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Normal and failure operation mode of resistojet thruster – experimental research on the laboratory model

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Abstract

Rocket thrusters of various types are used in space to change orbits, maneuver, and position control. The progressive trend in miniaturization of satellites also entails changes in propulsion systems. In recent years, electric rocket thrusters have become increasingly important. Resistojets are one of the simplest types offering thrust ranging from several to hundreds of millinewtons and use two types of energy: potential (pressure) and electrical. Electrical energy added by a resistive element – a heater – allows a significant increase in the temperature and specific impulse of the working medium. The paper considers the case of damage or lack of electrical power to the heater, which changes the engine operating mode from resistojet to coldgas. Experimental tests were carried out on a model of resistojet thruster operating in atmospheric conditions, both with the heater on and off. For the resistojet mode (heater on), three different variants of the flow delay to the heater activation time were considered. The analysis of results showed how the key propulsion parameters of the thruster change: specific impulse, total impulse, thrust and mass flow rate. For the tested model engine, wherein the resistojet mode the temperature was higher by approximately 120°C compared to coldgas, and approximately a 30% increase in specific impulse was observed. This demonstrates the advantages of the resistojet, where a heater failure "only" causes a reduction in the propulsion potential and not its complete loss. The spaceship or a satellite with resistojet thruster onboard has still the opportunity to accomplish mission goals.

Keywords: Thruster; Coldgas; Resistojet; Normal operation

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1. Introduction

Different rocket propulsion systems have been used for almost 70 years to conquer space. All of them can be divided into chemical, nuclear, electric, and thermal [1]. Advances in the third one are low propellant use, resulting in small thrust compared to other propulsion systems. Small forces are not a drawback in satellites where they are desired. They are divided into three groups: electrothermal, electrostatic, and electromagnetic. From all of them, electrothermal propulsions give relatively high thrust without the demand of an enormous power supply [2]. In this type, heat is the energy obtained from electricity used to expand and later expel gas through the nozzle, creating thrust. The first way to reach this force is arcjet with propellant heated by electric discharge in its flow, but it demands quite a huge current. It contrasts resistojets where power conditioning is simpler. A heat exchanger is a resistance wire through which fuel flows, gaining temperature and pressure.

Nomenclature

ISP – specific impulse, m/s
I_T – total impulse, Ns

Subscripts and Superscripts

r – real
t – theoretical

Abbreviations and Acronyms

AISI– American Iron and Steel Institute
CG – coldgas thruster
RJ – resistojet thruster

In the case of damage to the heater, this thruster could also serve as a cold gas propulsion in backup mode. Thus, part of the mission objectives may be saved if a less efficient thruster is still available. That family of thrusters needs only a valve that controls the flow of the working medium: gas, liquid [3] or even solid [4]. Both resistojet and cold gas operate with a wide group of propellants, such as gaseous hydrogen, carbon dioxide, nitrogen oxygen, hydrocarbons, and noble gases or liquid hydrazine, ammonia, and water [2]. Important information is whether the fuel is flammable, toxic, or reactive [5]. Those properties could limit use for safety reasons or possible damage to a stand.

Short reviews show that the thrust for cold gas is reaching values of a few millinewtons up to newtons [3,6,7]. It has a specific impulse typically between 300 m/s to 750 m/s, can operate under a 10 W power supply, and has a total weight below 2 kg. The same paper described resistojets with thrust from 10−200 mN and a specific impulse of 500–1500 m/s. Much more power is needed: 15–100 W which typically enables reaching 500−700°C. In the papers [8,9], researchers found that if there is an available bigger power source, the increase of specific impulse in resistojet thruster achieves 1.66−1.83 times higher than cold gas [8,9]. Thrust value could be enlarged by using multiple nozzles [10].

A resistojet thruster uses two types of energy: the potential energy of the pressure of the working medium located in the engine chamber and electrical energy, which increases its gas temperature, thereby increasing the engine's propulsion parameters. The profit from using electricity increases with the temperature of the working medium heated using a resistive circuit – a heater. The efficiency of the restistojet thruster is influenced by several factors: the type of gas used, the amount of pressure, and the temperature of the medium. During thruster operation, several different failure scenarios are possible, but one does not completely exclude the further use of a partially damaged engine. Such a scenario causes damage to the heater or a lack of electricity to power it. The paper describes a laboratory model of a resistojet thruster working in two modes: as a resistojet and in the case when the heater is a failure as cold gas.

2. The research stand

The research stand was built to conduct measurements of thruster performance. It consists of gas and power supply systems, a heating chamber, a nozzle, and a measurement system. A scheme of the stand is presented in Fig. 1a and Fig. 2 view of the real setup. The research thruster was made of 316 AISI stainless steel with three flow channels ending with a convergent-divergent nozzle. Two engine channels are connected to resistance heaters, increasing the working gas temperature. The third channel, located close to the outer wall, was used to recover heat from the walls of the inner channels. It decreases heat losses from the heaters to the walls. The heaters are supplied with 0.3 mm resistance wire, sheathed with ceramic insulation. The wire and ceramic insulation were enclosed in an Inconel alloy cover. The possibility of safe use of heating wire was up to 1000°C. It has an external diameter of 1 mm and a resistivity of 9 Ω/m. The research thruster is connected to a system equipped with a 24 V electromagnetic valve, a Venturi measuring tube upstream of the valve, static pressure sensors, and a buffer tank with a pressure regulator. The working gas was fed to the buffer tank from a high-pressure cylinder. The working gas is synthetic air (oxygen and nitrogen).

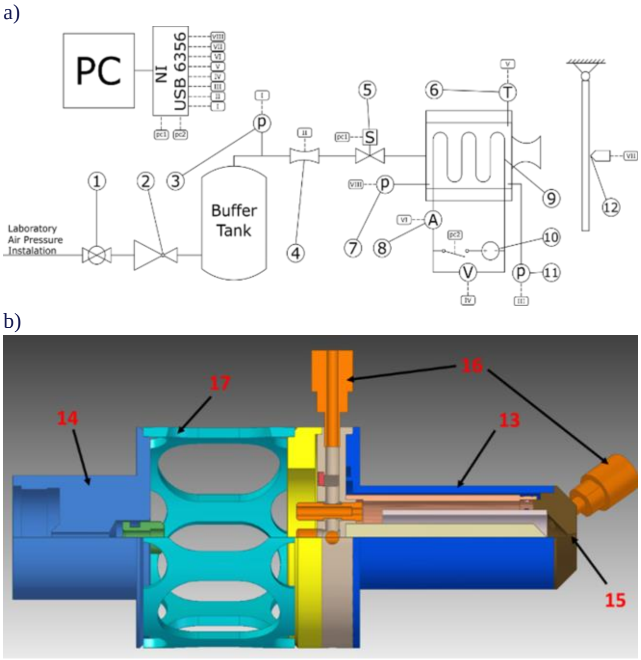

Fig. 1. The research stand: a) scheme: 1 – valve, 2 – pressure regulator, 3 – pressure in the feeding line (in front of the Venturi), 4 – Venturi tube, 5 – electromagnetic valve, 6 – temperature after the heater, 7 – pressure before the heater, 8 – current sensor, 9 – heater in the constructed thruster, 10 – power supply, 11 – pressure sensor at the nozzle inlet, 12 – baffle plate measurement system; b) view of the thruster: 13 – heater chamber (ϕ15 x 5 mm), 14 – control valve, 15 – nozzle, 16 – pressure/temperature ports, 17 – thermal barrier.

The measurement system was based on a National Instruments USB 6356 measurement card with 8 analog channels and a maximum sampling frequency of 1 MHz Keller PAA-23 pressure sensors with various measurement ranges were used, depending on the location. A Czaki company type K thermocouple was used to measure working medium temperature in three locations: the buffer tank and the inlet and outlet heating channel. The mass flow rate was calculated from the Venturi tube meas-

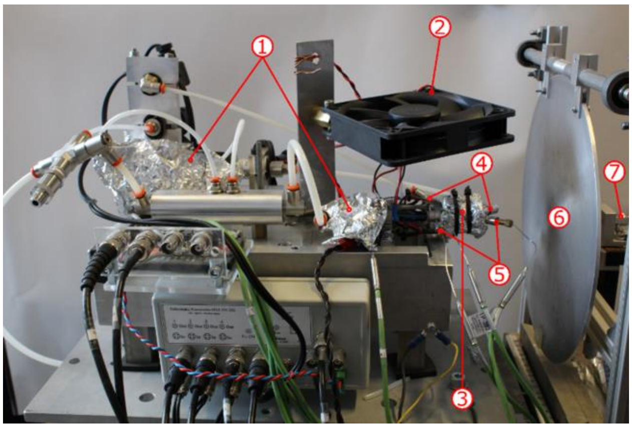

Fig. 2. View of the research stand. 1 – thermal isolation, 2 – cooling fan, 3 – isolation on the constructed thruster, 4 – pressure sensor connectors, 5 – thermocouple connectors, 6 – baffle plate, 7 – force sensor.

urements using the relation described in [11].

The model of resistojet thruster consists of three channels. After opening the control valve, the working medium flows towards the outlet nozzle and increases its temperature. The increase of the temperature of the working medium effectively can be controlled by the power (temperature) of the heater and the heat exchange surface, which affects the length of the flow channel. In the described thruster model, both parameters were optimally selected in the paper [11], taking into account the limitations related to the maximum temperature of the heater and the length of the heating channel itself. For the maximum temperature, the strongest limitation was the maximum temperature of the heater material – in this case, 1000°C was the limit. For the dimensions of the thruster model, a solution with three channels was adopted (two of them have heaters) where the flow is reversed twice before it reaches the nozzle, which is associated with pressure losses but reduces the surface-to-volume ratio of the thruster, which significantly minimizes heat losses.

3. Experimental results

A matrix of variable parameters was adopted to compare both thruster operating modes. Two parameters were selected: flow time and the flow activation time delay compared to the heater activation time. The flow time is related to the possibility of implementing the shortest possible single control pulse in the thruster. For a cold gas thruster, the times of single pulses can be counted in milliseconds. However, it should be noted that the structure of such an engine is very simple – it is a control valve and an outlet nozzle. For a resistojet engine, this time is longer because the flow channel's length must be considered. The channel should be long enough to increase the working medium temperature. The extension of the channel affects the inertia of the working medium flow, but on the other hand, it affects the possibility of increasing its temperature. Therefore, the resistojet thruster must have longer operating times for a single pulse. So, the length of a single pulse for the resistojet thruster is the limiting value.

The second important question to answer is when the flow will be turned on, in comparison to the time of heater switching. Heating of the heater takes some finite time, and activating the heater at the same time as the flow means that in the initial period, the resistojet thruster will work in cold gas mode. The time to reach the operating temperature will be longer due to the cooling effect of the working medium flow. Therefore, turning on the heater before starting the flow is reasonable. This means that working gas starts to flow around the warmed heater wire and almost immediately switches to working in resistojet mode. Therefore, the second tested parameter is the delay time (flow activation time relative to the activation time of the heater), but this parameter was only tested for resistojet mode. These parameters for all examined cases are shown in Table 1.

Table 1. Experiments matrix: a combination of the flow time and delay time for both cases of thruster work.

Delay time [s]	**Flow time [s]**					
	Coldgas			**Resistojet**		
	2	5	10	2	5	10
0	CG-Case 0.2	CG-Case 0.5	CG-Case 0.10	RJ-Case 0.2	RJ-Case 2.5	RJ-Case 0.10
1				RJ-Case 1.2	RJ-Case 2.5	RJ-Case 1.10
2				RJ-Case 2.2	RJ-Case 2.5	RJ-Case 1.10

The case name: "Name-Case X.Y" contains information about the working mode: "Name": CG – coldgas, RJ – resistojet, and X – delay time in second, Y – flow time in second, respectively. Each measurement point was repeated at least three times, each time returning the initial temperature of the stand to the same value. The cooling fan (2) shown in Fig. 2 was used for this purpose. Figure 3 shows the test stand's typical course of the measured parameters. The engine thrust was measured using the baffle plate method, which allows for spatial separation between the thruster and the plate with a force sensor. This means that vibrations caused by, e.g. actuation of valves, do not affect the thrust measurement. Thanks to the knowledge of the mass flow rate, it is also possible to calculate the specific impulse – the basic parameter of a rocket thruster.

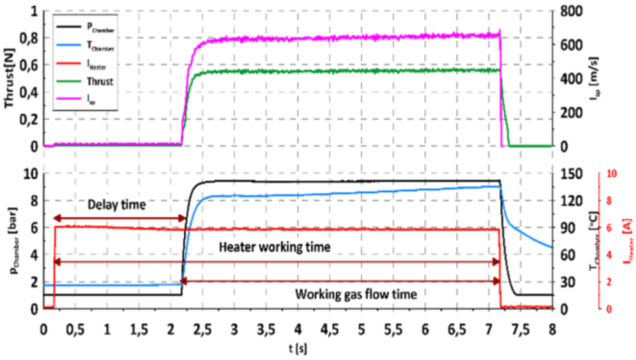

Fig. 3. Typical course of measured parameters.

The experiment mentioned above (Fig. 3), where the delay time was 2 s and the flow time was 5 s, is analyzed in detail in Fig. 4. It will see the heater warming up time, which shows a decrease in the current from 6.05 A to a stabilized value of 5.85 A (change of electrical resistance as a function of temperature). The heater current in the following part of the experiment ranges within ±0.66%, which shows how stable the energy transfer to the working gas was. The pressure at the outlet of a heating channel is varied within ±0.6%, and the temperature of the working gas about 340 ms after flow starts reaches approximately 125°C and increases by approximately 10 degrees for the next 5 seconds. It means that the thruster walls have not achieved a steady state.

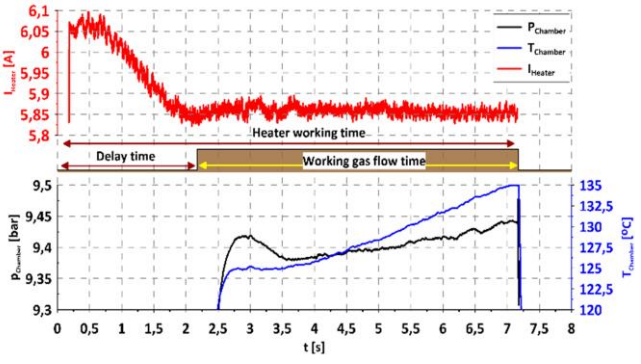

Fig. 4. Course of selected parameters of the experiment.

For all experiments performed, similar curves were obtained, as presented above. The propulsion parameters should be compared to the operation of the thruster in both modes (CG and RJ): the specific impulse and the total impulse were selected. A comparison of the specific impulse for the CG and RJ operating modes with three different delay times of turning on the flow (for RJ mode) is shown in Fig. 5, and the calculated values, including the total impulse, are shown in Table 2. To determine the theoretical ones, it was assumed that the thruster in the CG mode operates on a working medium at a temperature of 25°C, while in RJ mode with 150°C. In both modes, the same pressure was assumed in the engine chamber.

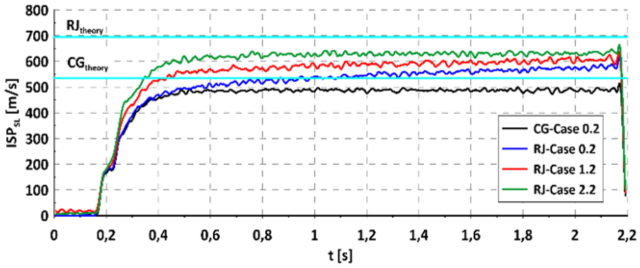

Fig. 5. Specific impulse in the function of time for all cases with 2 s of gas flow. Beginnings of flow are shifted to place them in one moment.

Table 2. Calculated propulsion parameters for both work modes of a thruster.

Case	ISP_t [m/s]	ISP_r [m/s]	I_{TT} [Ns]	I_{TR} [Ns]	I_{TR}/I_{TT} [%]
CG 0.2	535	487.5	1070.2	856.2	80
RJ 0.2	694.5	550.6	1389.3	944.6	64.9
RJ 1.2		590.3		1033.9	74.5
RJ 2.2		629.7		1105.7	79.5

Looking at the calculated parameters, two conclusions can be drawn. Firstly, it is beneficial to use a delay in starting the flow to the starting of the heaters, which increases the total impulse by 161 Ns (17%). Secondly, using a heater in the thruster increases the total impulse value in the RJ mode by approximately 29% compared to the CG mode.

Analyzing the graphs shown in Fig. 6, it can be concluded that the flow time is not important for the obtained specific impulse values. However, they confirm the validity of a delay in turning on the flow.

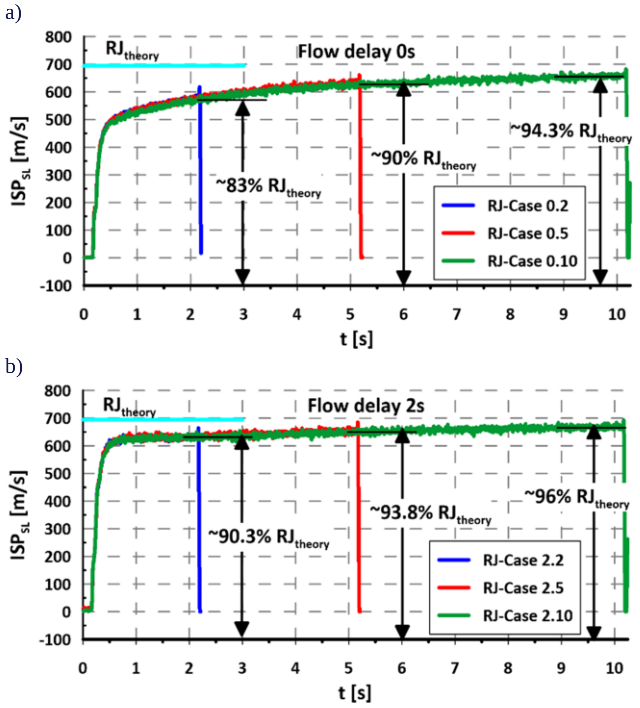

Fig. 6. Specific impulse in a function of time with different flow times: 2 s, 5 s, 10 s for: a) delay time – 0 s; b) delay time – 2 s.

From the driven spaceship's perspective, the most important parameter is the engine thrust. The transition from the RJ mode (e.g. in a failure situation) to the CG mode causes a slight increase in the thrust value (see Fig. 7) – in this case, the change is between 6.3% and 9.3%. This is because gas at a higher temperature has a larger specific volume, which causes a different mass flow rate through the same thruster geometry, confirmed by the graph shown in Fig. 8. The mass flow rate for the CG mode was assumed as 100%. For the RJ mode of operation, this flow value decreases. For short pulses of thruster operation, the drop depends on the delay time; for long operating times, it stabilizes at the same level. This is due to the thruster reaching the same operating temperature value – it is reached faster for cases where the delay time is longer.

The large impact of the delay time on the propulsion parameters is well illustrated by how fast the temperature at the nozzle inlet increases (see Fig. 9). We assume that the nominal temperature value for this analysis can be taken as a value between 9 and 10 seconds of the working time. If the flow is started with the heater, it takes as much as 5.805 s to reach 90% of the nominal value; for a 1 s delay, this time drops to 5.15 s, and for a 2 s delay, it drops to 3.247 s. If we take 75% as the reference level of the nominal value, these times are as follows: 3.155 s, 2.05 s and 0.2 s. For comparison, the temperature at this same point of the inlet nozzle is also shown; for three experiments with different working times, these differences do not exceed 0.4°C.

4. Summary

A research stand was presented, and experimental tests were carried out for a resistojet thruster, which can operate in normal and emergency modes. The tests were carried out for two main cases: in the coldgas mode - the influence of the duration of operation of a single pulse was checked; for the resistojet mode, the influence of operation time and the delay time of starting the flow to the time of starting the heater was examined. For the resistors operating mode, it was found that the delay in opening the flow is very significant. The efficiency (represented by the total impulse) increases significantly from 67.9% to almost 80%. From a control law point of view, the ideal shape of the thruster control pulse is a rectangle; in reality, we can only follow this shape. Experimental cases with a delay time of 2 second are most similar to the required shape. In the case of a failure scenario for a thruster, in the form of the inability to turn on the heater, the thruster can be switched to cold gas mode. The total impulse will also be 80% of the theoretical value while the mass flow rate increases and the thrust decreases slightly. From a control system point of view, the thruster delivers the same level of thrust, but the onboard resources for the propulsion system wear out faster; in other words, the time of its use is shortened. In many cases, such a failure scenario of the propulsion system allows for saving at least part of the mission objectives.

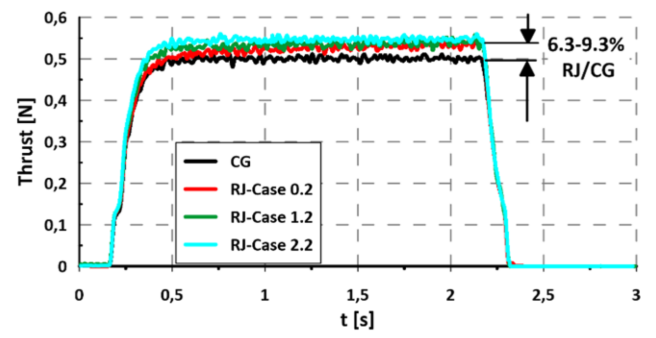

Fig. 7. Comparison of thrust as a function of time for CG and RJ work mode.

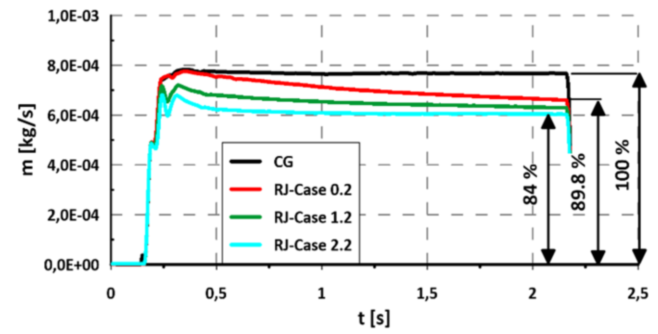

Fig. 8. Comparison of mass flow rate as a function of time for CG and RJ work mode.

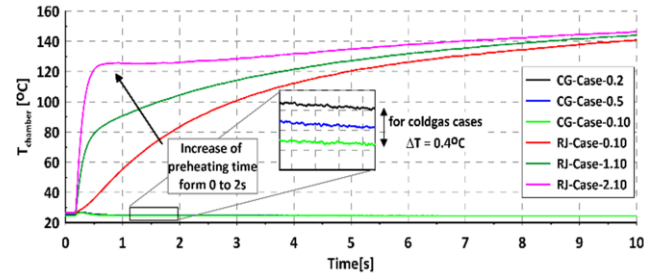

Fig. 9. Comparison of temperature profiles in CG and RJ working mode.

The conducted research allows for quantitative estimation of one of the emergency scenarios and is a starting point for planning research using a vacuum chamber, in which these effects can be examined in conditions more similar to real ones.

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