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Methods and means of the experimental research of the electrothermal arcjet thrusters of spacecrafts

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Abstract

The subject of the research in this article is the measurement of the main characteristics of the electrothermal arcjet thrusters in the process of the working fluid acceleration during the bench tests. The purpose is to form a bench research facility to study the characteristics of the electric heating propulsion system for use in a space tugboat, taking into account the launch dynamics, operating conditions and shutdown dynamics. Tasks: measuring the thrust of the electric propulsion system as the main characteristic in the established and transient mode; determining the flow rate of the working fluid correlated with the thrust; measuring the parameters of electrical consumption – currents, voltage, power in static and dynamic modes; measuring the external conditions of the simulating space environment, namely the vacuum, in the test chamber. The methods used are: tensometry, differential pressure gauge, four-probe measurement of power supplied to engine heaters, steam generator and tank of the electric heating system, ionization-thermocouple vacuum measurement. The following results have been obtained: the composition of the information and control system consisting of the tensometric sensor used with the electric heating propulsion system, flowmeter of the working body of the electric heating propulsion system, power meter of the heater, steam generator and the tank of the electric heating propulsion system, ionization-thermocouple sensors for vacuum determination. The software product for graduation of the tensometric sensor has been developed. The scientific innovation of the obtained results is as follows: the method of measuring the thrust of the electric heating propulsion system by means of tensometric sensor has been further developed, the method of measuring the flow of the working body of the electric heating propulsion system has been further developed, the method of measuring the power of the engine heater, steam generator, tank of the electric heating propulsion system has been further developed. For the first time an algorithm for graduation of the tensometric sensor for the electric heating propulsion system was developed and implemented in the software product.

Keywords: space tugboards; electric heating propulsion system; electrothermal arcjet thruster; thrust measurement method; working fluid flow measurement method for working body; heater power measurement method; vacuum measurement method in vacuum chamber.

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Introduction

The current trend in the development of microsatellites for near space exploration requires new means of maneuvering spacecrafts. For this purpose, it is beneficial to use the electric propulsion engines [1]. One of the solutions of the problem of delivering the microsatellites to a given orbital position can be the using of space tugboards with electric propulsion engines as dispensers for "positioning" the satellites constellation. In this regard, it is advantageous to use electric heating engines based on chemically active working fluids such as ammonia [2]. Engines of this type were developed by specialists of Yuzhnoye State Design Office and allow to provide orbital maneuver with a thrust of 50 mN and high propulsion cost, which distinguishes them from plasma propulsion engines. A quantitative analysis of the implementation of the propulsion system for a space tugboat and assessment of the launch dynamics defined the need of experimental studies of these parameters on the experimental stand. For studies it was used KhAI experimental base, where the distinctive feature of obtaining scientific results was the use of unified tools with methods that ensure the high accuracy of the results.

Setting the task of experimental studies of electric heating propulsion system

The main goal of experimental studies of electric heating propulsion system [3] is to get an array of data related by the main parameters. It is essential for estimation of quality of the propulsion system functioning, determination of its propulsion and consumption characteristics, identification of correlation with power supply characteristics considering the environmental conditions of the test, which are close to the reality. The main task can be divided into a number of subtasks, the solution of which will make it possible not only to evaluate individual parameters, but also their relationship both in the static process of the engine system operation and in the dynamics of launch and shutdown, which is important for mathematical modeling of operation and development of functional algorithms.

Therefore, the experiment setup involves the definition of tools and methods to include in the information and control system of research and testing of electric heating propulsion system with breakdown into the following, fundamentally different subtasks:

- measuring the engine thrust as a basic characteristic in steady-state and transient modes;
- determining the consumption of the working fluid that correlates with the thrust;
- measuring of parameters of electrical consumption – currents, voltage, power in statics and dynamics;
- measuring the environmental conditions of the space simulation, namely the vacuum in the test chamber.

When solving the listed subtasks, it is necessary to establish the limiting errors of the experiment and justify the appropriate choice of sensors and measurement methods.

Thus, the target of the study is the process of accelerating the working fluid in electric heating engine (EHE) working in a vacuum. The subject of study: measuring the main characteristics of EHE, in the process of accelerating the working fluid at the bench tests. The objective is to form a test bench for the study of the main characteristics of the electric heating propulsion system (EHPS) for use in a space tugboat, taking into account the dynamics of the launch, the operating conditions and the dynamics of shutdown.

Problem solving

We will treat the solution of the main task in sequence of subtasks. The experimental stand for measuring the performance of the EHPS includes the elements that solve the subtasks. The structural schema is presented in Fig. 1, where "EPS" is the power supply system of EHPS, "FSSS" is the storage and supply system of a working fluid, FM is the flowmeter, TE is the thrust meter of the engine, E is the engine, VC – vacuum chamber, VS is the vacuum sensor in the chamber, VP – the vacuum pump, ICS is the information&control system 1, 2, 3, 4 are the measurers of the flow of working fluid, of the engine thrust, of the power supply parameters, of the the vacuum, which are the part of the information & control system, PC is the personal computer, the Operator – the operator of the personal computer supervising experiment realisation.

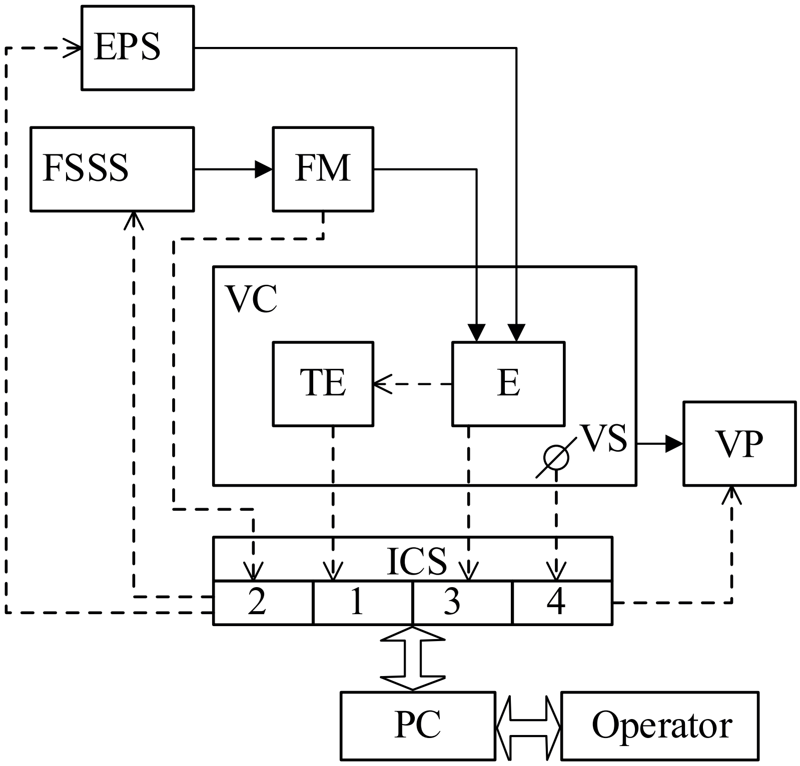


Fig. 1. The structural diagram of the experimental stand

Measuring the thrust of an electric heating engine has a number of features that distinguish the measuring process from measurements of plasma engines, where the thrust levels are tenths of a mN and micro fluid rocket engines, where the thrust is already the few N. The thrust range of electric heating engines is tens of a mN. Thus, thrust meters for EHE may not contain any complex moving devices with elastic or quasi-elastic elements with corresponding dampers [4]. Also for these devices it is not mandatory to use powerful strain-gauge units as for liquid rocket engines. Therefore, the main technical decision was to choose a tensometric (strain gauge) sensor.

The concept utilizes a method based on a strain gauge sensor BCL-300GM (Fig. 2).

The sensor switching scheme is based on the method with the bridge commutation of the sensing element, which makes it possible to exclude the influence of variation of voltage of the sensor power supply on the measurement results. This type of strain gauge sensor belongs to the resistor type, i.e. it is based on a resistor, whose resistance changes depending on its deformation [5, 6]. In this case the strain value is converted into an electrical signal that is easy to measure. To connect the strain gauge to the ADC is used a scheme with shielded twisted pair (Fig. 3), which eliminates the influence of external electromagnetic interference.

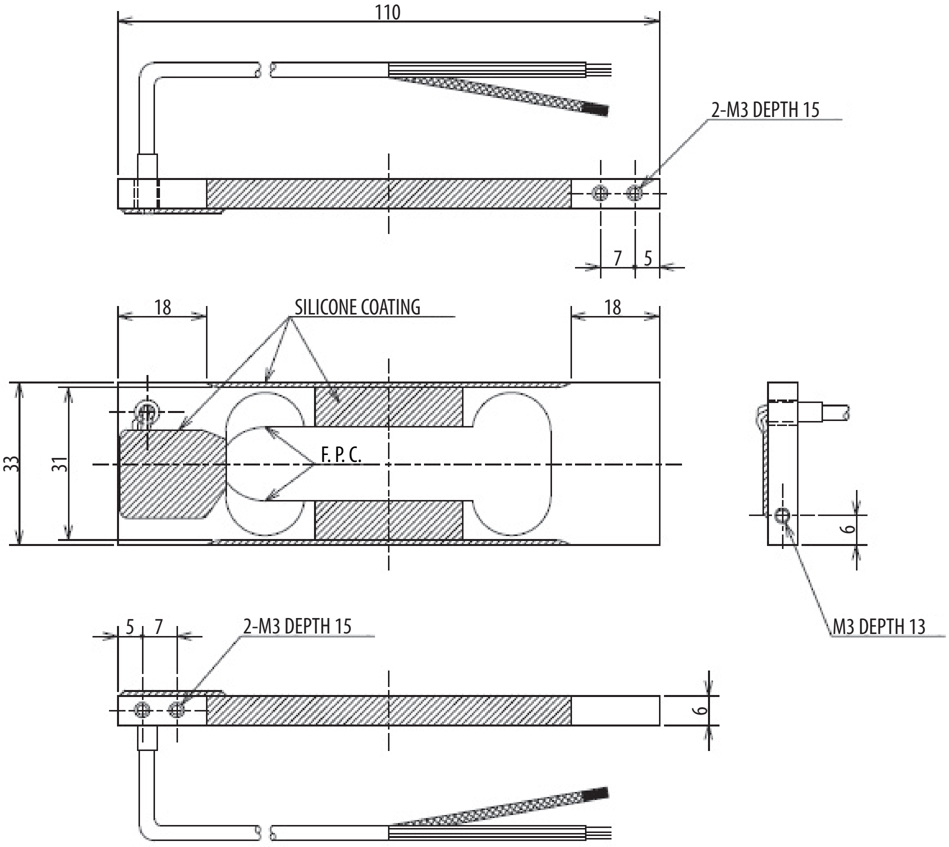


Fig. 2. Appearance of the sensor

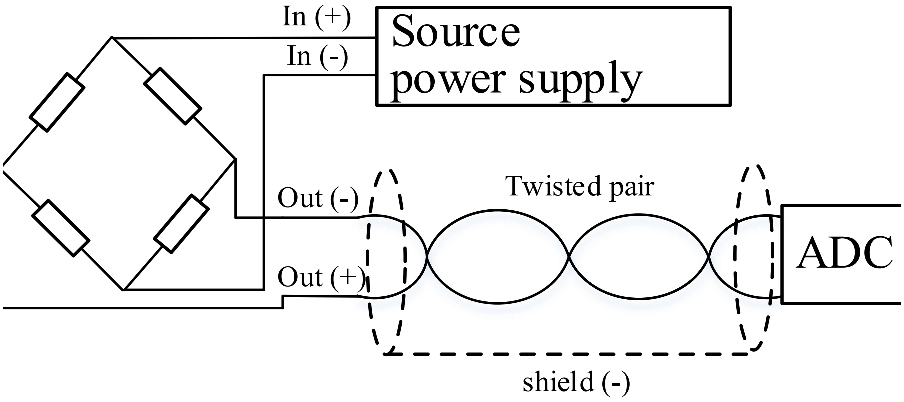


Fig. 3. Strain gauge switching circuit

By design, the sensor is mounted inside the vacuum chamber with a hanger with EHE mounted on it (Fig. 4).

The EHE thrust is measured at the launch and shutdown phases of the engine. The strain gauge is connected to a 16-digit sigma-delta analog-to-digital converter (ADC) based on AD7705BRZ-REEL [7], which in turn is connected to the meter.

To obtain the reliable data there are 10 measurements and the average arithmetic value of the switch-on thrust are calculated.

Table 1 shows the errors of the elements used in the EHE thrust determining method for obtaining the instrument error.

Let's consider the instrumental error as the error of indirect measurements and determine the method of error transfer

$$\Delta_{\text{tract}} = \sqrt{\Delta \text{Sg}^2 + \Delta \text{ADC}_{\text{tract}}^{\;\;2}}.$$

In the percentage equivalent we will get the instrumental error Δ_{tract} =1%.

For graduation of the strain gauge sensor, a software product was created, whose interface is shown in Fig. 5.

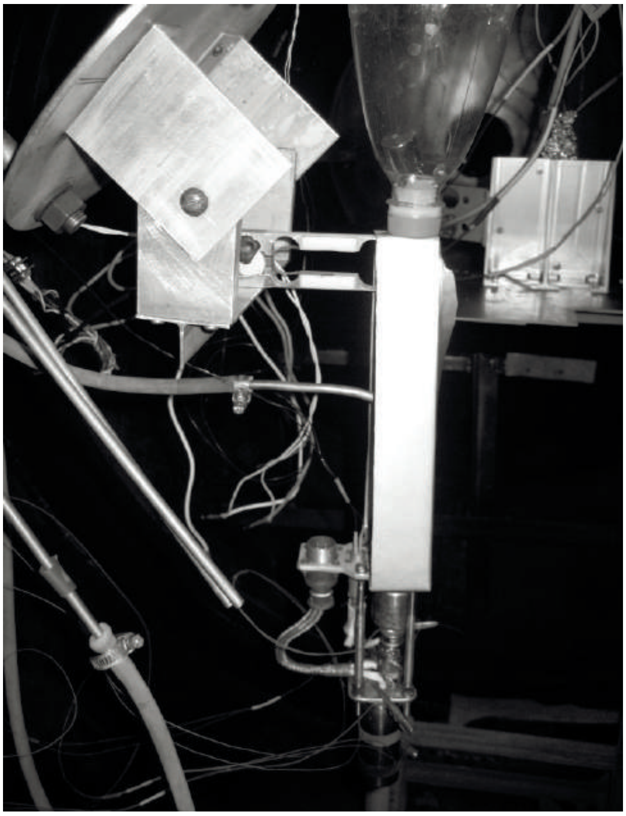
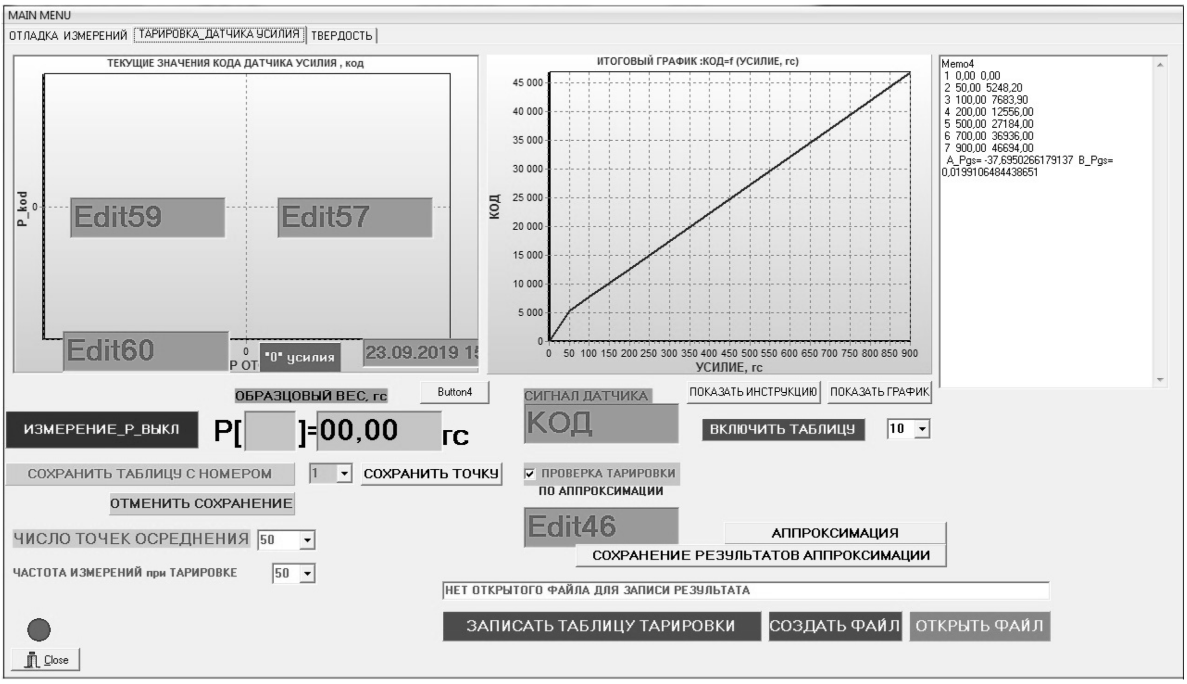


Fig. 4. Strain gauge BCL-300GM with hanger and EHE

Table 1

Ranges of measurements and percentage error of elements

Sensor name	Range of measurements	Percentage error
Strain gauge sensor BCL-300GM	345...450 Ω	±1%
Sigma-delta ADC AD7705BRZ-REEL	0.1…2 V	±0.003%



```
Memo4
 1  0,00  0,00
 2  50,00  5248,20
 3  100,00  7683,90
 4  200,00  12556,00
 5  500,00  27184,00
 6  700,00  36936,00
 7  900,00  46694,00
  A_Pgs= -37,6950266179137  B_Pgs=
0,0199106484438651
```

Fig. 5. Strain gauge graduation software interface

The graduation of the load cell movement measuring channel is included:

1. Testing of the displacement channel with a set of sample weights.
2. Obtaining the current readings of the force channel by initiating the “ИЗМЕРЕНИЕ_Р_ВЫКЛ” signal.
3. Determining the stable readings by the reference weights in the required measuring sequence for a given range in the “СИГНАЛ ДАТЧИКА” window.
4. Generation of the value of the reference weight value from the “ОБРАЗЦОВЫЙ ВЕС” display.
5. Saving the results in the field “СОХРАНИТЬ ТОЧКУ”.
6. Saving the whole range of measurements in the “СОХРАНИТЬ ТАБЛИЦУ” array or its cancellation “ОТМЕНИТЬ СОХРАНЕНИЕ” and assigning a graduation number.
7. Approximation of graduation in “АППРОКСИМАЦИЯ” and further “СОХРАНЕНИЕ РЕЗУЛЬТАТОВ АППРОКСИМАЦИИ”.

The measuring range of the strain gauge sensor is from 0 to 900 g. The number of averaging points and the frequency of measurements during graduation are also set in the program. Reference graduation weights according to the code MG-10-1100-10, used in accordance with OIML R 111-1:2008, are used as standard graduation tools. The appropriate code corresponding to the level of the input signal received from the strain gauge sensor is transmitted to the ADC for further work.

A specific feature of the EHE thrust strain gauge is the need to measure the transients when the engine starts and stops. This measurement requires a reduction of the aperture time of the ADC and the sensor inertia. The introduced measurement scheme allows to realize a single countdown in 10 milliseconds, which on a transient process of 3...4 seconds realizes up to several hundreds of points of traction dynamics change.

Flow measurement method of working fluid. The flow rate is a physical variable determined by the amount of liquid or gas passing through a cross section in a single time unit. A distinction is made between volume flow when the quantity of a substance is measured in volumetric units and mass flow when it is measured in mass units. The article considers the mass flow rate. We apply the method of measuring the flow rate by the pressure drop in the tank. It is based on gas laws, namely the Mendeleev-Clapeyron equation.

$$P_{\text{con}} V_{\text{con}} = M_{\text{con}} R T_{\text{con}},$$

where P_{con} – ammonia pressure, V_{con} – volume that ammonia takes, M_{con} – ammonia mass, R – gas constant, T_{con} – gas temperature. Thus, by measuring the pressure and temperature for two gas states in a tank, the average volume flow rate of the gas from the tank can be determined over time and normalized:

$$Q_{\text{con}} = \frac{V_{\text{con}}}{\Delta t}\left(\frac{P_{\text{con}1}}{RT_{\text{con}1}} - \frac{P_{\text{con}2}}{RT_{\text{con}2}}\right)\frac{1}{\rho_{\text{gd}}},$$

where Q_{con} – volumetric gas flow, ρ_{gd} – the gas density under normal conditions (pressure 101325 Pa and temperature 293 K).

The mass flow $\dot{m}_{\text{con}}$ is related to the volumetric flow Q_{con} by function $\dot{m}_{\text{con}} = \rho Q_{\text{con}}$, thus

$$\dot{m}_{\text{con}} = \frac{V_{\text{con}}}{\Delta t}\left(\frac{P_{\text{con}1}}{RT_{\text{con}1}} - \frac{P_{\text{con}2}}{RT_{\text{con}2}}\right).$$

For this method, a receiver of 111 liters is used (Fig. 6).

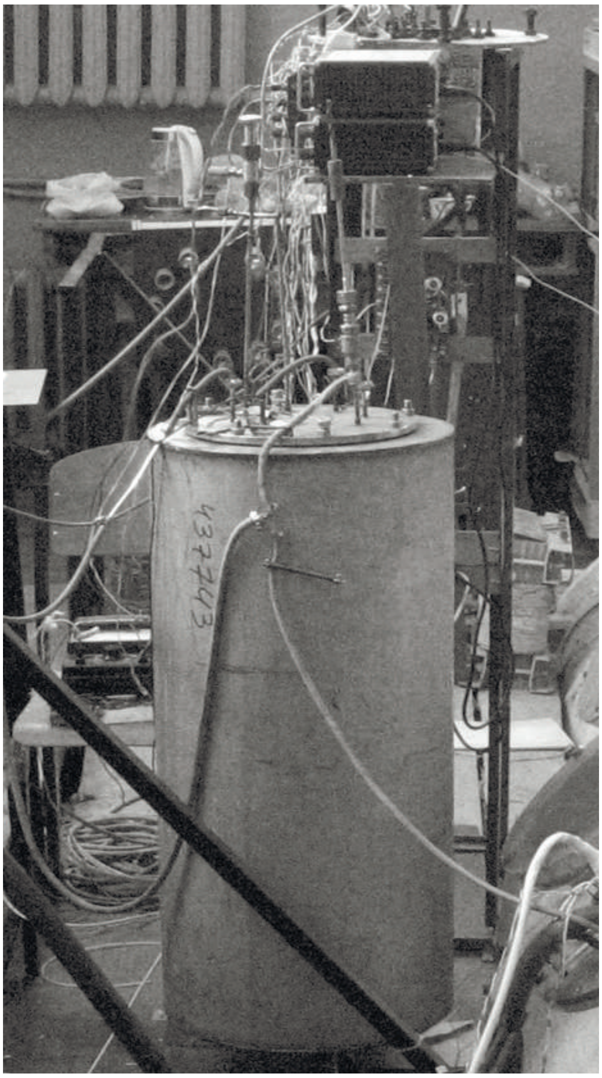


Fig. 6. Test bench receiver for determining the flow rate of the working fluid

Such a large receiver is designed to accumulate the working fluid and to compensate the pressure fluctuations, as well as for improving the accuracy of flow measurement (which can not be achieved on the standard receiver of the propulsion system – 1.4 liters). To measure the pressure inside the receiver, the pressure sensor mpx-4250 is used (Fig. 7), and for temperature measurement, the sensor TMP-36 is used (Fig. 8).

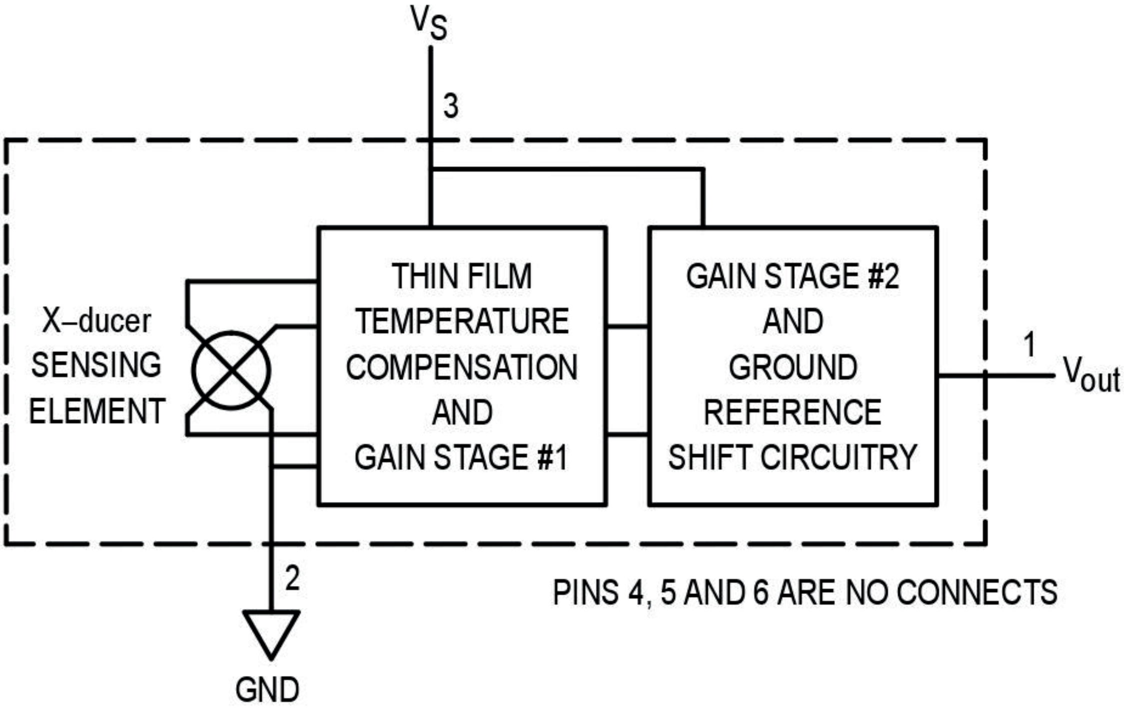


Fig. 7. The scheme of pressure sensor mpx-4250

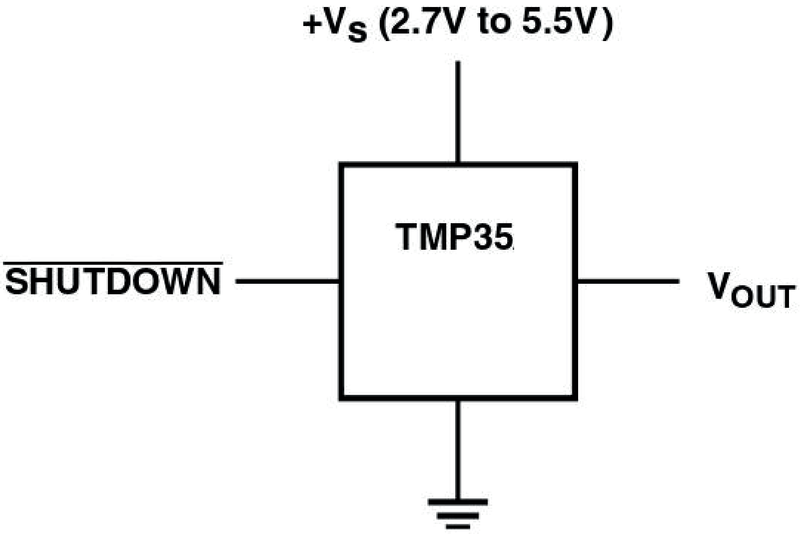


Fig. 8. The scheme of temperature sensor TMP-36

In this way, the task of measuring the flow rate of working fluid and thrust of electric heating engine can be solved completely. Table 2 below presents the errors of the elements used in the method of determining the working fluid flow in electric heating thruster for determining the instrument-induced error.

Table 2

Measuring ranges and percentage error of elements

Sensor name	Measurement range	Percentage error
Temperature sensor TMP-36	-40…+125 °C	±1.2%
Pressure sensor MPX4250	20×10^5 Pa...250×10^5 Pa	±1%
ADC AD7680BRMZ	0.1...2 V	±0.001%

Wire errors (the percentage error is less than 0.01%) can be neglected. Time is considered to be the computer time cycles of the personal computer (the percentage error is less than 0.001%), the error can also be neglected.

Thus, let's consider the instrumental error as the error of indirect measurements and determine the method of error transfer

$$\Delta_{\text{con}} = \sqrt{\Delta P_{\text{con}}{}^2 + \Delta T_{\text{con}}{}^2 + \Delta \text{ADC}_{\text{con}}{}^2}.$$

In a percentage equivalent we will get an instrumental error Δ_{con} = 1.42%.

The graduation of the temperature sensor is carried out according to the data of the standard thermometer according to OIML 84 2003 in the required work temperature range from 0 to 40 °C. The graduation of the pressure sensor, as well as the temperature sensor, is carried out by the computational method according to the standard manometer of OIML R 109:2009. The receiver with the volume of 111 liters is graduated at the NSC "Institute of Metrology", Kharkiv, according to the graduation act code DK 021-2015:71630000-3.

Method for measuring the power supplied to the heaters of engine, steam generator and EHPS tank. The scheme of the power sensor is shown in Fig. 9.

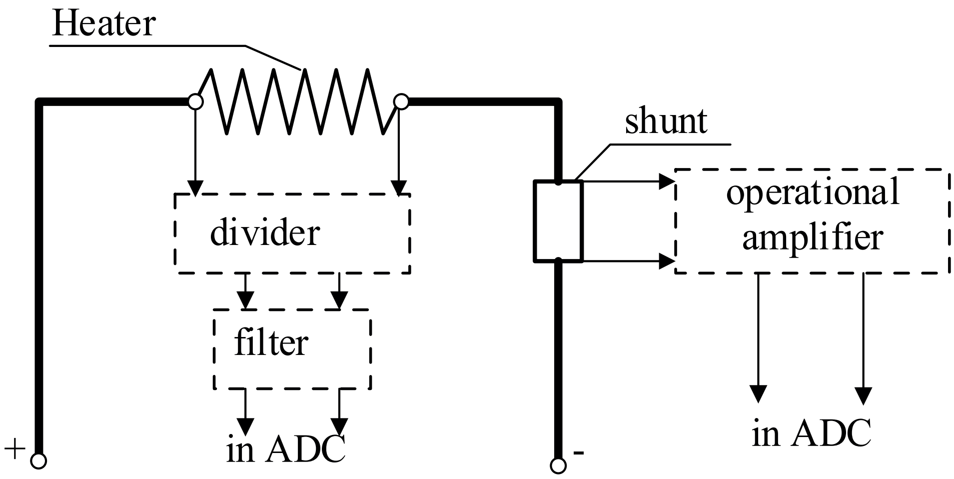


Fig. 9. The scheme of the sensor of power supplied to the tank, steam generator, engine

Here, the voltage splitter is a two-arm resistor splitter based on high precision stable resistors. The upper one, based on C5-35B0 W resistor, is 24 kΩ and the bottom one, based on C5-35B 50 W resistor, is 2 kΩ, with a minimum thermal resistance coefficient (TRC).

The filter represents resistance on the basis of resistor C5-35B 25 W – 1 kΩ and capacity on the basis of capacitor SMD2220 1 μF with 50 V connected in sequence. This part of the circuit is designed to reduce the measured voltage from 24 V to the required ADC sensitivity limit of 2 V. The FL-2 10 A 75 mV shunt is required to measure the current strength in the circuit, but its output voltage is 75 mV, which is insufficient for further transmission to the ADC. Operating amplifier MCP607 raises the shunt voltage of 0.75 mV to 2 V – ADC sensitivity zone.

Table 3 below shows the errors of elements used in the method of measuring the power supplied to the heaters of the engine, steam generator and EHPS tank.

Table 3

Measuring ranges and percentage error of elements

Sensor name	Measuring range	Percentage error
Resistor C5-35B 50 W – 24 kΩ	24 kΩ	±0.5%
Resistor C5-35B 50 W – 2 kΩ	2 kΩ	±0.5%
Resistor C5-35B 25 W – 1 kΩ	1 kΩ	±0.5%
Capacitor SMD2220 1 μF 50 V (X7R)	up to 50 V	±10%
ADC AD7680BRMZ	0.1...2 V	±0.001%
Electric shunt FL-2 100 A 75 mV	100 A	±1.5%
Operating amplifier MCP607	0.25...2.5 V	±0.01%
ADC AD7680BRMZ	0.1...2 V	±0.001%

Wire errors (the percentage error is less than 0.01%) can be neglected. The error of the capacitor can also be neglected, as it is installed as a smoothing filter and does not contribute to the system operation.

Let's consider the instrumental error as the error of indirect measurements and determine the method of error transfer

$$\Delta_{\text{Uload}} = \sqrt{\Delta R_{\text{up}}{}^2 + \Delta R_{\text{low}}{}^2 + \Delta R_{\text{filter}}{}^2 + \Delta \text{ADC}_{\text{Uload}}{}^2}.$$

In percentage equivalent we will get an instrument error Δ_{Uload} = 3.47%.

We will determine the instrumental error for current by the method of standard deviation

$$\Delta_{\text{Iload}} = \sqrt{\Delta I_{\text{shunt}}{}^2 + \Delta U_{\text{anpl}}{}^2 + \Delta \text{ADC}_{\text{Iload}}{}^2}.$$

In percentage equivalent we will get an instrument error Δ_{Uload} = 1.68%.

Vacuum measurement method in the experiment chamber. To measure the pressure inside the vacuum chamber of the experimental setup the vacuum gauge is used, which has been specifically developed for this purpose, on the basis of the manometric thermocouple transducer MTC-2, the scheme of connecting to the experimental facility is shown in Fig. 10, where 1 — case; 2 — filament; 3 — thermocouple; 4 — power inputs; 5 — thermocouple inputs, R_{shunt} — shunt, OA — operational amplifiers on the basis of ATmega128, Controller — control part of ATmega128, PS — power source on the basis of ATmega128, Out — output signal of the developed system.

The principle of operation of MTC-2 is based on the dependence of molecular heat conductivity of gas on its pressure. The transfer of heat comes from a thin metal thread heated by electric current, through thin gas to the vacuum pump.

In the thermocouple converter MTC-2, in the glass flask holders are fixed (1), on which the V-shaped heater made of thin wire (2) is fixed by spot welding, to the middle point of which the platinum-platinum-rhodium thermocouple is welded (3).

On a thread of the heater (2) passes a current of constant value, which heats the junction of the thermocouple (3), and in its circuit emerges thermo EMF.

Since the temperature of the heater depends on the pressure (density) of gas, its change will lead to a change in the EMF of the thermocouple, which through sigma-delta ADC enters the control unit based on ATmega128, and the filament current is also provided through ATmega128.

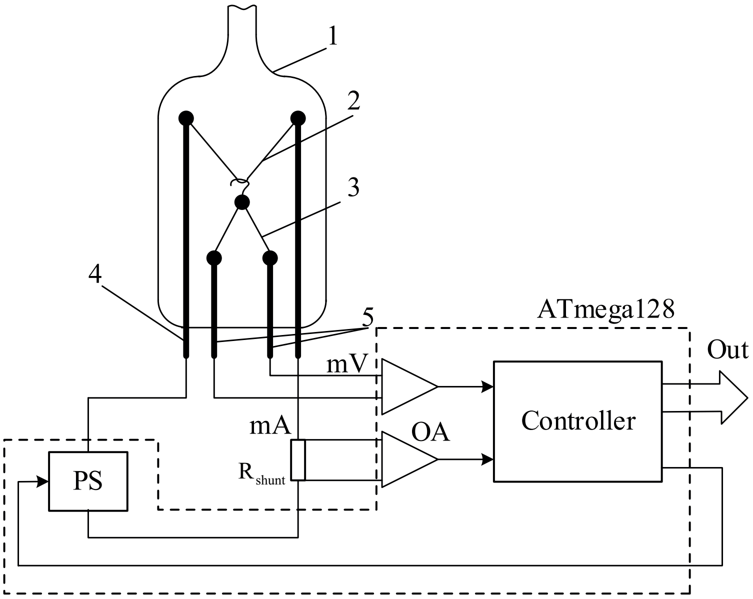


Fig. 10. Scheme of the thermocouple converter based on MTC-2

Table 4

Measuring ranges and percentage element error

Sensor name	Measuring ranges	Percentage error
BCL-300GM detector converter	0.133 Pa...666.6 Pa	±2%
Sigma delta ADC AD 7705BRZ-REEL	0-10 mV...2 V	±0.003%

Table 5

Test results of the thruster for the verification of the consumption and traction characteristics

Characteristics	Value		
	1 launch	2 launch	3 launch
Vacuum chamber pressure at start of launch, mm Hg	1.95×10^{-2}	1.95×10^{-2}	1.95×10^{-2}
Vacuum chamber pressure at the end of launch, mm Hg	1.7×10^{-1}	1.7×10^{-1}	1.7×10^{-1}
Pressure range of the stand receiver during thruster operation, kgf/cm^2	from 1.85 to 1.66	from 1.86 to 1.69	from 1.85 to 1.68
Thruster temperature control parameters:			
– duration, s	200	200	200
– average power consumption, W	205	210	202
Parameters when the thruster is switched on in flow mode:			
– duration, s	1140	1140	1140
– average power consumption, W	200	201	198
Average thrust per turn-on, mN	4.95	4.98	4.95
Average cost per turn-on, mg/s	19.35	19.33	19.35
Calculated value of specific impulse per switching on, m/s	2558	2593	2576
Duration of increasing the set value of the thrust to 90% from the moment the command is given to the electric valve ED1, s	Less than 1	Less than 1	Less than 1
Duration of decreasing the set value of the thrust to 10% from the moment of voltage cut-off at the electric valve, s	Less than 1		Less than 1
Steam generator running time, sec.	1100	1290	1320
Number of times the steam generator heater is turned on	105	100	110

Table 4 shows the error of the elements included in the vacuum measurement method in the chamber for the experiment.

Let's consider the instrumental error as the error of indirect measurements and determine the method of error transfer

$$\Delta_{\text{vacuum}} = \sqrt{\Delta\text{MTC}^2 + \Delta\text{ADC}_{\text{vacuum}}^{\;2}}.$$

In percentage equivalent we will get an instrument error Δ_{vacuum} = 2%.

The principle of graduation of a current of a heating element of the manometric transducer is that it is necessary to set such a current of the heating element that corresponds to thermo EMF of a thermocouple equal to 10 mV at pressures less than 0.133 Pa. At the plant manufacturing the MTC-2, the glass cylinder is vacuumized to the value 0.0133 Pa. At that the current is in the range of 100...125 mA.

Conclusion

In article the problem of obtaining an array of data interrelated on the main characteristics to assess the quality of the propulsion system operation is considered. For this purpose, the following is formulated:

- the method of measuring of the engine thrust as the main characteristic in the stable and transient mode;
- the method of determining the flow of the working fluid, correlated with the thrust;
- the method of measuring the power consumption parameters – currents, voltage, power in statics and dynamics;
- the method of measuring the environmental conditions of space simulation, namely the vacuum in the test chamber.

The analysis of the elements included in the sensors is carried out and the instrumental error for each method is calculated, the limiting errors of the experiment are obtained.

For graduation of strain gauge sensor a software product was created and the method of its graduation was developed.

As a result of the experiments, the arrays of main data of electric heating engines on the principal directions were obtained, namely, the experimental data on thrust, working fluid consumption, power consumption. For a number of launches of the propulsion system the data are summarized in Table 5, which shows the results reduced to 200 W power consumption.

The data on environmental conditions of space simulation, namely the vacuum in the test chamber, were obtained. The obtained experimental data make possible their further comparison with the data got with the help of the mathematical model of the electric heating propulsion system [3].

Методи і засоби експериментальних досліджень електронагрівних двигунів космічних апаратів

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Анотація

Предметом дослідження є вимірювання основних характеристик електронагрівного двигуна в процесі прискорення робочого тіла при стендових випробуваннях. Метою є формування стендових засобів дослідження характеристик електронагрівної рухової установки для застосування на космічному буксирі з урахуванням динаміки запуску, умов експлуатації та динаміки виключення. Завдання: вимірювання тяги електронагрівної рухової установки як основної характеристики в сталому і перехідному режимі; визначення витрати робочого тіла, що корелює з тягою; вимірювання параметрів електроспоживання – струмів, напруги, потужності в статиці й динаміці; вимірювання зовнішніх умов імітації космічного простору, а саме вакууму у випробувальній камері. Використовуваними методами є: тензометрія диференціального манометра, чотирьохзондове вимірювання потужності, яка подається на нагрівачі двигуна, парогенератора і бака електронагрівної рухової установки, іонізаційно-термопарний вакуумметр.

Отримано такі результати: визначено склад інформаційно-керуючої системи, що складається з тензометричного давача, застосовуваного з електронагрівною руховою установкою, витратоміра робочого тіла електронагрівної рухової установки, вимірювача потужності нагрівача двигуна, парогенератора, бака електронагрівної рухової установки, іонізаційно-термопарних давачів визначення вакууму. Створено програмний продукт для градуювання тензометричного давача. Наукова новизна полягає в тому, що отримали подальший розвиток такі методи: метод вимірювання тяги електронагрівної рухової установки за допомогою тензометричного давача, метод вимірювання витрати робочого тіла електронагрівної рухової установки, метод вимірювання потужності нагрівача двигуна, парогенератора, бака електронагрівної рухової установки. Вперше розроблено алгоритм градуювання тензометричного давача за допомогою програмного продукту, створеного для електронагрівної рухової установки.

Ключові слова: космічний буксир; електронагрівна рухова установка; електронагрівний двигун; метод вимірювання тяги; метод вимірювання витрати робочого тіла; метод вимірювання потужності нагрівача; метод вимірювання вакууму у вакуумній камері.

Методы и средства экспериментальных исследований электронагревных двигателей космических аппаратов

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Аннотация

Предметом исследования является измерение основных характеристик электронагревного двигателя в процессе ускорения рабочего тела при стендовых испытаниях. Цели: формирование стендовых средств исследования характеристик электронагревной двигательной установки с учетом динамики запуска и выключения. Задачи: измерение тяги в установившемся и переходном режиме; определение расхода рабочего тела; измерение параметров электропотребления – токов, напряжения, мощности в статике и динамике; измерение внешних условий имитации космического пространства, а именно вакуума в испытательной камере. Используемые методы: тензометрия дифференциального манометра, четырехзондовое измерение мощности двигателя, парогенератора, ионизационно-термопарная вакууметрия. Определен состав информационно-управляющей системы, состоящей из тензометрического датчика, расходомера рабочего тела, измерителя мощности нагревателя двигателя, парогенератора, датчиков определения вакуума. Создан программный продукт для градуировки тензометрического датчика. Получили дальнейшее развитие методы измерения тяги с помощью тензометрического датчика, измерения расхода рабочего тела, измерения мощности нагревателя двигателя, парогенератора, бака. Разработан алгоритм градуировки тензометрического датчика.

Ключевые слова: космический буксир; электронагревная двигательная установка; электронагревный двигатель; метод измерения тяги; метод измерения расхода рабочего тела; метод измерения мощности нагревателя; метод измерения вакуума в вакуумной камере.

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