# Resistojet thruster with a power system based on supercapacitors

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This paper presents research into a resistojet model that can be powered by supercapacitors for satellite propulsion applications. The performance of the system, calculated including a preliminary study of mass and power budget, shows that this solution has potential for a certain range of space missions. The main problem when designing a pulsed resistojet is the compromise between the thermal capacity of the resistojet and the heat transfer efficiency of the device. When the heater is used in pulsed mode, it should have low mass and thermal capacity in order to reduce the energy required to heat the devices. On the other hand, the main technical restriction in resistojet thrusters is heat transfer due to the laminar regime of the flow in the heater. The heat transfer area should be as large as possible, but the mass of the device limits any such increase in area. In this research several design options were considered in an attempt to find the optimal solution. After research on the oscillating element and porous heater, capillary tubes directly heated by the current were determined to be the most effective solution.
A power supply based on supercapacitors was constructed. It consists of 30 supercapacitors of 300 F each, connected to deliver 70 V of voltage, 10 F of total capacitance and maximum peak power of 5 kW.
Research for three different gases – ammonia, propane and butane – was conducted and the results are presented in this paper.

**Key words:** resistojet, thruster, satellite

## Introduction

The importance of small and medium sized satellites has been increasing in recent years. An appropriate propulsion system must be developed alongside the increased range of application. In many missions, the volume and mass of the propulsion system make up more than half of the satellite or space probe. Reduction of mass and volume of the propulsion system demands the use of devices of high specific impulse and high density storable propellants. The best specific impulse is obtained by ion engines, but the thrust is very small. High density propellants are offered by chemical propulsion. However, satellite thrusters typically use hydrazine and nitrous tetraoxide, which are extremely toxic substances. Therefore, if a mission needs thrust in the range of 0.1÷1 N and high specific impulse at the level of 200 s electro-thermal propulsion can be considered as an effective and cheap solution. It is especially attractive in the design and development of small satellites, which are very often built by organizations with limited resources [1] . Electro-thermal propulsion is much safer and easier to handle, but the big problem here is the high demand for electric power, especially when pulses of large total impulse are required.

In order to overcome this problem, a new kind of resistojet is proposed. The resistojet is powered not directly from the satellite power system, but from supercapacitors.

## Rocket Propulsion

The general classification of rocket engines can be by energy source or function. The resistojet, which is the subject of this paper, belongs to the thruster group. The main characteristic feature for this group is the fact that thrusters do not have a driving function – they are used for secondary tasks such as: position control, catapult, gas generator etc.

In the case of energy source classification, resistojets are non-chemical, electric, electrothermal devices. Full classification of rocket engines by energy source is shown in Fig. 1.

The principle of operation of the resistojet thruster is very simple: the working gas is electrically heated during direct contact with a hot surface in the heating chamber and expands through the nozzle. The simplicity of construction translates directly into a high reliability coefficient and lower mission costs. One very interesting feature of the solution is the fact that even if the most delicate element is damaged – the heater – the system is still operable and can still be used as a "cold gas". In such case, feeding gas consumption is higher, but the damage will not lead to the mission being interrupted or aborted.

Precise positioning requires work in a pulse mode. Where cold gas is used, the most important problem is the fast reacting valve delivering the gas into the nozzle. In the case of a resistojet another problem is crucial – the power requirement to heat up the gas during the pulse. The power

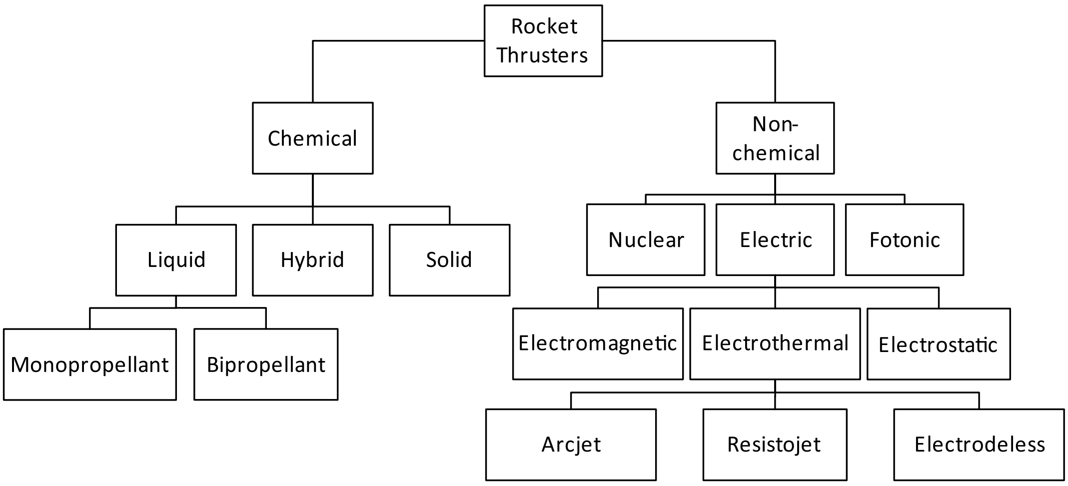


Fig. 1. Rocket engines classification based on energy source [2], [3], [4]

supply needs to be able to deliver very high power into the gas in a short period. On the other hand, it should not have a significant impact on the spacecraft power system or other inboard apparatus. The device which meets those requirements is a supercapacitor with very high power density.

## Study on a heater design

The main goal of the work was to build a working model of a resistojet thruster which would be able to deliver 0.5 – 1N of thrust with high specific impulse with a dedicated power supply system based on supercapacitors. Gaseous ammonia was chosen as the main propellant, but the construction of the research stand allows the gas to be changed very easily. During preliminary calculations, calculated specific impulse of 1800 m/s and 1N thrust were obtained for the ammonia propellant. To achieve such parameters, the gas needs to be heated to about 1000K. Due to the use of an ammonia propellant, all elements of the thruster and gas feeding system are made of stainless steel. The two most important issues with a resistojet are having: a lightweight heater and an effective power delivery system. Many heater design concepts were considered. Some of them seem to be a good solution, some did not attain the desired performance level while others did not even reach the research level. In this section the history of development of a final version of the thruster is described.

### Bulb glower concept

The mass of the heat exchanger can be reduced by using lightweight heat transfer elements (e.g. heating coil) heated directly by electric current.

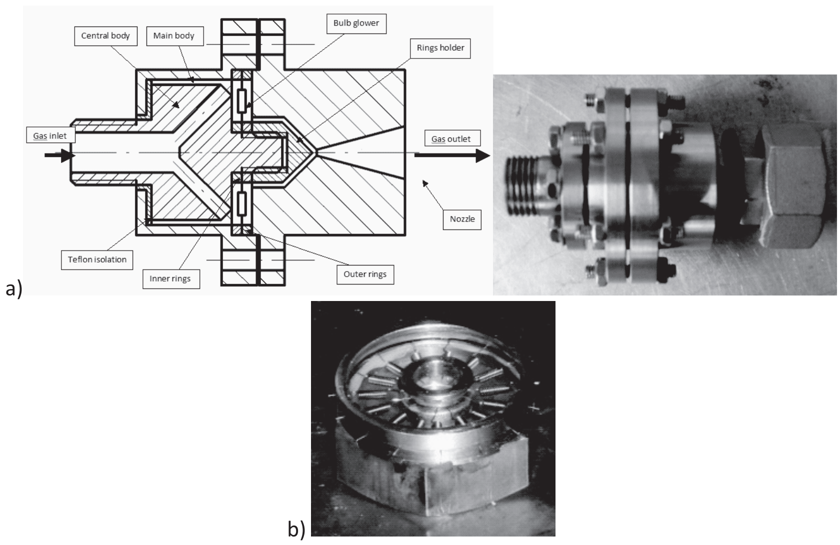


Fig. 2. Model of the resistojet with a heater based on bulb glowers: a) technical drawing and model, b) used heater

55 W car bulb glowers were chosen to model this element. They seemed to be a good solution due to their resistance to vibration, high temperature and gaseous atmosphere. The first model of resistojet, used only for material and temperature tests, is shown in Fig. 2. The glowers were tested for nitrogen as the propellant. The choice of propellant in this first phase of research was driven by safety considerations. Nitrogen mass flow was set to 1.1 g/s at feeding pressure of 5 bar. Then the voltage was triggered (12 V). Each test took 30 seconds. Each experiment could not last too long, for fear of melting the teflon elements used as an electrical insulation in construction of the model.

The measured temperatures (measured at the nozzle outlet and recalculated to the chamber conditions) confirmed that a single pass of the gas through the wire rises the temperature by about 100 K.

Despite initial promising results, the material of the glower was relatively quickly eroded by the gas. The extent of glower deterioration was checked by measuring the current in a circuit. The first signs of glower destruction appeared after 430 s. From preliminary calculations the requested pulse duration is 0.5 second, which gives 800 pulses of the thruster. The estimated rate of wire erosion is $2.3 \times 10^{-4}$ mm/s which is too high for the application and the idea of using bulb glowers in direct flow was abandoned.

## Oscillating heater

According to several publications (e.g. [5]) the heat transfer can be significantly increased by using elements which vibrate with a frequency of an order of several hundred Hz. In order to check the possibility of using a vibrational element in a resistojet application, CFD simulations were performed. The simulations proved that at the flow conditions proposed in the resistojet, performance can indeed be improved. Whereas the heat transfer coefficient can be increased by up to 7 times at 1000 Hz, the frequency of 300 Hz ensures good results. Unfortunately, simulation of a driving system based on an electromagnetic coil, which would be able to deliver desired frequencies, revealed that it would be large and heavy. The idea was left for future consideration.

## Porous elements

The next task was to investigate the feasibility of using a porous heater in the development of the resistojet thruster. Two types of porous elements were used: 10 mm long with pore size of 35 micrometers and 6 mm long with pore size of 80 micrometers. Both were made of stainless steel and had a 10 mm diameter. The very low electric resistivity (1.2 – 5.5 Ω/m) excluded the possibility of direct, resistance heating, because of the unacceptably high current levels involved. To solve this problem the idea of indirect heating—internal and external—was developed. For internal heating, the bulb glower was placed in a drilled channel. The biggest problem was the need for electrical isolation between the porous element and the glower. This was achieved by covering the channel wall with a ceramic layer. The next problem was the connection between the glower and the power wire, which could only be done by making a clipping connection.

The other way to heat the element was to wrap it with resistance wire. In this case, two ceramic insulation layers were needed – one to insulate the heating wire from the porous element and the second between the porous element and the casing of the thruster.

Both ideas are shown in Fig. 3.

After a few series of experiments at different power levels and mass flow rates it was found that, in both cases, the achievable power levels were too low to ensure the required temperatures, because the heaters were damaged too early. Moreover, the heater construction process was long, hard and not repetitious. The idea was changed due to the construction problems, the high price of the porous elements and the fact that the established level of performances was unachievable.

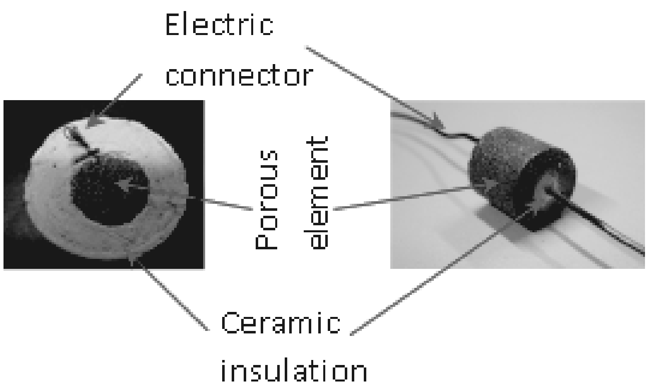


Fig. 3. Heater based on porous elements

## Capillary Tubes

The last idea proposed was based on directly heated capillary tubes. The first analysis was conducted for stainless steel tubes with an inner diameter of 1 mm and wall thickness of 0.3 mm. Electrical resistance of a 1 m long tube allows direct heating by electric current. It was found that it is possible to build a power system using commercially available supercapacitors and electronic switches (solid state) which enable the use of high current to directly heat the metal. The available peak voltage is about 60 V and peak current about 75 A.

The general idea of the resistojet with capillary tubes is very simple. The tube is connected through the electronic switch to a battery of supercapacitors. When the switch is on, the electric current heats up the tube and the propellant flowing through the tube to a nozzle. After the pulse, the current flow is switched off and supercapacitors are recharged by the spacecraft power system.

Several models of the resistojet with a heater based on capillary tubes have been built. Descriptions of early versions of the resistojet based on this idea can be found in [6]. The last version of a thruster (see Fig. 5, Fig. 6) with a major construction modification was done after the simulation aimed at determining how the size of the area around the pipe influences the results. This made it possible to establish the optimal distance between the pipes and the chamber walls. To achieve optimal distribution of the tubes inside the heating chamber, the shape of the whole thruster was changed into a tetrahedron. The thruster walls were made of 0.3 mm stainless steel sheets and laser welded, delivering a reduction in the mass of the thruster compared to previous versions. After some additional minor modifications, the final version of the thruster consists of a tetrahedron shape heater with 8 pipes of length 115 mm organized in such a way that the tubes are connected serially from an electrical point of view. For the gas flow, the pipes are organized in parallel, which makes the pressure drop insignificant. A ceramic element was installed on every pipe to prevent the pipes from making contact with each other and short circuiting (see Fig. 4). A central pipe was replaced by a solid element because of the extreme conditions (highest temperature and high thermal expansion)

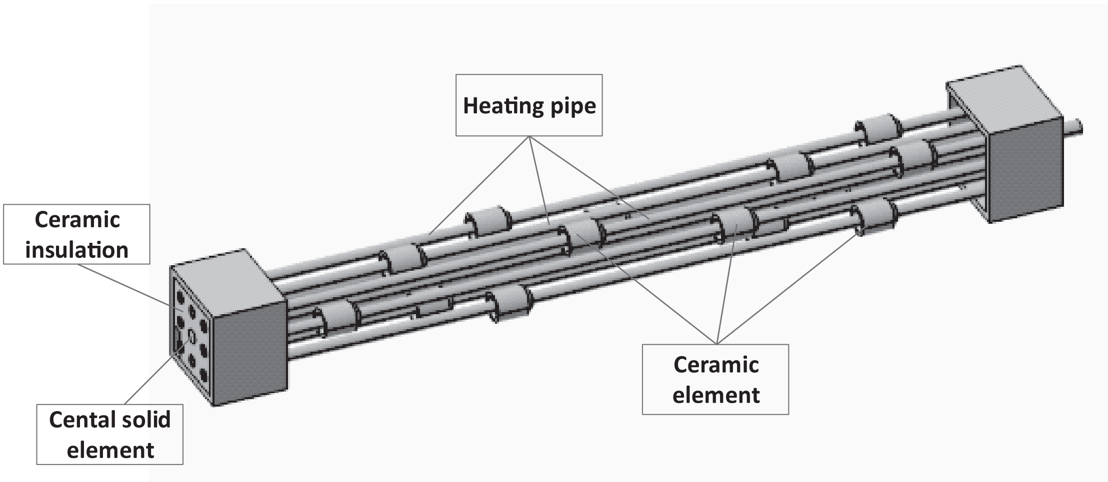


Fig. 4. Final version of the heater based on capillary tubes

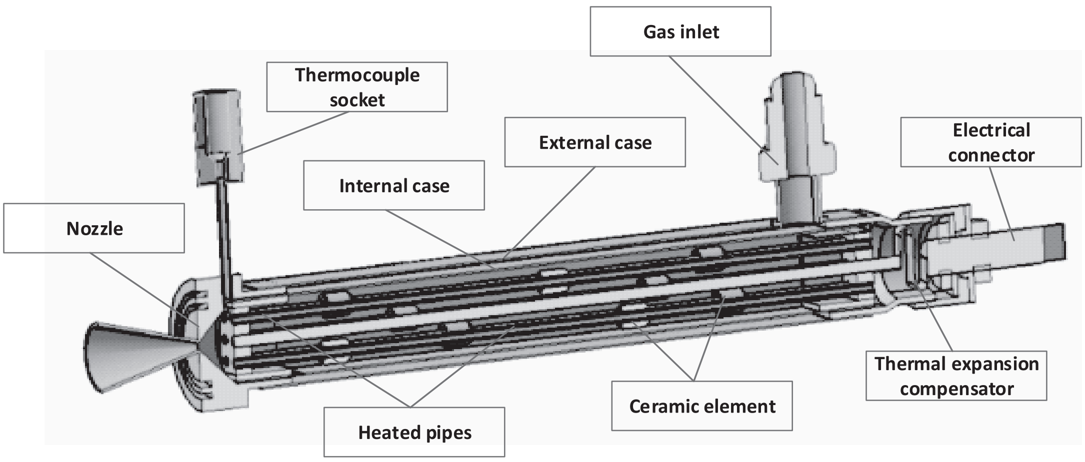


Fig. 5. Model of the resistojet based on capillary tube concept

Fig. 6. Final version of the resistojet thruster

and possibility of damage. The final version of the heater is shown in Fig. 4 and the whole thruster is presented in Fig. 6 and Fig. 6.

## Power Supply System

One of the most important issues of operating in pulse mode is the very rapid heating of the working gas. The power supply has to be able to deliver very high power into the gas in a short period. On the other hand, it should not have a significant impact on the spacecraft power system or other inboard apparatus. The device which meets those requirements is the supercapacitor. A single supercapacitor is able to deliver voltage of 2.5 V but it can work with high current (max. current for the supercapacitors used is 231A, continuous current – 25 A). Serial connection of several capacitors allow high power levels to be achieved (6.4 kW in the proposed construction) for short periods of time while the supercapacitor is discharged, and the average power consumed for charging the supercapacitor is in the range of tens of Watts, which is an acceptable value even for small satellites. The supercapacitor stores energy and, due to its small internal resistance, is able to release it in a very short period of time with high current. The concept of the resistojet thruster with a power supply based on supercapacitors is shown in Fig. 7.

During normal flight the system is kept in standby mode. If any maneuvers are required, the supercapacitors are charged by the spacecraft electric power system. To have the thruster powered by the supercapacitors alone, they are disconnected from the charging system before starting the thruster and work independently. During the work of the thruster, the system is discharged by the resistance of the resistojet circuit. After they are switched off, the supercapacitors are reconnected to the charging system and can be recharged if required. Due to the first assumption , a completely empty supercapacitor should be recharged within 10 minutes, but as during one pulse the aggregated energy is not totally used up, in practical terms the charging time is shorter.

The device consists of following elements:

- supercapacitors' set with voltage balancing devices;
- discharging resistor with relay;
- output circuit, consisted of solid state relay (SSR), shunt resistor and reverse diode;
- supercapacitors' set charger;
- auxiliary power supply;
- main controller with chargers regulator;
- insulated voltage and current measurements.

Model of a system created for the simulation purposes is shown in Fig. 8. The model consists of a simplified set of supercapacitors, the power supply IDC1 and switch



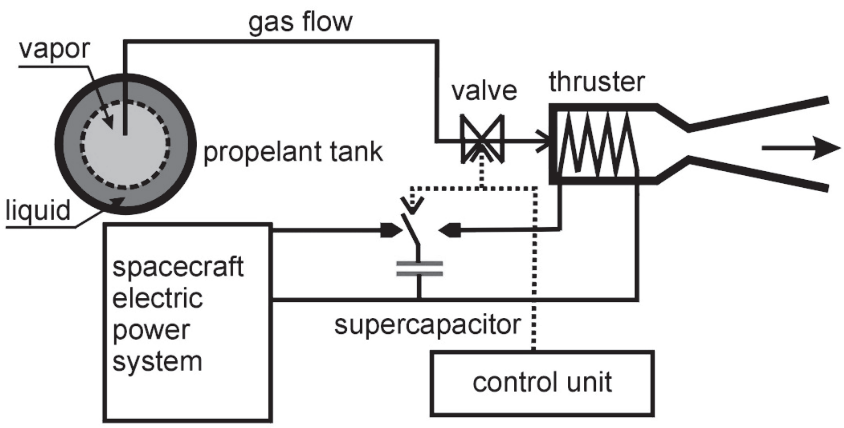


Fig. 7. The concept of a resistojet powered by supercapacitors

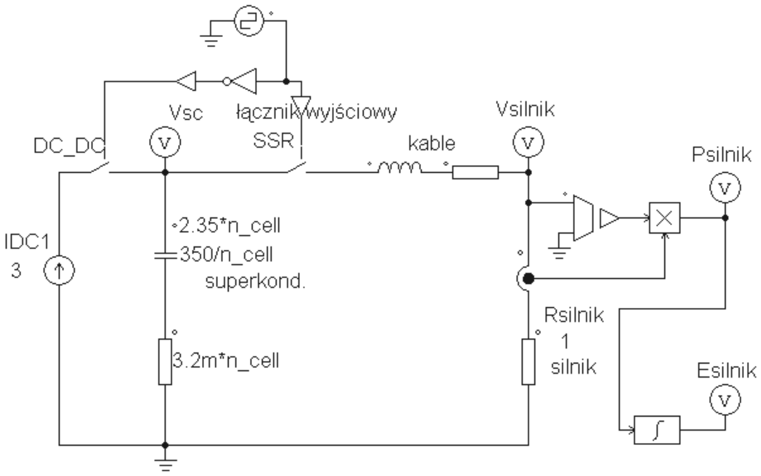


Fig. 8. Simulation model of the system's principle of operation


| Capacitor model | LSUC 002R8L 0350F EA |
|---|---|
| Rated Voltage | 2.8 V |
| Capacitance tolerance | -10% / 10% |
| Lifetime | 10 years |
| Cycle lifetime | 500 000 cycles |
| Max. current | 231 A |
| Continuous current | 25 A |

Fig. 9. Supercapacitors used in the power delivery system with basic information [7]

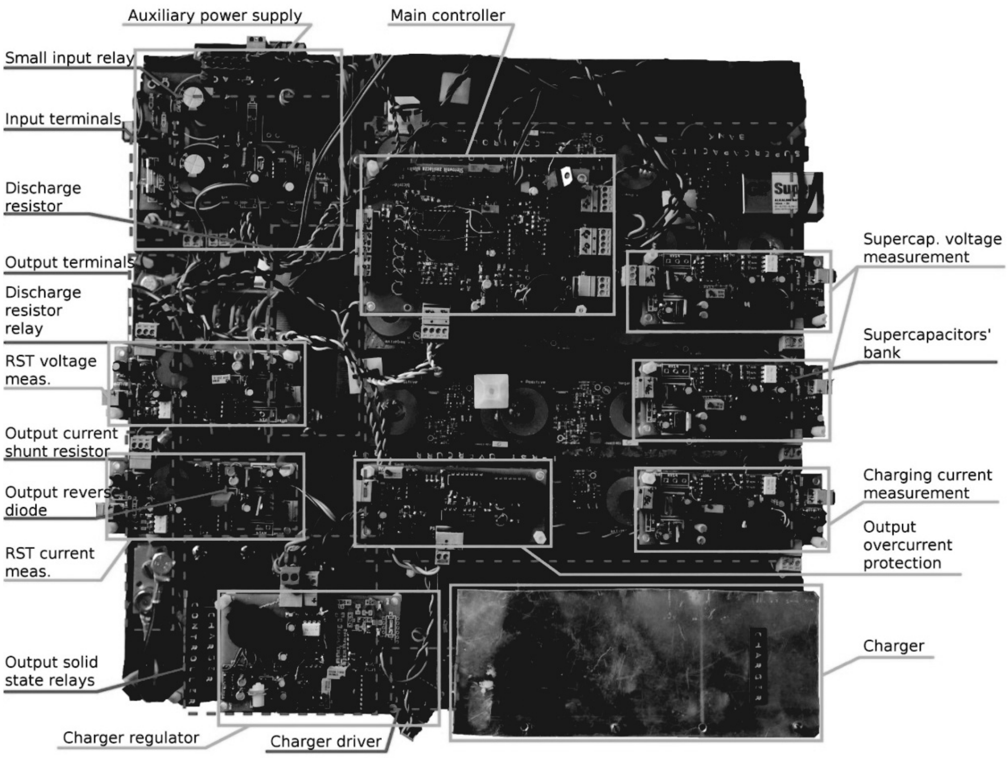


Fig. 10. View of the resistojet power supply system: dashed lines – bottom, power layer; continuous lines – upper, control layer

DC_DC, reflecting the charger converter of 3 A and SSR switch and resistor Rsilnik reflecting the RST thruster behavior. Other elements are used as a measuring device, respectively, Vsc – measurement of the supercapacitors set voltage, Vsilnik – measuring the voltage at the terminals of resistojet, Psilnik – the power consumed by the thruster, Esilnik – energy emitted in the thruster. Wires connecting the thruster and a set were modeled as inductance and resistance.

The results of the simulations prepared using Powersim (PSIM) software showed that for 80V supercapacitor bank voltage and time of 1 s, the power released to 1 Ω resistojet heater is approximately 4.6 kW. The energy transferred into the heater in every pulse is ~ 4.3 kJ. The discharging impulses are separated by intervals of 20 s. This time is sufficient to recharge the supercapacitors between pulses.

The physical power supply system is based on LS Ultracapacitor devices, produced by LS Mtron company (Fig. 9). Each of them has capacitance of 350 F and can deliver voltage of 2.8 V. The whole bank consists of 30 supercapacitors in serial connection, which gives a maximum output voltage of 84 V and capacitance of 11.67 F.

The device can be fully controlled by external signals, e.g., from the control computer. It is equipped with a series of protection mechanisms (overcurrent, overvoltage) and measurement devices. Thanks to visual indicators, the device can be readily checked for correct operation and any problems can be found quickly. The view of the device with main components marked is shown in Fig. 10.

## Results

The first series of experiments were performed to determine the relation between the specific impulse and the initial voltage of the supercapacitors power supply for gaseous ammonia as a propellant. The procedure in every experiment was the same; after the first second of data acquisition the gas valve and current flow were started. To make the results more reliable, every configuration was repeated five times and then the initial voltage was increased. The whole system was controlled by computer software. Owing to the pulse mode assumption, only the first second of the gas flow was taken into account in the results. The experiments last 6 seconds so as to allow the heater to cool down after the current is switched off, for safety reasons.

Two values of specific impulse ($I_{sp}$) were considered as a comparative criterion for different voltage levels. The first one is the local maximum specific impulse – the mean value of the highest region of $I_{sp}$. The second value is calculated for the 1 s long pulse – the mean value calculated from the first second of the experiment.

The results for ammonia propellant are summarized and shown in Fig. 11.

One of the most important problems as regards the impulse mode of a resistojet thruster is the thermal capacity of its heater. Thermal capacity prolongs the time required to heat up the heater, which is an undesirable effect for pulse mode work. To obtain better results preliminary heating was introduced. The power of the heater started before the gas valve was opened, which gave some extra time to heat up the heater. The gas was supplied to the very hot, pre-heated heater allowing the gas temperature to rise very fast, and sending the specific impulse higher. Due to the high power of the heater, the time delay between the electric current and gas flow cannot be too long, because the heater could be destroyed. To find the optimum volt-

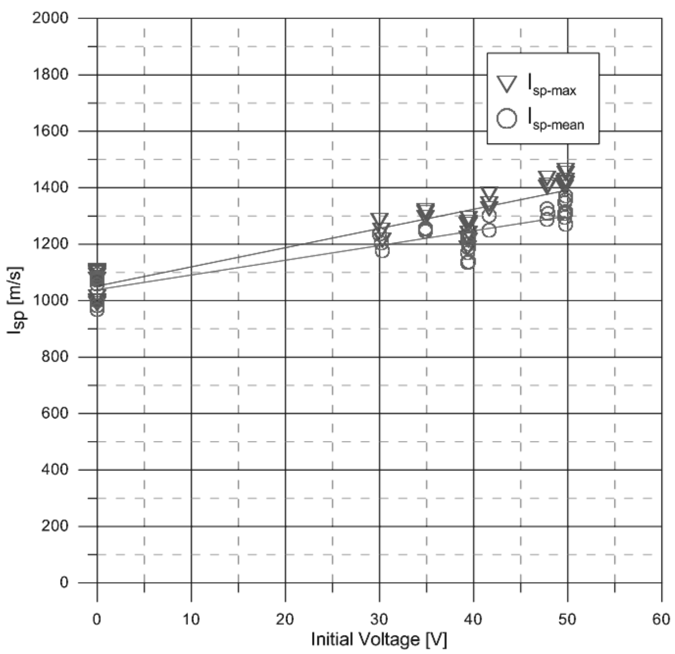


Fig. 11. Experimental results: Influence of the voltage change on the specific impulse for the final version of the resistojet fed by ammonia

age and time delay, another set of experiments were conducted. The first stage of research was conducted at 45 V. The time delay was increased from 0 s to 2.0 s every 0.1 – 0.2 s. The results showed that every second of time delay raises the specific impulse by ~ 100 m/s. In the second phase the voltage was increased to 50 V. The results of the influence of time delay on specific impulse for ammonia propellant is shown in Fig. 12.

The construction of the test stand and the thruster enables an easy change of propellant. Consequently, this facilitates the study of alternative propellants. Butane and propane have been proposed as additional propellants. Due to their different thermo-dynamical properties, in the first phase of the research, the influence of the initial voltage of the power supply on specific impulse was investigated for both propellants. The research started without power from the supply, so the thruster worked as a cold gas. Then the initial voltage was increased discretely up to 50 V. Results are presented in Fig. 13.

The second phase of research was to check the investigate of the time delay between the gas and power starts. In this case, the initial voltage was the same in each experiment and the time delay was increased in the same way as in the case of the ammonia propellant. Results for butane and propane are presented in Fig. 14.

As it can be noticed in Figures 11-14, all propellants had a good response for heating and the specific impulse improved as the voltage rose. In case of ammonia and propane further increase of specific impulse is achievable by increasing the time delay between power and gas starts. In case of butane propellant this effect is almost unnoticeable in this configuration.

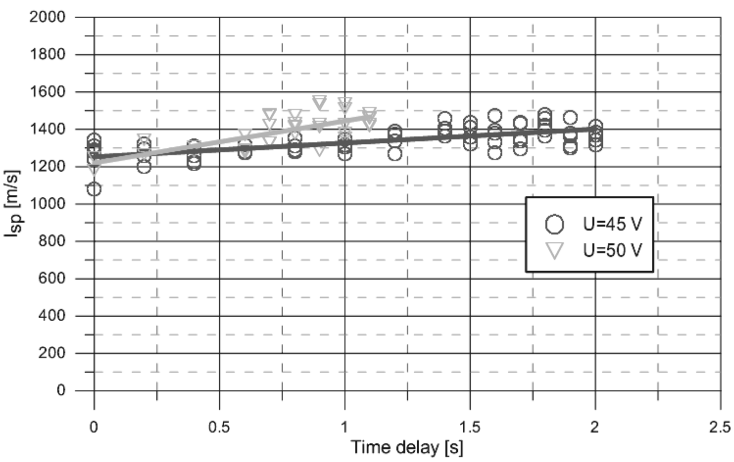


Fig. 12. Influence of time delay on specific impulse for ammonia propellant

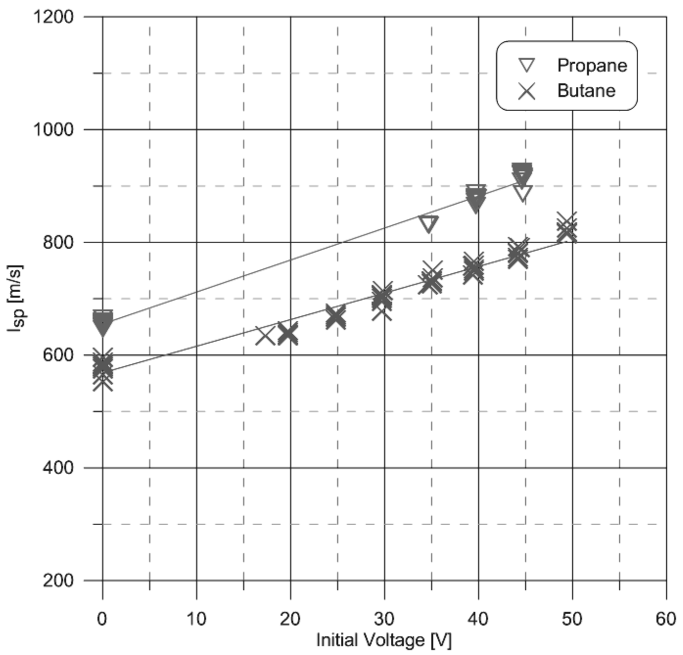


Fig. 13. Influence of the initial voltage on specific impulse for additional propellants

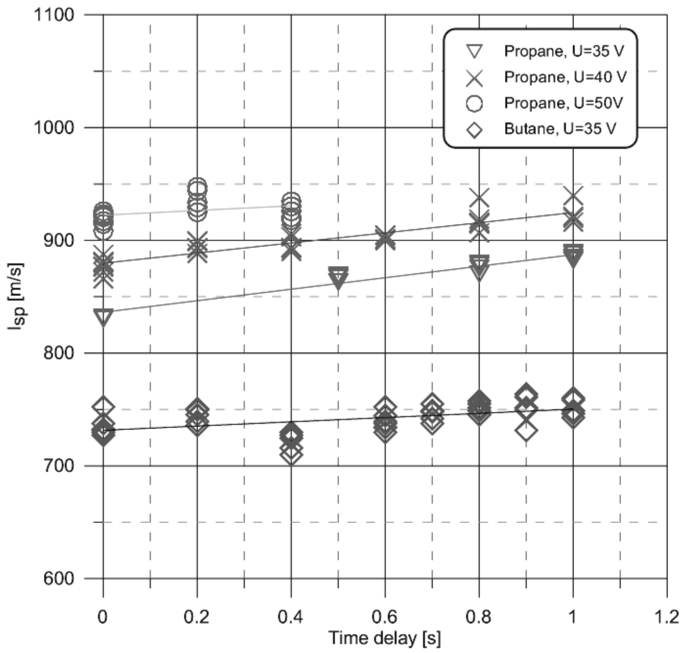


Fig. 14. Influence of voltage changes and time delay on specific impulse for additional propellants

The highest performance was obtained with using the ammonia propellant. It also has the best response for power introduction – the improvement of specific impulse compared to cold gas system is almost 50% (~1000 m/s for cold gas comparing to ~1500 m/s for 50 V with 1s time delay) while using a propane let to achieve a 38% improvement (680 m/s for cold gas and 940 m/s for 50 V with 0.4 s of time delay) and butane no more the 37% ( 590 m/s for cold gas and 810 m/s for 50 V). The weak response of the butane on time delay might be caused by low vapour pressure and should be investigate in the future.

## Summary

The paper describes a project involving a resistojet thruster with a power delivery system based on supercapacitors for small and medium satellite applications.

Several different concepts of the resistojet thruster were developed. The idea of a heater based on capillary tubes was found to be the most simple and effective solution. A power supply based on supercapacitors was developed and built. It seems a good solution if rapid power delivery is required. It is crucial for the impulse work of resistojets in attitude control systems.

Investigations of the initial voltage and the time delay between the power and gas starts were conducted for three propellants: ammonia, propane and butane. The resistojet fed by ammonia produced the best performances. All propellants had a good response for heating and the performances improved as the voltage rose. Also the time delay can improve performances for ammonia and propane. In the case of butane the influence of the time delay on specific impulse is not noticeable. Improvements in terms of the specific impulse can significantly impact a satellite mission. It makes it possible to lower the mass of the propellant and cut the costs of the mission. On the other hand, additional mass can be used for additional equipment and an extended mission.

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## References

[1] P. Smith, R. McLellan and D. Gibbon, "Smallsat Propulsion," w *5th IAA Symposium on Small Satellites for Earth Observation*, Berlin, Germany, 2005.
[2] W. Ley, K. Wittmann and W. Hallmann, Handbook of Space Technology, John Wiley & Sons, 2009.
[3] S. Torecki, Napędy Lotnicze - Silniki Rakietowe, Warszawa: Wydawnictwa Komunikacji i Łączności, 1984. [4] R. G. Jahn, Physics of electric propulsion, Mineola, New York: Dover Publications, Inc, 2006. [5] S. Dey i D. Chakrborty, "Enhancement of convective cooling using oscillating fins," *International Communications in Heat and Mass Transfer,* pp. 508- 512, March 2009.
[6] L. Mezyk, A. Kobiera, L. Boruc, P. Biczel and P. Wolanski, "New Kind of Resistojet With Power System Based on Supercapacitors," in *5th European Conference for Aerospace Sciences.*, Munich, Germany, 2013.
[7] LS Mtron Hi-tech center, "LS Supercapacitor," [Online]. Available: http://www.ultracapacitor.co.kr/ultracapacitor/cell.html. [Data uzyskania dostępu: 04 March 2014]. [8] S. W. Janson, H. Helvajian, W. W. Hansen and J. Lodmell, "Microthrusters for nanosatellites," in *The Second International Conference on Integrated Micro Nanotechnology for Space Applications*, Pasadena, CA, 1999.