UDC 629.7.063.2
DOI: 10.15587/1729-4061.2023.287007

OPTIMIZATION OF THE ACCUMULATOR TANK FILLING MODES OF THE XENON FEED SYSTEM FOR ELECTRIC PROPULSION SYSTEM

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The object of the study in this work is pressure spikes in the accumulator tank of the xenon feed system for electric propulsion. The presence of significant pressure spikes in the accumulator tank of the feed system causes a change in the mass flow and, accordingly, a significant deterioration of the thruster parameters – thrust, specific impulse and efficiency. The problem that was solved in this work is to find ways to reduce pressure spikes while minimizing the volume of the accumulator tank without using additional elements. The analysis of literary sources showed that the specified problem is typical and has not been solved for small-volume accumulator tanks yet. To solve this problem, theoretical and experimental determination of pressure spikes that occur during the work on feedback from sensors was carried out, and an improved method of filling the accumulator tank was proposed. As a result of research, it was determined that pressure spikes that go beyond the permissible range (±3 %) appear at an inlet pressure of 3.5 MPa. With an increase of inlet pressure, the pressure spikes also increase. As a result of research, it was found that for an inlet pressure of up to 3 MPa, it is appropriate to work on feedback from pressure sensors. For pressure values from 3 to 6 MPa, it is necessary to use the experimentally obtained formula to determine the accumulator tank filling time. For a pressure of more than 6 MPa, it is necessary to work in the bang-bang mode. The research made it possible to determine the optimal modes of filling the accumulator tank. Presented modes allow to use a small-volume accumulator tank with the minimization of the valve activations number, in which stable operation of the thruster is maintained. The conclusions obtained as a result of the research can be useful for most developers of feed systems for electric propulsion

Keywords: operation modes of the feed system, pressure spikes, methodology of accumulator tank filling, bang-bang, feedback from pressure sensors

Received date 26.06.2023
Accepted date 04.09.2023
Published date 25.09.2023

***How to Cite** Yurkov, B., Asmolovskyi, S., Pererva, V., Voronovskyi, D., Kulagin, S. (2023). Optimization of the accumulator tank filling modes of the xenon feed system for electric propulsion system. Eastern-European Journal of Enterprise Technologies, 5 (2 (125)), 78–86. doi: https://doi.org/10.15587/1729-4061.2023.287007*

1. Introduction

The xenon feed system (XFS) is an essential part of the electric propulsion system. The accuracy and stability of the parameters, as well as the reliability of the XFS, guarantee the supply of the required amount of working substance with the specified accuracy to the anode and cathode units of the thruster. It ensures the necessary thruster operating modes and the necessary parameters of the electric propulsion as a whole.

One of the main characteristics of the XFS is the accuracy of maintaining working substance mass flow, which is assigned depending on the thruster, and is up to ±5 %, which is noted in works [1–3]. At the same time, the accuracy of maintaining the mass flow rate depends on the accuracy of maintaining the pressure in the XFS. An accumulator tank is the most often used to stabilize and reduce the pressure from high (12.5 MPa) to working (0.1–0.2 MPa) in the XFS.

Based on accumulator tank feed systems are reliable and cheap, however, compared to feed systems that use proportional valves, they have large dimensions and weight. In case of decreasing the volume of the accumulator tank, pressure spikes are observed in the accumulator tank which leads to exceeding the permissible values of the mass flow rate and, accordingly, unstable operation of the thruster. Thus, reducing the magnitude of pressure spikes (increasing accuracy) in the accumulator tank when reducing its volume is an urgent scientific task and requires additional scientific research.

2. Literature review and problem statement

The paper [4] gives the results of research on the dependence of the pressure maintenance accuracy in an accumulator tank on its volume when using feedback from pressure sensors to fill the accumulator tank. A pressure hold accuracy of ±4 % is shown to be provided by a 1 L accumulator tank, and an accuracy of ±2 % is provided by a 4 L accumulator tank. The need to increase the volume of the accumulator tank to increase the accuracy of pressure maintenance is associated with the method of filling the accumulator tank, as well as high values of inlet pressures. However, this approach does not solve the issue of ensuring the accuracy of pressure maintenance in the accumulator tank of ±5 % with smaller accumulator tank volumes (0.45 L). The need to reduce the volume of the accumulator tank is due to strict requirements from spacecraft manufacturers regarding the size and mass of its subsystems.

An option to overcome the above-mentioned shortcomings is the use of two-stage pressure regulation, which allows to reduce the value of the inlet pressure. For example, in works [5, 6], a mechanical pressure regulator is used to preliminarily reduce the pressure in front of the accumulator tank. This makes it possible to maintain pressure in a narrow range with a reduced volume of the accumulator tank. However, the mechanical pressure regulator has lower reliability, compared to solenoid valves, and a shorter lifetime. In [7], an additional high-pressure accumulator tank was used. This approach is more reliable in comparison with the use of a mechanical pressure regulator, but it leads to the complication of the XFS.

The main purpose of maintaining the pressure of the accumulator tank in the narrow range is to ensure the required mass flow rate of the working substance to the electric propulsion thruster. In this way, it is possible to use an alternative method to ensure the required mass flow accuracy of the XFS without maintaining the pressure of the accumulator tank in the narrow range due to the use of flow regulators after the accumulator tank. The work [8] investigated the use of a thermothrottle as a regulator of the working substance flow, which made it possible to expand the maintained pressure range in the accumulator tank, thereby reducing its volume. However, the disadvantages of this approach are the inertia of the thermothrottle and the increase in power consumption of the XFS. A way to overcome the inertia of the thermothrottle can be the use of proportional valves. This approach is used in [9]. But this method leads to complications in the design and increases the price of the XFS.

Another way to ensure the required accuracy of mass flow to the thruster without increasing the volume of the accumulator tank, using two-stage regulation or flow regulators after the accumulator tank is to change the methodology of filling the accumulator tank. Such a solution is presented in works [10, 11], which propose the use of the "bang-bang" mode as a method of filling the accumulator tank. In this method, instead of one long opening of the valve to completely fill the accumulator tank, frequent short-term opening of the solenoid valves is performed, which allows the pressure in the accumulator tank to be gradually increased to the required level. This approach allows maintaining the pressure in a small volume accumulator tank with the necessary accuracy for a wide range of inlet pressures. However, the disadvantage of this method is that it leads to an excessive number of solenoid valves activations at low inlet pressure. As a result, this approach reduces the lifetime of the XFS or requires the use of solenoid valves with a high service life.

Maintenance of the working substance flow rate is a critical parameter that affects the main values of the thruster parameters – thrust, specific impulse, and efficiency. The methods of ensuring the necessary consumption of the working substance specified in the works [4–11] do not solve all the requirements put forward by the spacecraft to the XFS-mass, dimensions, power consumption, service life, reliability, and price. All this makes it possible to assert that it is appropriate to conduct research devoted to the improvement of the accumulator tank filling method in order to improve the feed system characteristics while reducing the volume of the accumulator tank.

3. The aim and objectives of the study

The purpose of this study is to optimize accumulator tank filling modes while reducing the volume of the electric propulsion feed system with minimization of solenoid valve activations. This ensures the supply of the working substance to the anode block and the cathode with the necessary accuracy, which ensures the necessary characteristics and stable operation of the electric propulsion thruster.

In accordance with the set goal, the following tasks were formulated:

– to improve the method of filling the accumulator tank on the basis of theoretically and experimentally determined dependences of pressure spikes in the accumulator tank on the inlet pressure;

– experimentally confirm the accuracy of maintaining the pressure of the working substance in the accumulator tank when using the improved filling methodology, which will ensure stable operation of the electric propulsion system.

4. The study materials and methods

The object of the study is pressure spikes in the accumulator tank during its filling in the XFS developed for the SPS-25 electric propulsion system. The presented XFS differs from the previous one, for the electric propulsion system SPS-40 [12], in reduced dimensions to compete with the feed systems that use proportional valves in terms of mass and size requirements. And also using a galvanically decoupled analog-to-digital converter. This converter receives the signal from sensors with minimal loss and transmits it to the power processing unit (PPU) instead of using a filter, which reduces noise during thruster operation [13]. This innovation makes it possible to increase the accuracy of pressure sensors and reduce the likelihood of their failure during thruster operation. The general view of the XFS for the electric propulsion system SPS-25 is presented in Fig. 1

Fig. 1. General view of the xenon feed system for the electric propulsion SPS-25

The study was conducted using the following equipment:

1. Laboratory xenon loading cart (Fig. 2), the main elements of which are Swagelok connectors, a 7-μm filter FL1-H-3M-7, a Drastar 072S-0500C-1S pressure regulator, a branch of stainless steel pipelines AISI 321, a Swagelok hose SS-FM4PM4SM6-100CM and a tank with xenon which is used as a xenon source.

Fig. 2. Laboratory xenon loading cart

2. Pressure booster (Fig. 3). Whereas the pressure in the tank for electric propulsion missions exceeds 10 MPa, and the pressure in the laboratory xenon loading cart is much lower. There is a need to use a device that makes it possible to increase and adjust the pressure level at the XFS entrance to simulate work at various stages of electric propulsion system operation. The change in pressure occurs due to the change in the volume of the pressure booster cavity and is controlled by a calibrated up to 16.7 MPa pressure sensor Omega PX459.

Fig. 3. Pressure booster

3. The SPS-25 PPU was developed by the Flight Control company (Fig. 4), which passed qualification tests for compliance with the specified characteristics. With the help of PPU SPS-25, pressure control and control of solenoid valves of the XFS are carried out.

Fig. 4. Power processing unit SPS-25

The study and the value of pressure spikes in the XFS for SPS-25 (Fig. 5) were carried out at different values of inlet pressure and a constant value of temperature.

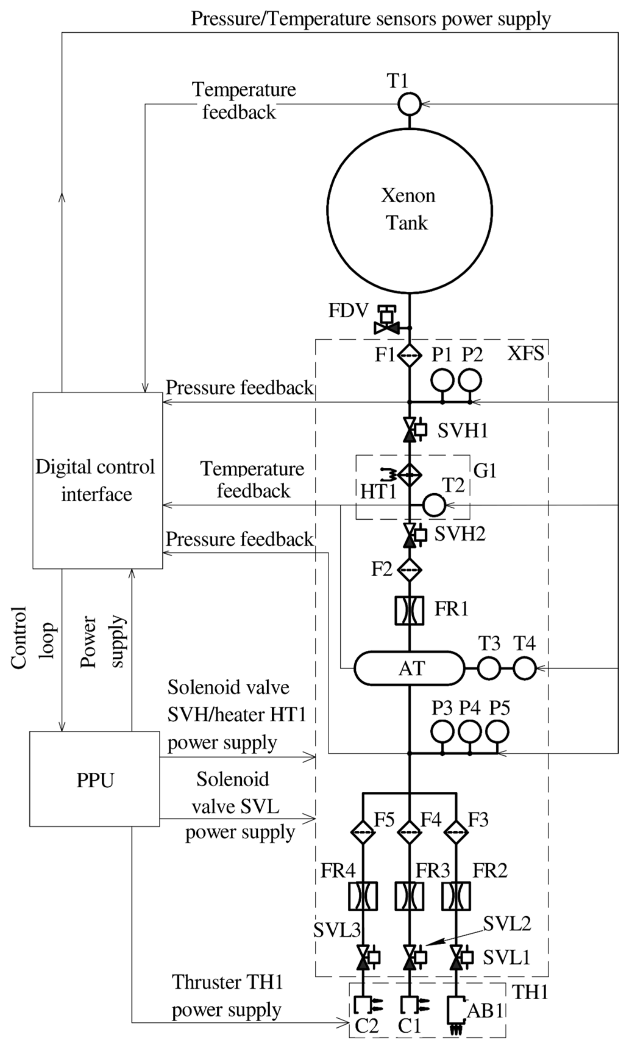

Fig. 5. Structural diagram of the electric propulsion system SPS-25: T – Temperature sensor; FDV – Fill and drain valve; P – Pressure transducer; F – Filter; SVH – High pressure solenoid valve; FR – Flow restrictor; HT – Heater; G – Gasifier; AT – Accumulator tank; SVL– Low pressure solenoid valve; TH – Thruster

The study procedure consisted of two stages. At the first stage, the maximum values of pressure spikes in the accumulator tank during its filling were theoretically and experimentally investigated by feedback from pressure sensors. The study was conducted in the range of inlet pressures from 2 to 7 MPa and compared with the obtained calculated values.

The working substance (xenon), which is stored in a high-pressure tank, when SVH1, SVH2 valves are activated, fills the accumulator tank AT through the flow restrictor FR1 and the filter F2. The pressure in the accumulator tank AT rises to the set maximum working pressure, according to the values of the pressure sensors P3–P5, after which valves SVH1, SVH2 are closed. Valves are controlled by the control unit in the PPU. Feedback from pressure sensors with a range of ±2 % was used as the main accumulator tank filling mode, as well as 1 % as compensation for pressure spikes after closing the valves.

According to the data obtained at the first stage, the dependence of pressure spikes in the accumulator tank and the time of filling the accumulator tank on the inlet pressure was determined. Based on these dependencies, the method of filling the accumulator tank was improved.

In the second stage, the reduction of pressure spikes in the accumulator tank at the corresponding inlet pressures was experimentally confirmed using the proposed method in the entire pressure range (up to 12.5 MPa) for the electric propulsion system SPS 25.

To simulate the flow of xenon from the accumulator tank to the thruster during experiments solenoid valves SVL1 and SVL2 were in the open state. The outputs of solenoid valves SVL1 and SVL2 were connected to the vacuum pump through Bronkhorst flowmeters. This made it possible to measure the mass flow at the minimum, nominal and maximum pressure values in the accumulator tank using specialized programs Bronkhorst FlowView 1.23 and FlowPlot V3.35 (Fig. 6).

Registration of parameters was carried out after each cycle of measurements, the value of inlet pressure, pressure of the accumulator tank, and temperature were recorded.

In the course of the experimental studies, the pressure measurement in the XFS was carried out by calibrated ICS-NH pressure sensors of 0.5 MPa (P3, P4, P5) for the accumulator tank pressure and 18 MPa (P1, P2) for the inlet pressure with an error of 0.75 % FS. The pressure in the accumulator tank was determined as the average value of the readings of three pressure sensors P3, P4, P5, and at the inlet as the average value of the readings of two pressure sensors P1 and P2. The absolute error of pressure sensors was determined by the following formula for measuring devices with the same error:

$$\Delta_{av} = \frac{\Delta}{\sqrt{n}}, \tag{1}$$

where Δ_{av} – resulting measurement error;
Δ – absolute error of the measuring device;
n – number of identical measuring devices.

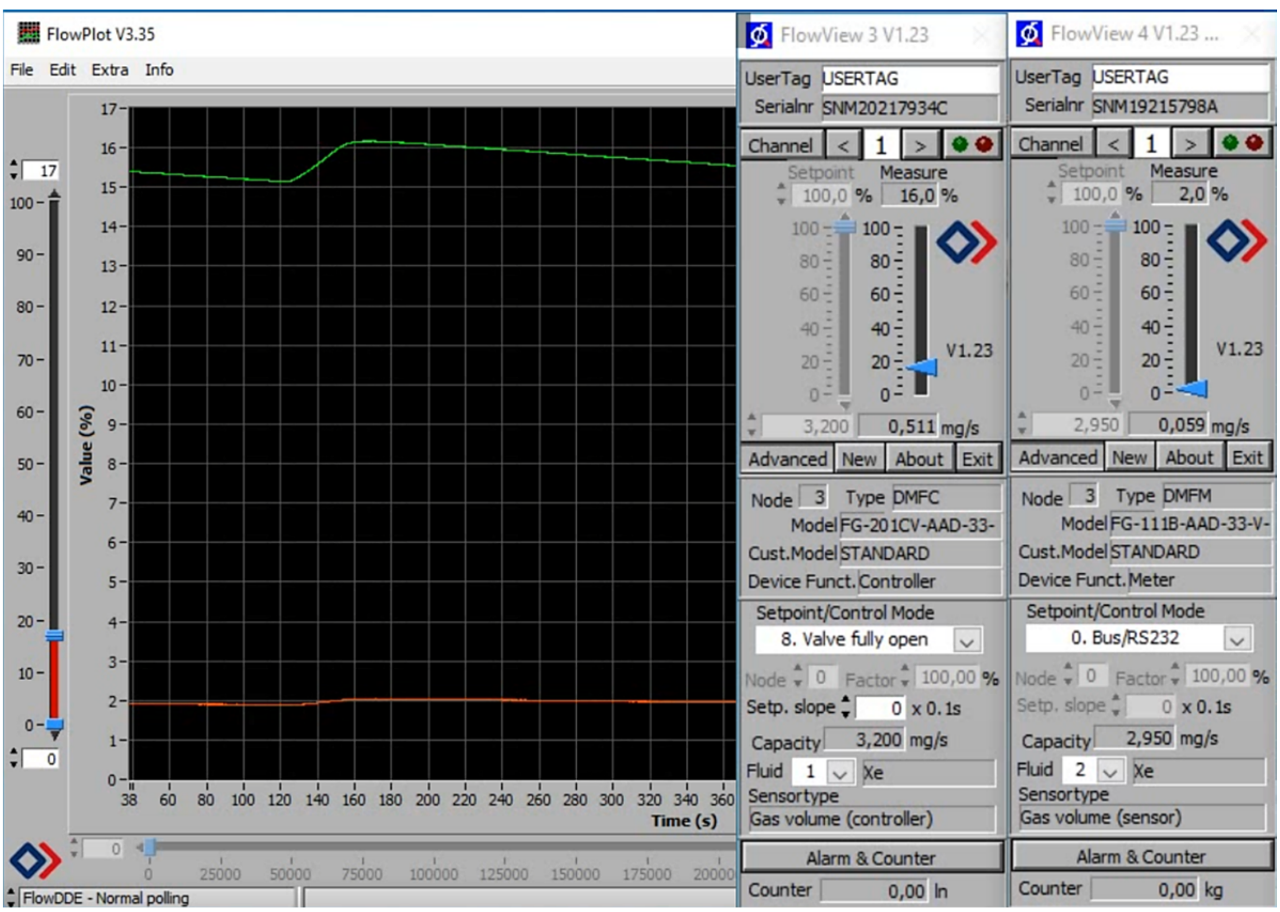

Fig. 6. Registration of mass flow rate parameters during pressure spikes

5. Results of pressure spikes studies in the accumulator tank of the xenon feed system

5. 1. Development of an improved accumulator tank filling method

Due to the decrease in the volume of the accumulator tank, increased values of pressure spikes after closing solenoid valves SVH1 and SVH2 were expected when using the method of filling the accumulator tank with feedback from pressure sensors. These pressure spikes are related to the equalization of pressures in the cavity, between the solenoid valve SVH2 and the flow restrictor FR1 (in which xenon has accumulated with a pressure equal to the pressure in the tank) and the accumulator tank. The pressure spike for one of the experimental points is shown in Fig. 7. From Fig. 7, it is shown that after closing the solenoid valve SVH2 at a pressure in the accumulator tank that exceeds the nominal value by 2 %, the pressure in the accumulator tank continues to increase and exceeds the nominal value by 5 % at the highest point.

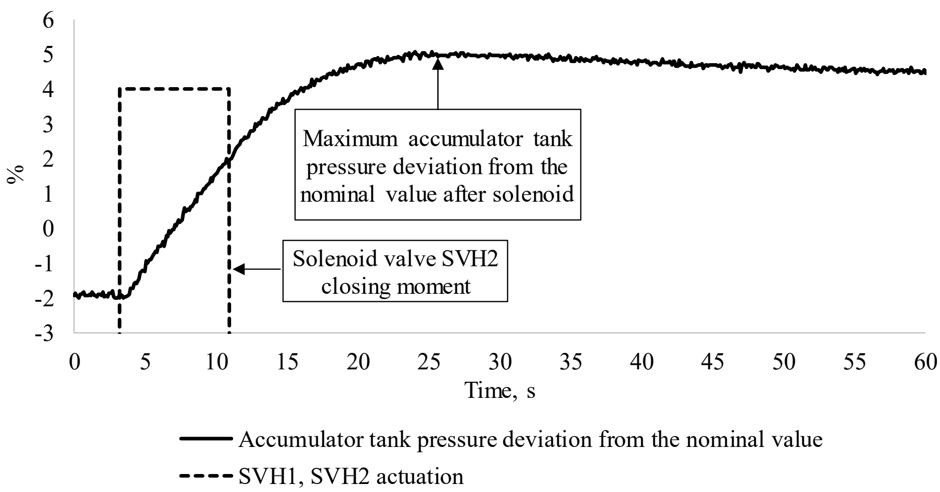

Fig. 7. Experimental values of the accumulator tank pressure deviation from the nominal value during work with feedback from pressure sensors at an inlet pressure of 5.9 MPa and a temperature of 28 °C

The values of pressure spikes in the accumulator tank were preliminary determined by the following formulas:

$$\delta P_{AT} = \frac{P_{ATmax}}{P_{ATnom}}, \quad (2)$$

$$P_{ATmax} = \frac{M_{XeCav} + M_{XeAT}}{V_{Cav} + V_{AT}} = \frac{V_{Cav} \cdot \rho_{XeCav} + V_{AT} \cdot \rho_{XeAT}}{V_{Cav} + V_{AT}} \cdot R \cdot T, \quad (3)$$

where δP_{AT} – maximum pressure deviation in the accumulator tank from the nominal value, after closing the solenoid valve SVH2, %;

P_{ATmax} – maximum value of the pressure in the accumulator tank after the completion of pressure equalization, Pa;

P_{ATnom} – nominal value of the pressure maintained in the accumulator tank, Pa;

M_{XeCav} – mass of xenon in the cavity between the solenoid valve SVH2 and the flow restrictor FR1 after closing the solenoid valve SVH2, kg;

M_{XeAT} – mass of xenon in the accumulator tank after closing the solenoid valve SVH2, kg;

V_{Cav} – volume of the cavity between the solenoid valve SVH2 and the flow restrictor FR1, m^3;

V_{AT} – accumulator tank volume, m^3;

ρ_{XeCav} – xenon density in the cavity between the solenoid valve SVH2 and the flow restrictor FR1 after closing the solenoid valve SVH2, kg/m^3;

ρ_{XeAT} – xenon density in the cavity between the solenoid valve SVH2 and the flow restrictor FR1 after closing the solenoid valve SVH2, kg/m^3;

R – gas constant of xenon, J/(kg·K);

T – temperature of xenon, K.

Then an experimental determination of the maximum pressure deviations in the accumulator tank from the nominal value and the accumulator tank filling time was carried out in the range of inlet pressures from 2 to 7 MPa, after closing the solenoid valve SVH2. The solenoid valve SVH2 was closed by feedback from the accumulator tank pressure sensors, at the level of 2 % from the nominal pressure.

The results of calculations and experimental determination of the maximum pressure deviations in the accumulator tank from the nominal value and the accumulator tank filling time after closing the solenoid valve SVH2 are shown in Fig. 8, 9. The calculated values are overestimated because the xenon flow from the accumulator tank to the thruster was not taken into account during the calculations. In Fig. 9 accumulator tank filling time – the time period from the moment of issuing the command to open solenoid valves SVH1 and SVH2 to the moment of issuing the command to close them. Solenoid valves SVH1 and SVH2 were closed by feedback from pressure sensors when the pressure in the accumulator tank was +2 % of the nominal value.

Based on the obtained data (Fig. 8), it was established that at the inlet pressure of more than 3.5 MPa, the pressure in the accumulator tank exceeds the permissible 3 % range after the filling is completed. A further increase in inlet pressure leads to an even greater pressure deviation in the accumulator tank.

To provide the required accumulator tank pressure range, simply changing the adjustment range from ±2 %, for example, to ±1 %, would not give the desired result. Because when the tank pressure is more than 5 MPa, in any case, the overflow in the accumulator tank will occur. It also leads to an increase in the frequency of solenoid valves operation, which shortens the service life of the XFS.

Therefore, an improved methodology that allows to reduce pressure spikes in the accumulator tank without increasing its volume was developed.

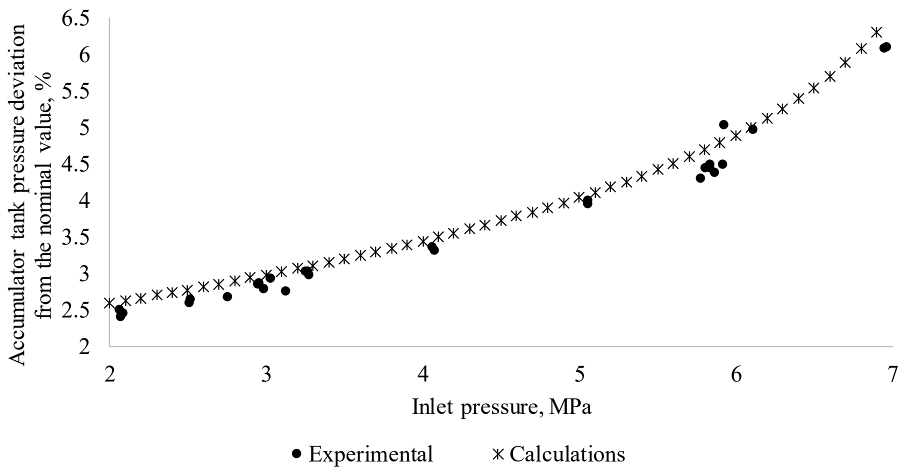

Fig. 8. Accumulator tank pressure deviation from the nominal value during work on feedback from pressure sensors

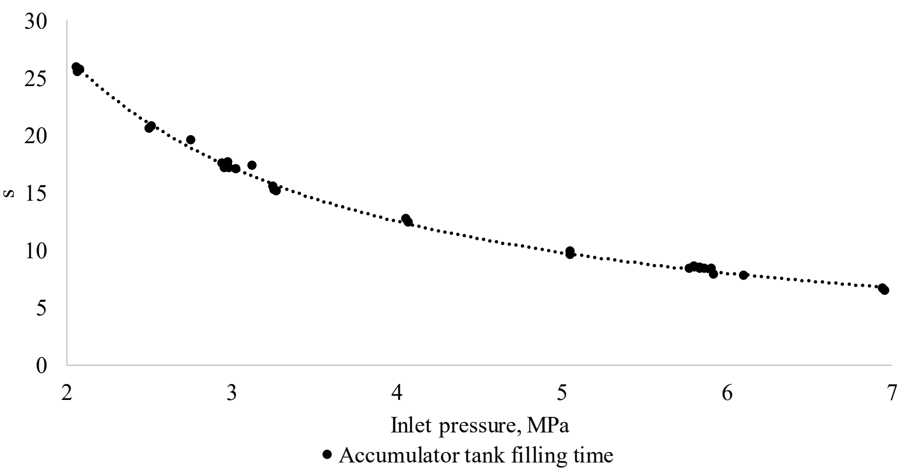

Fig. 9. Experimental values of accumulator tank filling time

It is proposed to divide the accumulator tank filling procedure into several sections taking into account the change in the tank pressure to optimize the number of valve activations and maintain the accumulator tank pressure in the required range.

The first section: when the pressure in the tank is up to 3 MPa, the filling of the accumulator tank is carried out on the basis of feedback from the pressure sensors in the range ±2 % of the nominal value.

The second section: when the pressure in the tank is more than 3 MPa and less than 6 MPa. Filling is carried out by simultaneously opening solenoid valves SVH2 and SVH1 for a period of time t_{open} (seconds), which is determined by the empirical formula:

$$t_{open} = 17.44 - 2.9 \cdot P, \qquad (4)$$

where P – the current value of the pressure in the tank (Pa).

Formula (4) to determine the duration of accumulator tank filling is established based on the XFS test results and depends on:

– nominal pressure in the accumulator tank;

– volumes of the accumulator tank and the cavity between the solenoid valve SVH2 and the flow restrictor FR2;

– accumulator tank filling time;

– minimum operating temperature.

Formula (4) was obtained by approximation of the SVH2 valve opening time determined values taking into account the pressure spikes after its closure t_{op} for the range of inlet pressures from 3 to 6 MPa according to the following formula:

$$t_{op} = \frac{1.5 \cdot \delta_{ATnom} - \delta P_{AT}}{\delta_{ATnom}} \cdot t, \qquad (5)$$

where δ_{ATnom} – pressure range maintained in the accumulator tank relative to the nominal value, %;

δP_{AT} – maximum pressure deviation in the accumulator tank from the nominal value, after closing the solenoid valve SVH2 for the given inlet pressure (Fig. 8), %;

t – accumulator tank filling time for the given inlet pressure (Fig. 9), s.

The results of experiments and calculations of t_{op} and comparison with the proposed formula (4) to determine t_{open} are shown in Fig. 10. As can be seen, formula (4) corresponds to the solenoid valve SVH2 opening time at the minimum xenon temperature (20 °C) at the flow restrictor inlet. Since the pressure spikes increase with decreasing temperature and accordingly decrease accumulator tank filling time, which is the worst case.

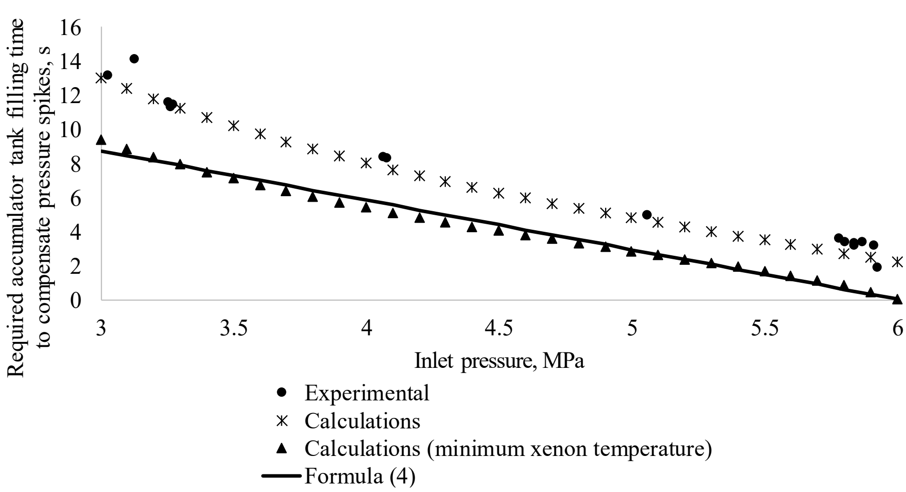

Fig. 10. Results of determining the accumulator tank filling time to compensate for pressure spikes after solenoid valve SVH2 is closed

The third section: when the pressure in the tank is ≥6 MPa. Filling is carried out by briefly opening the solenoid valve SVH2 (20 ms) while the valve SVH1 is closed. After the solenoid valve SVH2 is closed, the solenoid valve SVH1 opens for 5 s to restore the pressure in the cavity between the solenoid valves SVH1 and SVH2. While the SVH1 valve is closed, the short opening duration of the SVH2 solenoid valve allows to reduce inlet pressure of the flow restrictor, and accordingly, pressure spikes after SVH2 is closed.

5. 2. Experimental confirmation of the presented method to maintain xenon pressure in the accumulator tank with required accuracy

Experimental confirmation of the presented method to maintain xenon pressure in the accumulator tank with required accuracy was carried out in the range of inlet pressure from 2 to 12.5 MPa.

Fig. 11 shows a comparison of the deviation from the nominal pressure at work with feedback from pressure sensors and the proposed method of filling the accumulator tank. It can be seen that in the entire working range (up to 12.5 MPa) of the tank pressure for electric propulsion system SPS-25, the pressure in the accumulator tank is within the tolerance of ±3 %.

From Fig. 11, it can be seen that for the first section (inlet pressure up to 3 MPa), the accuracy of pressure maintenance according to the improved method corresponds to the method of filling the accumulator tank using feedback from pressure sensors. For the second and third sections (inlet pressure greater than 3 MPa), the use of an improved filling method allows to increase the accuracy of pressure maintenance in the accumulator tank up to 4 times (at maximum inlet pressure).

The proposed method of filling the accumulator tank has been successfully tested and used for the SPS-25 electric propulsion system that was installed on the spacecraft. Telemetry data obtained from the onboard computer are shown in Fig. 12.

Fig. 12 confirms the maintenance of the pressure in the accumulator tank within the specified limits, which ensures the necessary mass flow rates for the nominal operation of the electric propulsion system in orbit.

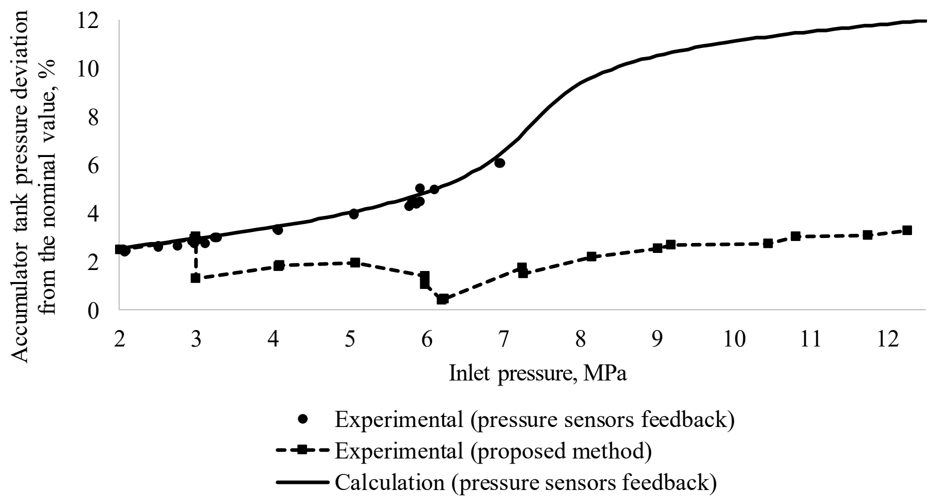

Fig. 11. Comparison of accumulator tank pressure deviation from nominal according to the new method and the method based on feedback from pressure sensors

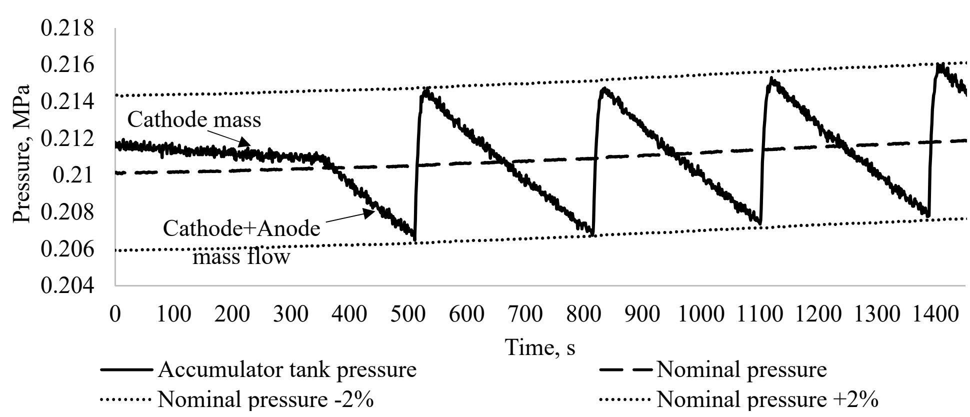

Fig. 12. Telemetry of pressure maintenance in the accumulator tank during electric propulsion system operation on board the spacecraft

6. Discussion of the results of pressure spikes studies in the accumulator tank of the xenon feed system

As is known from [4], reducing the volume of the accumulator tank leads to a decrease in the accuracy of maintaining the pressure in it when using the method based on feedback from pressure sensors to fill the accumulator tank. This is due to the increased values of pressure spikes, which occur due to the accumulation of xenon with high pressure in the cavity between the solenoid valve and the flow restrictor installed along the accumulator tank filling line. Subsequent xenon overflow from the cavity to the accumulator tank leads to an increase in pressure in it (Fig. 7).

As a result of theoretical and experimental studies, the dependence of pressure spikes in the XFS SPS-25 accumulator tank on the inlet pressure (Fig. 8) at filling according to feedback from pressure sensors was determined. According to Fig. 8, the inlet pressure over 3.5 MPa leads to exceeding the permissible pressure maintenance accuracy (±3 %), which negatively affects the parameters of the electric propulsion thruster. Therefore, it became necessary to improve the method of accumulator tank filling, which makes it possible to maintain the required pressure range of the accumulator tank.

Based on the obtained data, Fig. 8–10 and theoretical calculations according to formulas (2), (3) and (5), an improved method of filling the accumulator tank was developed. This method changes the approach to the accumulator tank filling depending on the inlet pressure. The process of accumulator tank filling was divided into three sections:

– when the pressure in the tank is up to 3 MPa, the filling of the accumulator tank is carried out on the basis of feedback from the pressure sensors;

– when the pressure in the tank is more than 3 MPa and less than 6 MPa. Filling is carried out by simultaneously opening solenoid valves SVH2 and SVH1 for a period of time, which is determined by the formula (4);

– when the pressure in the tank is ≥6 MPa. Filling is carried out by briefly opening the solenoid valve SVH2 (20 ms) while the valve SVH1 is closed.

Experimental verification of the proposed method confirmed the accuracy of pressure maintenance in the range of ±3 % in the entire range of inlet pressures (Fig. 11). This made it possible to successfully use the proposed method to maintain pressure in the accumulator tank of XFS SPS-25 (Fig. 12) in orbit on board the spacecraft.

In contrast to [4], where the method to fill the accumulator tank based on feedback from pressure sensors is used, the proposed method makes it possible to reduce accumulator tank volume without deteriorating in accuracy of pressure maintenance. This becomes possible due to the fact that the proposed method takes into account the inlet pressure. Also, unlike [5–7], the proposed method does not require the use of two-stage pressure regulation. This makes it possible to simplify the design of the XFS and reduce its weight and dimensions. Since the proposed method allows maintenance of accumulator tank pressure in the given range, accordingly, there is no need to use a working substance flow regulator as proposed in works [8, 9]. This makes it possible to simplify the design of the XFS, reduce energy consumption and cost. In contrast to [10, 11], where the «bang-bang» mode is used, in the proposed method short-term valve opening is used only for high inlet pressures of more than 6 MPa. Therefore, changing the method of filling the accumulator tank from «bang-bang» to the proposed one enables a reduction in the number of solenoid valve activations and increases the service life of the XFS. This becomes possible due to the fact that at inlet pressures of less than 6 MPa, the accumulator tank filling according to the proposed method takes place in one solenoid valve actuation. While for the "bang-bang" mode, the number of activations increases as the inlet pressure decreases.

The proposed three-stage method of accumulator tank filling can be used for any electric propulsion XFS that uses an accumulator tank to reduce high pressure to working pressure. However, the limitations of using the proposed method are related to the fact that it is calculated for specific values of inlet pressures, volumes of the accumulator tank and the cavity between solenoid valves and flow restrictor for XFS SPS-25. Therefore, for its use in other systems, it might be necessary to clarify the values of the inlet pressures at which the transition to another filling mode takes place and the time of filling the accumulator tank.

The disadvantage of the proposed method is that the accumulator tank filling time for the second section was determined for the minimum working substance temperature at the entrance to the XFS. Therefore, at higher temperature values accumulator tank will be underfilled. It does not lead to a deterioration of the thruster parameters but will increase the number of solenoid valve activations compared to the case with completely filled accumulator tank. Therefore, further development of the proposed method will take into account the temperature of the working substance in formula (4), which will additionally increase the service life of the XFS.

7. Conclusions

1. As a result of theoretical and experimental studies of XFS SPS-25, it was confirmed that the reduction of the accumulator tank volume leads to the occurrence of pressure spikes in the accumulator tank, which go beyond the permissible ±3 % range of the nominal value. Research in the range of inlet pressure from 2 to 7 MPa made it possible to determine the dependence of pressure spikes in the accumulator tank on the inlet pressure. Based on the obtained data, the method of accumulator tank filling was improved to ensure the necessary pressure in the system, with a reduced volume of the accumulator tank and stable electric propulsion system operation.

2. Pressure maintenance in the accumulator tank of XFS SPS-25 with the required accuracy using the improved method of filling the accumulator tank was experimentally confirmed in laboratory conditions and as part of the spacecraft in orbit according to telemetry data. In accordance with the results of the study, the accuracy of pressure maintenance in a small-volume accumulator tank (0.45 L) was better than ±3 % for the entire range of inlet pressures from 2 to 12.5 MPa. At the maximum inlet pressure, the improved method of accumulator tank filling enables to increase accuracy of maintaining the pressure in the accumulator tank by 4 times compared to the based on feedback from the pressure sensors method.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The research was carried out as part of the electric propulsion system SPS-25 development by Flight Control LLC.

Data availability

The data will be provided upon reasonable request.

Acknowledgments

The authors express their gratitude to all employees of Flight Control LLC, who participated in the preparation and creation of conditions for conducting these studies.

The authors express their special thanks to Max Polyakov, without whose constant support the operation of the laboratory and the conduct of these studies would not be possible.

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