DEVELOPMENT AND REFINEMENT
OF HIGHLY EFFICIENT 150 J APPT

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Abstract

Operation conditions for a majority of small spacecrafts (SSC) with the mass ranging from 50 kg up to 500 kg require regular correction for their orbits that makes it necessary to use small-scale propulsion systems (PS) capable to operate efficiently under the conditions of limited power consumption (up to 20-200 W). Because of relative simplicity and cheapness of SSC, simplicity and cheapness of PS should play not the last part in this choice.

From this point of view, ablative pulsed plasma thruster (APPT) having many engineering and operational advantages /1, 2/ is the most perspective option for SSC. However, low thrust efficiency of the widely known "traditional" APPT limits its real capabilities in the control /3/.

Design, technologic and operational simplicity of the "traditional" thruster were kept in the APPT developed during the few previous years. Along with this, new thruster is characterized by a highly efficient operating process offering thrust efficiency of up to 20-40% within the stored energy range of 50-200 J.

This paper presents the development and refinement results for the APPT with the stored energy of 150 J (APPT-150) that may be used rather efficiently for a control within the power consumption range of ~20-200 W.

Introduction

Several publications (4, 5, 6, 7, for example) were devoted to the APPT developed by RIAMEl. It was shown there that one of the essential differences of this thruster from the "traditional" one is the transfer from the decaying oscillating electric discharge with the characteristic number of the discharge current oscillation half-periods from 3 to 6 to the discharge /4, 5/ with one half-period of current oscillations.

In the case of new APPT, the duration of discharge current half-period is about 10 μs that in view of distinctions of its geometry is close to the optimum value from the point of view of reducing the propellant loss through the sides.

It is shown in /3, 4/ that in the case of transfer from oscillating to aperiodic discharge substantial transformation of entire operating process in the thruster takes place causing the reduction in propellant consumption by 30-40%, increase in its efflux rate by 50-70% and thrust efficiency growth by 100% and over.

As indicated in /6, 7, 8/, highly efficient APPT-150 is capable to solve the control tasks for a SSC of up to 500 kg in mass.

During the period since the above publication APPT-150 engineering model (Fig. 1) was developed and refined. This model is capable to operate efficiently within the power range of 20-200 W. Total “dry” mass of APPT-150 based PS is about 7 kg, while adjustment flexibility and control simplicity are beyond competition among the thrusters of other designs. Maximum total pulse, for the generation of which the application of APPT-150 may be efficient, is ~ $10 \cdot 10^4$ Ns.

APPT-150 description

1. APPT-150 discharge channel

Discharge channel (Fig. 2) is formed by two propellant bars and two plane electrodes. The back insulator is made of refractory ceramics of boron nitride or aluminum oxide type. For minimizing the inductance and ohmic resistance of the thruster outer circuit, the discharge channel is connected inflexibly to the energy storage and is located as close as possible to its electric outlets. Thermal isolations of heat-conducting ceramics are used for reducing the heat flows from the discharge channel to the storage. All electric outlets and buses connecting them are made in such a way that maximum uniformity in the current flow is secured.

As the experience of APPT development, presented partially in /9, 10, 11/, shows, the discharge channel geometry influences substantially the thruster operating process. Optimum dimensions of the channel for APPT-150 were optimized from the point of view of obtaining maximum thrust efficiency at the thrust impulse bit of about 4.5 mN and appeared to be as follows:

- Bar height – 42 mm;
- Bar length – 35 mm;
- Channel width (gap) in the input cross-section – 10 mm.

Gap between bars in the channel input cross-section near the cathode remained unchanged practically during the process of their preaging and equal to the width of the retainer shoulder, while near the anode the gap width grew and by the moment of the bar shape stabilization it appeared to be about 15 mm. During the same period, the gap in the bars outlet cross-section grew substantially and then stabilized. After the process stabilization (~50000 discharges) the gaps between bars comprised about 10 mm and 20-25 mm, correspondingly. The shape of the bar working surfaces became complicated, while the APPT thrust efficiency grew by about 10% during the preaging process. It was revealed that the working length of electrodes for APPT-150 should be no less than 70-80 mm for obtaining maximum thrust efficiency and reducing their erosion. With this, for the reducing the electrode erosion, minimum anode width should be no less than 40 mm, and that of the cathode should be no less than 30 mm. Investigation of the influence of the shape and angle of electrode “opening” upon thrust efficiency showed that the plasma rate, and thus the APPT thrust efficiency, depend upon these factors also. The results on electrode shape inffuence upon the thrust efficiency is in good agreement with the results presented in /12/.

Application of sharpened electrodes leads to the growth of APPT thrust efficiency by 5-10%. The same result is obtained when the total angle of electrode “opening” is increased from 0^0 (parallel electrodes) до 20^0. It may be supposed that the variation in APPT efficiency is first of all associated with the changes in the discharge channel inductance when its geometric parameters are changed.

Total growth of APPT thrust efficiency due to the above changes may comprise up to 20%.

`2. Propellant

One of real possibilities for substantial increase in APPT operating process efficiency is in replacing Teflon by a lighter and easier ionized substance. Until now, numerous attempts to choose such substance offering required priorities, as well as thermal and physical characteristics, did not succeed /13, 14/. A run of tests is being made by the RIAME MAI currently, in which polymeric compound on the resin glass basis with some additives improving its physical characteristics is used as propellant. First starts of the APPT laboratory model with the stored energy of 120 J resulted in the growth of its thrust efficiency from 27% to 37%. Results obtained provide experimental confirmation for the possibility to improve the APPT characteristics substantially due to the application of alternative propellant.

3. Capacitive energy storage

Capacitive energy storage is the most important APPT element that in many respects defines its lifetime, as well as its characteristics in mass and overall dimensions. It should be noted that the transfer to the aperiodic discharge, that is accompanied by elimination of multiple variations in the voltage polarity, reduction of the discharge current amplitude values (down to 30-40 %), and energy losses in the storage, improves substantially the conditions of its operation. The APPT capacitive energy storage may be made in a form of several capacitors connected as a battery or in a form of monoblock. Both options have their own advantages and disadvantages.

Results of test-bench refinement for the APPT-150 laboratory model with the storages of both types defined our choice in favor of the battery made on the basis of four coaxial capacitors with the metal film. Mass and overall dimensions for one capacitor are as follows:

- Body diameter – 75 mm;
- Height – 105 mm;
- Mass – ≈ 1.0 kg.

Capacitor terminals are coaxial, body being one of the terminals.

4.Discharge initiation unit (DIU)

The APPT-150 DIU is a high-voltage discharge device. When ceramic discharger is being opened, high voltage is applied to the igniter being a two-step three-electrode system, the electrodes of which are placed into the ceramics (Al_2O_3) that is not consumed during the thruster operation and disposed inside the hole in the cathode.

5. Power processing unit (PPU)

APPT is an exclusively simple thruster in the design and service relations, so the arrangement of its PPU is rather simple also. So, APPT-150 PPU generates voltage of definite nominal value at the output that is applied directly to the thruster electrodes and to the primary winding of the DIU high-voltage transformer. From two to four telemetry channels and the same number of commands formed by the PPU or main computer are required for APPT control.

PPU, the efficiency of which comprises up to 90% at the power consumption of 100-200 W, was designed within the frames of the APPT engineering model development. According to assessments, the PPU specific mass in the on-board modification will be no worse than 120 W/kg that secures high characteristics in mass and overall dimensions for it.

Results of APPT-150 test-bench refinement

Values for APPT-150 thrust, mean-mass plasma efflux velocity, propellant (Teflon) consumption, and thrust efficiency, obtained at the power consumption of 50-200 W, are presented in this part.

Much attention is paid currently throughout the world to the development of small Hall thrusters of SPT design intended for solving the small satellite control tasks. It was made comparison for the main parameters of APPT-150 and one of the best, for to-day, small Hall thrusters of BHT-200-X2B type with the nominal power of 200 W. Power range, within which it was made (50 – 200) W allows to solve many tasks for the small satellite orbital control.

Characteristics of APPT-150 at the power consumption of 50-150 W were obtained during its test refinement, while for the power consumption of 200 W they were obtained by approximation of functions, the pattern of which is close to linear for APPT. Main technical characteristics for APPT-150 are presented in the Table.

Table

No.	Characteristics	APPT-150
1	Stored energy, J	150
2	Discharge channel type	Rail, with plane electrodes
3	Power consumption, W	50 – 200
4	Impulse bit, mNs	~ 4.5
5	Average thrust, mN	1.5 – 6.5
6	Specific impulse, s	~ 2000
7	Propellant consumption, kg/pulse	$2.2 \cdot 10^{-7}$
8	Thrust efficiency, %	~ 30
9	APPT total “dry” mass (PPU including), kg	~ 7.0

Characteristics of APPT-150 and BHT-200-X2B were compared using the data presented in /15/. Thruster BHT-200-X2B will be further referred to as BHT-200 for simplicity.

So, power dependencies for the propellant consumption (Fig. 3), average thrust (Fig. 4), mean-mass plasma efflux velocity, and specific impulse (Fig. 5) and thrust efficiency (Fig. 6) are presented hereafter.

It is obvious from Fig. 3 that APPT-150 propellant mass consumption in its absolute value is lower substantially than that of the BHT-200. With this, absolute difference in propellant consumption grows with power consumption. However, while analyzing data of Fig. 3, one should not forget that within the power range of over 100 W BHT-200 has noticeable advantage over APPT-150 in the level of thrust produced (Fig. 4). So, it is necessary to compare BHT-200 and APPT-150 thrusters in such parameter as effective propellant consumption (consumption referred to the thrust generated) that is presented in Fig. 7. As is evident, APPT-150 has noticeable advantage over BHT-200 in the effective consumption also up to power lever ~ 200 W.

Thrust generated by BHT-200 and APT-150 as a function of discharge power is presented in Fig. 4. The behavior of curves allows making a conclusion on substantial advantage of BHT-200 in this parameter within the range of power consumption of 150 W and over. But within the lower power range the BHT-200 advantage is not so evident. Thus it follows that APPT-150 may have advantage over BHT-200 while solving the tasks of small satellite stationkeeping, when high thrust is not required as a rule, but in the case of orbit forming, especially when strict time limitations are applied for this operation, BHT-200 is advantageous.

Capabilities of APPT and BHT in characteristic adjustment are illustrated by Fig. 5. It is obvious that velocity of plasma efflux out of the APPT-150 channel is close to 20 km/s within the entire power range and that it exceeds substantially the corresponding parameter for BHT-200.

Curves for the thrust efficiency of BHT and APPT, presented in Fig. 6, demonstrate the advantage of APPT-150 in this most important parameter within nearly entire power range under study.

Analysis for the test results obtained

The first that to our mind should be stated on the basis of the data presented, is high competitiveness of highly efficient APPT.

So, as is evident from Fig. 3-7, within the power consumption range of up to 200 W the highly efficient APPT-150 is on a par with BHT-200, while at the power of up to 120 W it exceeds it in all main parameters practically.

It is important that within the power range of up to 150-200 W APPT-150 is advantageous in the specific parameters also (thrust efficiency, specific propellant consumption, specific impulse), and this witnesses of a rather high level of its operating process organization achieved.

As to the issues of design, technologic and exploitation complexity of APPT-150 and BHT-200, the advantage of APPT is incontestable. This predetermines low cost for its production and exploitation comparing to the corresponding cost for any Hall thruster.

Thrust of over 1-3 mN is not required for solving many tasks of the small satellite orbital flight control, thus, average power consumed by propulsion system may not exceed ~ 50-120 W. Within this range exactly the advantage of APPT-150 over the small Hall thrusters is obvious.

Conclusion

New ablative pulsed plasma thruster with the stored energy of 150 J, developed by RIAME MAI, is characterized by thrust impulse bit of ~ 4.5 mNs, specific impulse of ~1900–2000 s, thrust efficiency of ~ 30 %, and has good characteristics in mass and overall dimensions. Its application for solving the tasks of small satellite orbit control is the most efficient within the range of power consumption from 50 W to 150-200 W. APPT operation within this power range allows the majority of control tasks for to the small satellites bo be solved. Recently the decision in relation to APPT-150 manufacturing by NIIEM Russian space firm for use in propulsion system of low orbital SSC constellation "Vulkan" was made. It is assumed that APPT-150 will be commercialized in the immediate future.

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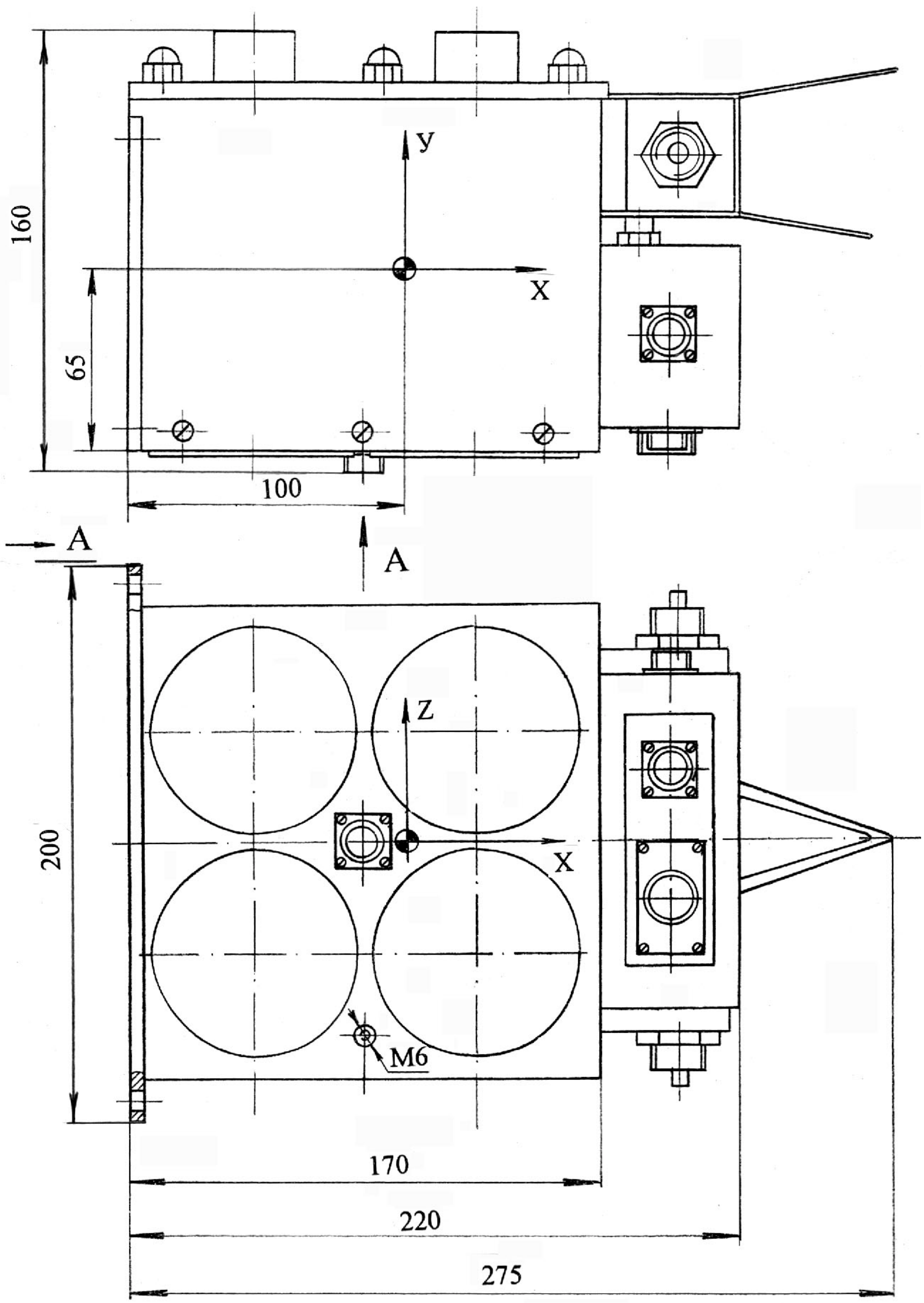

Fig. 1

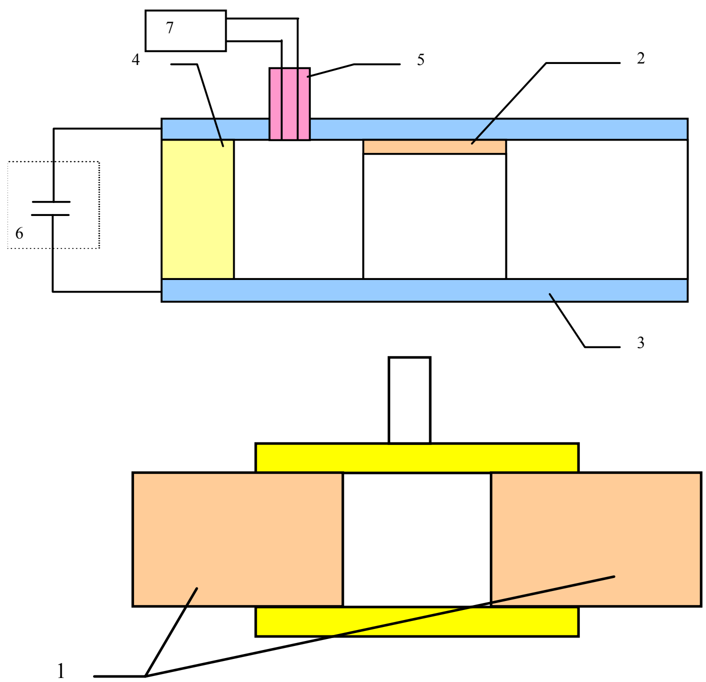
7
4
5
2
6
3
1

Fig. 2

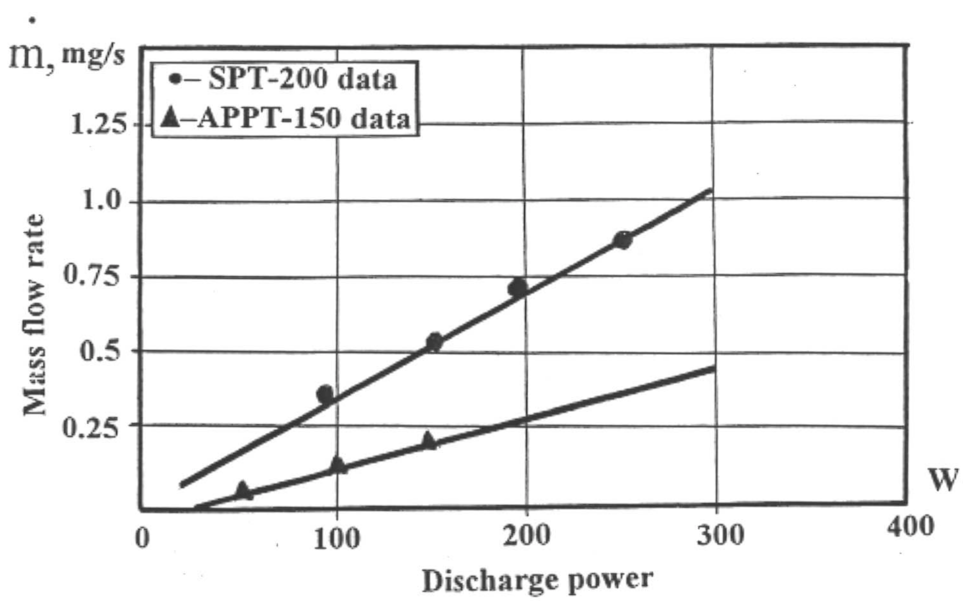
ṁ, mg/s
•– SPT-200 data
▲–APPT-150 data
1.25
1.0
0.75
0.5
0.25
Mass flow rate
W
0
100
200
300
400
Discharge power

Fig.3

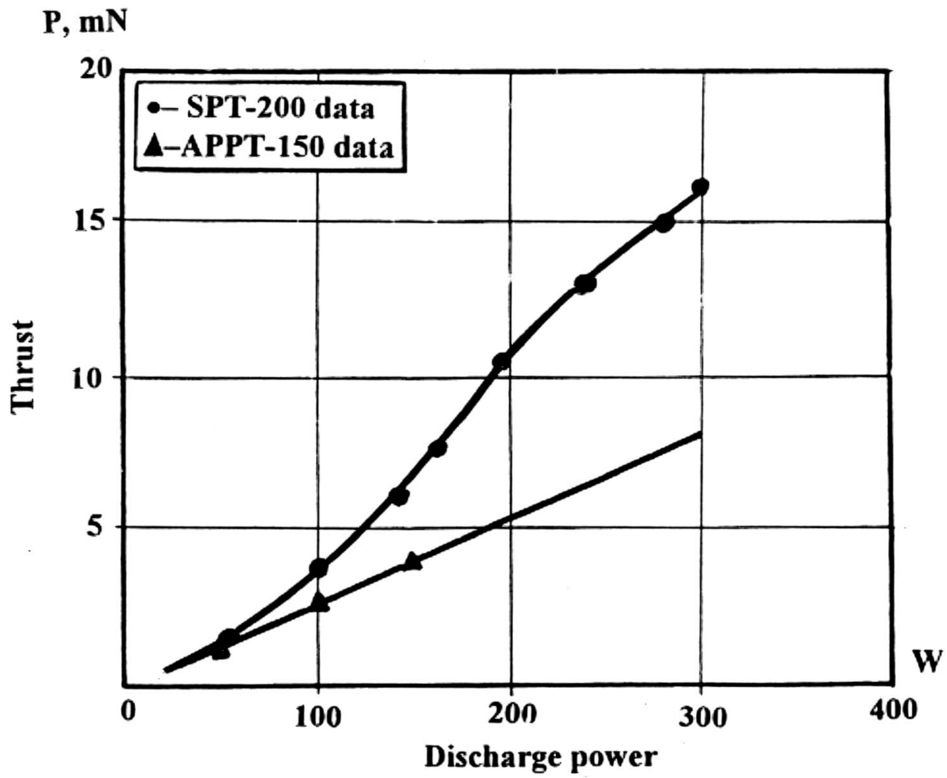
P, mN
Thrust
•– SPT-200 data
▲–APPT-150 data
20
15
10
5
0
100
200
300
400
W
Discharge power

Fig. 4

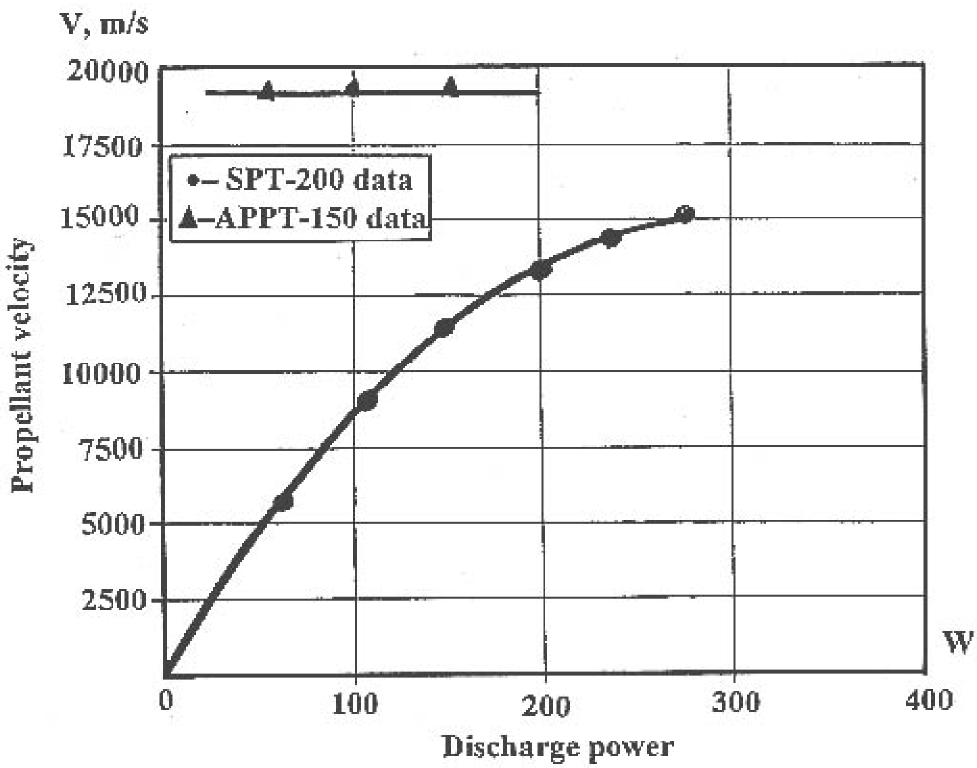
V, m/s
Propellant velocity
•– SPT-200 data
▲–APPT-150 data
20000
17500
15000
12500
10000
7500
5000
2500
0
100
200
300
400
W
Discharge power

Fig. 5

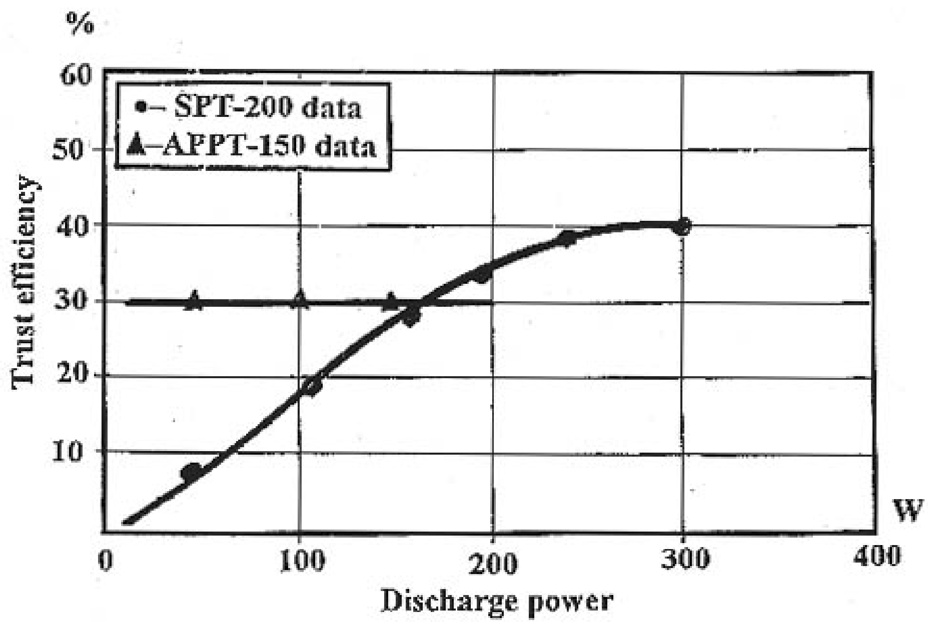
%
60
50
40
30
20
10
Trust efficiency
•– SPT-200 data
▲–APPT-150 data
W
0
100
200
300
400
Discharge power

Fig. 6

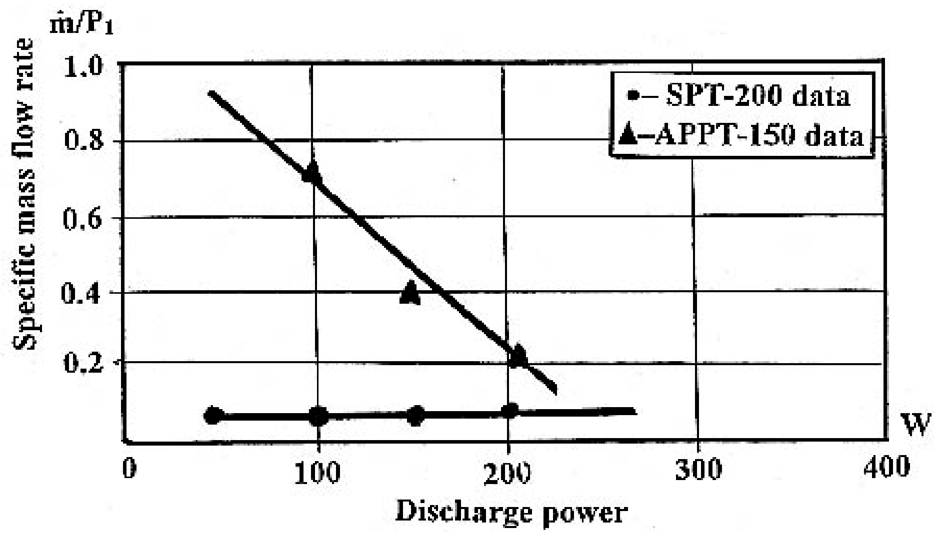
ṁ/P1
1.0
0.8
0.6
0.4
0.2
Specific mass flow rate
•– SPT-200 data
▲–APPT-150 data
W
0
100
200
300
400
Discharge power

Fig. 7