Experimental Study of Plasma Parameters in High-Efficiency Pulsed Plasma Thrusters * +

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The experimental investigations of plasma parameters in high- efficiency APPT were carried out with the aim of more full understanding of physical processes in APPT and further increasing the efficiency of APPTs developed by RIAME MAI in recent years. The upgraded APPT laboratory models with bank energy in the range from 40 J to 150 J were created and refined. The thrust efficiency of new APPTs was increased substantially (up to 0.28 at bank energy of 150 J). The variation of electron density and current linear density in upgraded APPT models was investigated by laser interferometry and magnetic probe methods, correspondingly. Plasma component velocities and electron temperature in APPT channel were measured by spectroscopic methods of plasma diagnostics. On the basis of these experiments the important information about APPT operation processes was obtained and the main distinctive features of high-efficiency APPT were established.

Introduction

Growth of interest to ablative pulsed plasma thruster (APPT) is quite explained because APPTs are almost ideal thrusters for small spacecrafts (SSC) both from the view-point of their compatibility with SSC power supply and control systems and the cost of manufacturing and operation. APPTs can be used for solving different problems on controlling SSC with the mass of up to several hundreds of kilograms. Among these problems are maintaining the orbits of high-orbit and low-orbit SSC, orbit raising and SSC positioning into operation point, low-orbit SSC drag making up, etc.

The APPT thrust is resulted from electromagnetic and gas-dynamic acceleration of the ablated and ionized mass of Teflon used as a propellant. Although the simplicity of basic design is the distinctive feature of APPT, this thruster type is characterized by complicated physical processes, which are still not clearly understood. In spite of promise of APPT for SSC flight control there is a circumstance which restricts its wide application. This is relatively low thrust efficiency which equals to 0.10…0.12 for typical APPT at bank energy of 100 J. In order for the whole complex of control problems for small spacecrafts to be solved, a thruster is required which would be capable to create effectively the total thrust impulse of ~10^5 N·s at thrust efficiency not less than 0.25…0.30 and specific impulse of ~1500…2000 s. This means the necessity of APPT efficiency rising by two times and more.

Main reason for the thrust inefficiency for typical APPT is a mismatch in time of two processes. They are: forming of plasma flow and forming of current sheet. The second one provides the plasma blob effective electromagnetic acceleration [1].

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The typical duration of plasma flow forming and accelerating is about 10 µs. Taking into account that total duration of discharge is close to 15 µs, it should be expected that the most part of propellant will be accelerated by electromagnetic forces and plasma average velocity will be close to current sheet velocity of ~ 25 km/s. However, only small share of propellant (20…50 %) is accelerated by the action of electromagnetic forces in APPT discharge channel in reality, and plasma flow velocity at the channel outlet is only equal to 8…12 km/s [2].
Propellant and velocity losses take place because discharge current of typical APPT has oscillatory nature with duration of the first half-period of ~ 2…3 µs. The magnetic probe measurements show that at such kind of discharge mode the area of maximum current density moves only within the first discharge half-period [3]. During the rest time of discharge of 12…15 µs in duration, the current sheet moves with insignificant velocity close to discharge channel back wall. During this time, current exerts thermal influence on the propellant providing its additional evaporation. In the absence of effectively acting electromagnetic forces, all additional propellant released into discharge channel is accelerated only up to thermal and sub-thermal velocities (~1…5 km/s). Thus at electric discharge duration of about 15 µs an electromagnetic mode of plasma acceleration operates effectively during a period of 3 µs only. In our opinion this circumstance is the main reason for a real great lag between the plasma forming process and the discharge current forming process in typical APPT.
The operating process analysis shows the necessity of transition to the aperiodic discharge in the thruster [4, 5]. The optimal discharge duration must be equal to 8…10 µs by our experience. This value is close to duration of propellant flow formation process and it creates conditions for plasma effective acceleration. The optimization of discharge circuit and accelerating channel made possible developing APPTs with improved specific parameters as compared to typical APPTs [3]. This allows the field of the APPT rational application under SSC controlling to be extended.
This paper is devoted to plasma parameter study in high-efficiency APPT laboratory models with bank energy of 40…150 J providing essential advantages before typical APPTs. These investigations were aimed to understand peculiarities of physical processes in upgraded APPTs created by RIAME MAI. In the course of experiments the optical and magnetic probe methods of plasma diagnostics were used.

Upgraded Ablative Pulsed Plasma Thrusters

The upgraded ablative pulsed plasma thrusters developed by RIAME MAI in recent years can be considered as the promising thrusters for small spacecrafts because of essential increase in thrust efficiency as compared to typical APPTs.
The upgraded APPT laboratory models with bank energy within the range from 40 to 150 J were created for the purpose of optimizing the thruster parameters. Propellant of thruster models was Teflon. The APPT models include all principal components of a flight APPT: the discharge channel unit, capacitor bank, supplying buses, the discharge initiation unit, etc.
The design concept of the discharge channel unit is shown in Fig.1. The APPT channel is formed by flat electrodes, two Teflon bars and back insulator. APPT model electrodes are manufactured of copper. The back insulator is made of alundum plates, which have been pasted together. They are mounted in yoke made of glass-cloth laminate. The APPT discharge initiation is carried out by three-electrode igniter, which is powered from the discharge initiation unit with the output voltage of up to 30 kV.

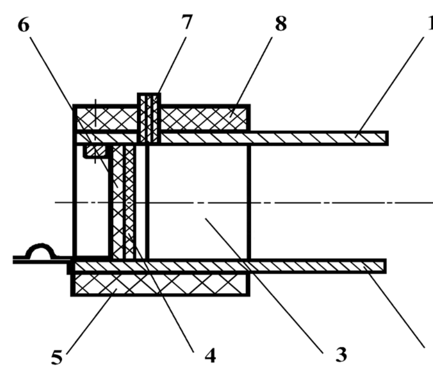

Figure 1 – Discharge channel unit schematic
1 – cathode, 2 – anode, 3 – Teflon bars, 4 – back insulator, 5 – basis, 6 – yoke, 7 – igniter, 8 – cover.

During the experiments APPT models were mounted inside the vacuum chamber, in which the residual gas pressure of ~ 10^{-4} Torr was maintained. Discharge current was recorded by using Rogowski coil with RC – integrator and digital memory oscilloscope. The multi-channel generator of pulses was used as synchronizing instrumentation.
The pendulous device developed by RIAME MAI was used for measurement of mean thrust during the

APPT operation in the frequency mode and for determination of APPT impulse bit. Full propellant mass consumed for a given time was measured by weighing the Teflon bars by high-sensitive balance and then the mean propellant consumption per pulse was determined.

The APPT thrust efficiency and the mean velocity of blob (specific impulse) were defined by the well-known relations on the basis of measured APPT bank energy, impulse bit and mean propellant consumption per pulse.

The experimental refinement of APPT laboratory models has shown considerable improvement in performances and also some changes in physical processes taking place in the discharge channel. In all investigated models the current pulse form was close to aperiodic one. The optimal correlation between discharge circuit parameters and discharge channel dimensions was found for upgraded APPTs. This allowed the thrust efficiency of APPTs to be increased by the factor of 2…2.5 within the mentioned range of stored energy.

The basic integral parameters of APPT models at bank energy of 40 J, 100 J, 120 J and 150 J are presented in Table 1.

Table 1. Performances of upgraded APPT models.

Model	PPT-40	PPT-100	PPT-120	PPT-150
Discharge energy, J	40	100	120	150
Impulse bit, mN·s	0.95	2.7	3.0	4.0
Propellant consumption per pulse, mg	0.065	0.15	0.155	0.19
Thrust efficiency	0.17	0.24	0.25	0.28
Specific impulse, s	1500	1800	2000	2100

The model of 100 J bank energy (PPT-100) has the thrust efficiency of 0.24. For comparison it should be pointed out that in typical APPT the thrust efficiency η_t amounted to 0.12 at energy W = 100 J, impulse bit P_{bit} = 2.2 mN·s and specific impulse P_{sp} = 1100 s [3]. The thrust efficiency of PPT-150 model is equal to 0.28 and this value is now the highest among all known APPTs of rail type operating in the energy range under consideration.

For further APPT efficiency increasing as well as for retaining the achieved efficiency at APPT flight prototypes manufacturing it is necessary to understand more clearly the physical processes in thruster discharge channel.

In order to clear up features peculiar to upgraded APPTs the plasma component velocities and the electron temperature in APPT were measured by spectroscopic methods. The knowledge of velocities for plasma particles (atoms and ions) taking part in creation of reactive force as well as electron temperature in APPT channel can be very useful for understanding the physical processes in plasma of high-efficiency APPT.

Plasma particle velocities were determined by the use of Doppler method in the course of experiments at the upgraded APPT model with energy storage of 60 J [3]. The monochromator with diffraction grating and the photomultiplier were used for recording the spectral line profiles by scanning of plasma spectrum. The Doppler shifts of investigated spectral lines were determined on the basis of the observation of moving plasma both in longitudinal and transverse directions relative to the APPT axis.

The spectral lines of carbon (CI, CII) and fluorine (FI, FII) located in the spectrum band from 390 nm to 640 nm were chosen for these experiments. The measurements have shown that the velocities of APPT plasma components such as carbon atoms and ions and fluorine atoms and ions fall within the range from 13.9 to 18.8 km/s. These velocities exceed the ones for typical APPT [3] and agree satisfactorily with average plasma blob velocities at the channel outlet for upgraded APPTs (~16 km/s at bank energy of 60 J) obtained on the basis of measured integral parameters.

The electron temperature of plasma blob was measured by the method of relative intensity of spectral lines [6]. These experiments were carried out at the PPT-100 model and spectral lines of fluorine ion (FII) with wave lengths of 429.92 nm and 320.27 nm were used for spectroscopic measurements. The choice of these lines is conditioned by the necessity of satisfying the diagnostic method requirements and obtaining the sufficient measurement precision [6]. As a result of these measurements the value of average electron temperature in discharge channel amounted to 1.3…1.4 eV for PPT-100 model.

Laser Interferometry of High-Efficiency APPT Plasma

The objective of these experiments was to analyze physical process peculiarities in high-efficiency APPT by studying temporal and spatial distribution of electron density in the APPT discharge channel and in plasma flow outside the channel.

The electron density N_e in plasma of PPT-100 model was measured by laser interferometer [6, 7]. The interferometer used during the experiments was one of the versions of classical three-mirror laser interferometer [6]. Active resonator of the interferometer is a single-mode helium-neon laser. Passive resonator, in which the investigated APPT plasma is placed, represents a semi-confocal resonator with length $L_r \sim 1$ m. The output mirror of this resonator with the focal distance of 1 m has the reflection coefficient of 95 % for the wavelength of 632,8 nm.

To generate periodic oscillations of optical length in the passive resonator, the output mirror is installed on a piezo-electric ceramic plate, to which the modulating voltage of ~ 10 V with frequency of 50 Hz is supplied. The registration of optical signal is carried out by photomultiplier.

Some precautionary measures were taken for the purpose of reducing a level of optical system vibrations and light interferences in the receiving part of photomultiplier accompanying the APPT operation and also of improving the noise immunity of the electrical circuit.

The synchronization of measurements was carried out by multi-channel pulse generator making it possible to adjust measurement process in time with an accuracy of 0.1 μs. All incoming data was recorded by two digital memory oscilloscopes. Periodic displacement of output mirror in the passive resonator provides the registration of interferometer instrumental function used as a calibration signal.

At the presence of APPT plasma in the passive resonator its optical length varies because of changing the refraction index in the resonator and according to this the fundamental frequency of radiation leaving the resonator varies [8]. Because the three-mirror interferometer operates as an amplitude-frequency discriminator with linear performance, the frequency shift caused by plasma will cause proportional change in laser power ΔE at the exit of the interferometer. The registration of interferometer signal, which is proportional to ΔE, and the measurement of instrumental function parameters (period, front duration, amplitude) makes possible finding the quantity $Q(x,y,t) = N_e \cdot d$ in an investigated point with coordinates x, y at time t (d is the plasma size along the probing ray direction).

In order to determine the electron density distribution $N_e(x, y, t)$ averaged along the probing ray direction (z axis), it is necessary to measure APPT plasma flow boundaries and plasma blob size d(x, y) along z axis in investigated points.

The plasma flow boundaries at the PPT-100 model outlet were determined by the use of shields positioned at different distances from the cut of electrodes. A thin film including products from Teflon decomposing was deposited on these shields while APPT model was operating in a frequency mode. The film takes up some area on the shield, the boundaries of which, apparently, correspond closely to plasma blob boundaries.

Measurements of plasma blob boundaries near the cut of electrodes have shown that the plasma blob at APPT outlet is deflected to a small angle from a discharge channel axis in the cathode direction. This peculiarity of APPT is apparently connected with manifestation of Hall effect and action by transverse electromagnetic force pressing a plasma flow to the cathode. The angle between the direction of plasma blob motion and APPT channel axis amounts to ~ 6^o for the PPT-100 model.

The electron density N_e was measured by laser interferometer in interelectrode space of APPT channel and outside the channel. The points, in which measurements of N_e were conducted, are located along the discharge channel axis, close to the cathode and anode, and also outside of APPT at the distance of 5 cm from electrodes along line, perpendicular to the direction of plasma blob motion.

Figure 2 shows variations in maximum electron density N_e^{max} when plasma is moving along the APPT channel axis inside and outside the APPT.

Curve 1 in this figure corresponds to the upgraded APPT and the curve 2 illustrates similar distribution N_e^{max}, obtained during the experiments with typical APPT. In Fig. 2, near the measured values of N_e^{max}, the instants of time from the beginning of discharge are also displayed, which correspond to the appearance of the area of plasma with the indicated values N_e^{max} in the investigated points of APPT.

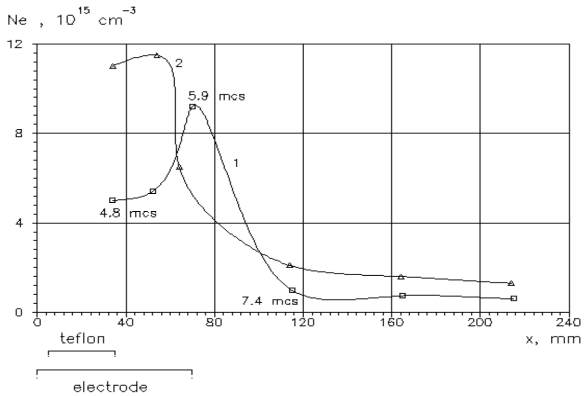

Figure 2 – Time-dependent distributions of maximum electron density along the APPT channel axis
1 – the upgraded APPT
2 – the typical APPT

It is seen that in upgraded APPT and typical APPT the distributions of N_e^{max} differ from each other. In upgraded APPT when plasma is moving from the cut of Teflon bars to the cut of electrodes the electron density is increasing. This is apparently connected with discharge expanding at the end of the first half-period to the entire surface of electrodes between the cuts of bars and electrodes, with increasing of current density close to cut of electrodes and with existing of outflow currents. This result is in good agreement with data of magnetic probe measurements presented in [3] and in this paper.

According to [3] in typical APPT the electric current is localized and at the end of the first half-period of discharge the maximum of current density is found close to the cut of Teflon bars. Then as the current sheet is moving to the APPT channel outlet the current density decreases, that results in reduction of electron density.

When plasma blob is moving outside the APPT channel the electron density decreases, that may be explained by expansion of plasma after its escaping from APPT.

Values for time-varying electron density N_e^{max} in points of APPT channel close to the cathode (curve 1) and anode (curve 2) are displayed in Fig. 3.

It is seen that beyond the cut of propellant bars close to the cathode the electron density is higher, than close to the anode.

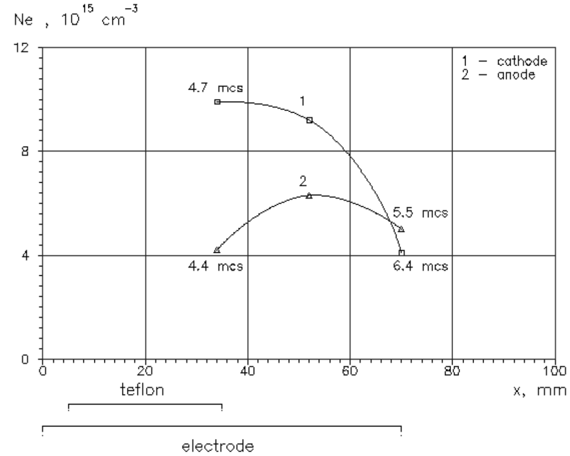

Figure 3 – Time-dependent distributions of maximum electron density in the APPT channel close to cathode and anode

It is apparently explained by deflection of plasma to the cathode under the action of transverse electromagnetic force.

Measurements of electron density outside the channel show, that the distribution of N_e^{max} across plasma blob at the distance of 5 cm from cut of APPT electrodes is non-symmetrical relative to the direction of plasma blob motion (under the angle of 6^o to the APPT axis) and in the part of blob close to cathode the values of N_e^{max} are higher than close to anode.

Results of interferometric measurements show also, that the area of plasma with maximum electron density close to anode moves much faster, than close to cathode. So by estimations, the average velocity of area with maximum value of N_e near the anode section from the cut of Teflon bars to the cut of anode amounts to ~ 32 km/s, whereas the similar velocity near the cathode is equal to ~ 21 km/s. The difference between velocities of plasma motion near anode and cathode means, that the lines of maximum values of N_e and, hence, lines of electric current in APPT channel are inclined to electrodes. It is apparently connected with the influence of Hall effect. The manifestation of similar effect was detected in [9] under high-speed taking photos of electrical discharge in PPT using noble gases as a propellant.

Thus, the experimental study of dynamics and distributions of electron density in the upgraded APPT model carried out by method of laser interferometry has revealed peculiarities of physical processes in high-efficient APPT.

Magnetic Probe Investigations of Current Dynamics in APPT Channel

In this paper investigations of discharge current dynamics in upgraded APPT channel were continued by using magnetic probe method for two new APPT models (PPT-120 and PPT-40) being the further development of models investigated in [3]. Performances of PPT-120 and PPT-40 models are presented in the Table 1.

The problem of experimental result processing is reduced to searching for the function of discharge current linear density $J_y(x)$, magnetic field $B_z(x)$ of which would correspond to experimentally measured distribution $B_z^{exp}(x)$ best of all. In parallel with computation of current linear density distribution $J_y(x)$ the time-average current linear density $<J_y(x)>$ and inductance of discharge channel L were computed.

The experimental technique and procedure of experimental data processing have been detailed in [10]. The magnetic probe of an inductive type contained in a ceramic tube with exterior diameter of 2.5 mm was used. The sensitivity of the probe was equal to 640 Gs/mV. During measurements the probe was moved along channel axis at equal distances from both electrodes and propellant bars. For moving the probe a remotely controlled positioning device with two degrees of freedom was used.

The discharge current oscillogram of the PPT-120 model with the first half-period duration of 10.5 μs is presented in Fig. 4.

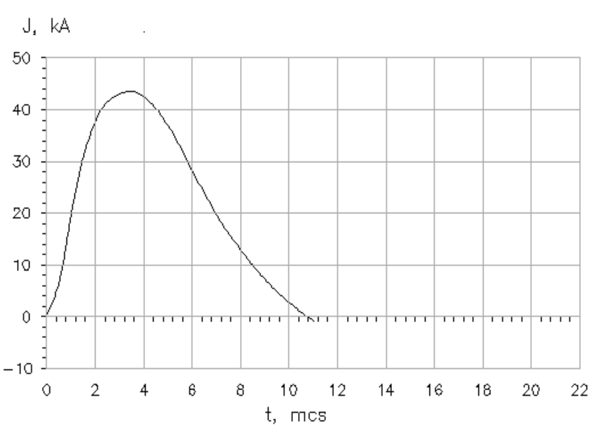

Figure 4 – Time dependence of discharge current for PPT-120 model

It is seen that current pulse of this model is closely related to aperiodic pulse since the second half-period is entirely absent in the oscillogram. However the current pulse shown in Fig. 4 differs from a classic aperiodic one because the current becomes zero at the fixed time, but it is not approaching zero asymptotically when the time tends to infinity.

Figure 5 presents distributions of current linear density $J_y(x)$ along the length of channel at different instants of time obtained by magnetic probe measurements. Figure 6 illustrates the distribution of time-averaged current linear density $<J_y(x)>$ along the length of PPT-120 channel.

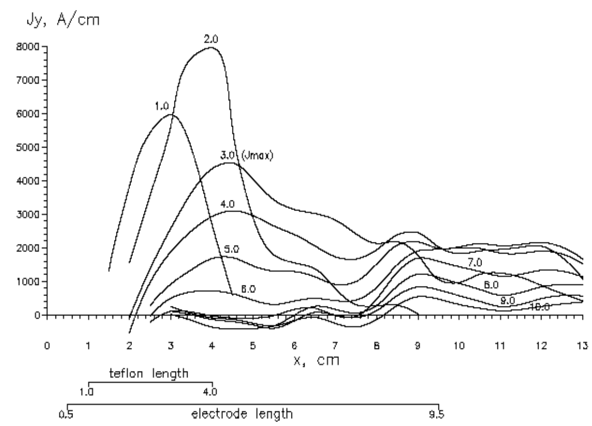

Figure 5 – Current density distributions in PPT-120 model at different instants of time (in μs)

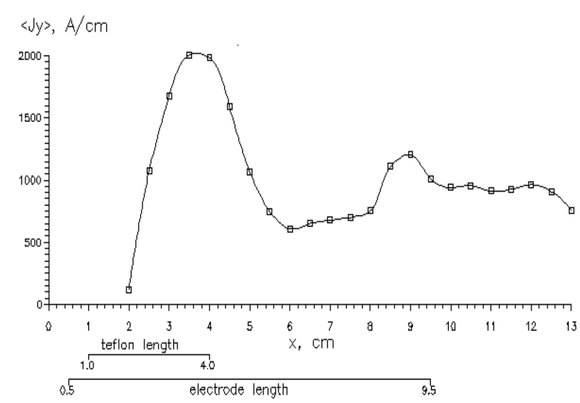

Figure 6 – Distribution of time-average current density for PPT-120 model

As it is seen from Fig.5 at t > 2 μs the discharge expands for the whole length of electrodes in the channel zone between the cuts of Teflon bars and electrodes and becomes practically distributed without any moving current sheets. At t > 3 μs the curve of current linear density takes the characteristic "double-peak" shape (Fig. 5, Fig. 6).In this case, the first maximum of current density is localized adjacent to the cut of propellant bars and the second maximum is localized adjacent to the cut of electrodes. Starting from t = 7 μs and up to the end of the first half-period, the whole current is practically flowing close to the cut of electrodes with the outflowing of significant part of current beyond electrodes. Similar experimental results were obtained by authors also for upgraded PPT-100 model in [3]. In typical APPT with an oscillatory discharge the outflow currents are not detected.

Probably, increasing of thrust efficiency in upgraded APPTs is connected with such non-standard for a typical APPT distribution of current.

The PPT-40 model was designed as APPT laboratory model with reduced bank energy of ~ 30…40 J. In so doing, the objective was to retain the high thrust efficiency, which is inherent to upgraded APPTs. The distribution of discharge current linear density $J_y(x)$ in this model was analogous to other new APPT models. However, because of small dimensions of the channel, the current practically at once expanded throughout the entire channel. At t > 1.0 μs the discharge became distributed. As a whole the current density distribution had the form characteristic of high-efficiency APPT.

Conclusion

The complex of works on further increasing of APPT efficiency and experimental investigation of upgraded APPTs was conducted for the purpose of more full understanding of APPT operating processes.

The upgraded APPT laboratory models with bank energy in the range from 40 J to 150 J were developed by RIAME MAI. The optimal correlation between discharge circuit parameters and discharge channel dimensions was found. This made possible more than twofold increasing of thrust efficiency (up to 0.28 at bank energy of 150 J) in comparison with typical APPTs.

The experimental study of dynamics and distribution of electron density and current linear density in APPT plasma was carried out by using of the laser interferometer and magnetic probes. It was found out that upgraded APPTs and typical APPTs have different nature of electron density variation. The data for electron density distributions are in good agreement with magnetic probe measurements of current density in APPT channel.

The investigations of discharge current dynamics in upgraded APPTs have substantiated that the discharge is distributed throughout the whole electrode length in the channel zone between cuts of Teflon bars and electrodes.

It is revealed that the Hall effect has influence on electron density and current density distributions in APPT channel and also on the plasma blob deflection in the cathode direction beyond the channel.

The experimental investigations of APPT plasma parameters allowed the main peculiarities of upgraded APPTs be established, which are responsible for essential improvement of thruster specific performances.

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