missiles of the same type but different production batches (made on the basis of the same technological documentation) shows that, due to the difference in the quality of the ingredients used in the rocket fuel production process, the threat level of aircraft engine's compressor stall from which the missiles are fired changes. The currently used acceptance tests and the apparatus do not allow to detect the threat at the production stage. For this reason, the authors undertook the task to solve the problem in a global manner using potassium salt charges. The introduction of an additional element in the form of an oxidiser rod into the combustion chamber of a rocket engine powered with rocket fuel results in a significant reduction in the exhaust gases temperature and limiting the degree of rocket engine's gaseous products after-combustion, in particular carbon monoxide.

However, the conducted research shows that this method of limiting flame after-combustion causes changes in the rocket engine's mechanical, dynamic and ballistic parameters. The greater the mass of the used K_2SO_4 charge, and hence the lighter engine powder charge mass (by increasing the combustion chamber's volume), the worse missile's ballistic parameters. Because of this, actions aimed at developing the salt charge with lower mass, hence lower effect on the ballistic parameters, which was confirmed with laboratory tests, were undertaken. The authors plan to conduct supplementary ground field tests using salt charges with lower mass, and then to conduct field tests in flight aimed at confirming finally the K_2SO_4 potassium salt charges' operation efficiency.

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