PAPER • **OPEN ACCESS**

Multicomponent Arcjet plasma Parameters

To cite this article: V Gorbunkov *et al* 2018 *J. Phys.: Conf. Ser.* **944** 012040

Multicomponent Arcjet plasma Parameters

V Gorbunkov, V V Kositsin, V I Ruban and V V Shalay

Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

E-mail:vigorbunkov@list.ru

Abstract. To determine the plasma arc parameters of an arcjet thruster, the kinetic theory of gases is used. We can find a well-known statement about the adiabatic character of the compression process due to the growth of the gas temperature in a change in its spectral composition and in the Doppler effect. The use of tungsten in the nozzle design details explains the appearance of atoms of this element in the plasma volume.The emission spectra of tungsten allow us to indirectly judge the temperature of the arc discharge and its character. Absorption of the long-wavelength wing of the line contour at λ = 465.987 nm substantiates our conclusion about the consumption of the anode material in the process of operating the arcjet. The Doppler shift of the emission lines of argon allows us to determine the rate of the gas jet escape. The results of the study can be useful in the design of aircraft.

1. Introduction

The small closed volume occupied by the gas plasma is a feature of the correcting propulsion systems of spacecraft (PSSC) [1]. The inter-electrode distance and cavity diameter do not exceed a few millimeters. The walls of the arcjet chamber are heated to a certain temperature. Particles of matter emit and absorb photons, so equilibrium between particles of matter and radiation can be established [2]. The laws of equilibrium radiation play an important role in the gases kinetic theory. They determine the accuracy of propulsion systems plasma parameters.

It was noted [3] that due to the Langmuir probe measurements performed in the jet of the reactive 1 ... 2- kW engine at an argon pressure of P_{Ar} = 6 bar, the electron temperature was 1 … 2 eV higher than the temperature of the neutral gas in the flare.

The electron density was in the range 10^{10}–10^{13}cm^{-3}, which is also much higher than the Sakha equilibrium for temperature ($T_{Ar}\approx$1000K) and gas concentration ($n_{Ar} \approx 10^{17}$cm^{-3}), but much lower than the equilibrium temperature for the electron temperature, which did not allow agreement between the model Thermal equilibrium and experiment. This allowed the authors [3] to come to the conclusion that the temperature T_e = 1 ... 2 eV most fully reflects the arc electron temperature.

A simulation of an electro-thermal 240-W arcjet propulsion system in the quasi-neutral plasma approximation was carried out in [4]. A three-component plasma at P = 2.5 bar is considered from argon atoms, their ions and electrons. The closeness of the electron temperature T_e = 16 000K to the maximum axial gas temperatures T_{Ar}, = 11 500 K near the narrowing part of the nozzle, as well as their separate reduction to 5000 K and 3300 K at the nozzle exit is noted. The thermal equilibrium state observed between 30 % of the divergence between the axial electron and gas temperatures is significantly disturbed in the expanding part of the nozzle due to a drop in the electron density in the radial direction.

A high level of electron temperature increases the ionization and electrical conductivity level when cooling the gas layer near the walls of the arcjet chamber. This allows us to regard the plasma as quasineutral, and assume that the surface of the electrodes is adiabatic for T_e. At the same time, it is known [5] that when the gas is heated without heat exchange with surrounding bodies, adiabatic compression is observed due to the growth of the gas temperature and, according to the Doppler effect, its spectral composition should change. The model [6] allows us to see how the emission spectrum of an resistojet plasma changes when passing through a nozzle.

We will use the experimental setup [6] to analyze the parameters of a multicomponent plasma of an resistojet. We will take into account the anode material, since it is not important to establish an equilibrium between matter and radiation, in the collision with which particles the atoms are excited.

2. Experimental setup

The model of an arc electrothermal arcjet was investigated (Fig. 1). The discharge cavity is a quartz tube 1.3 mm thick, 6.4 mm in diameter, geometrically located inside the cylindrical body of the arcjet [6].

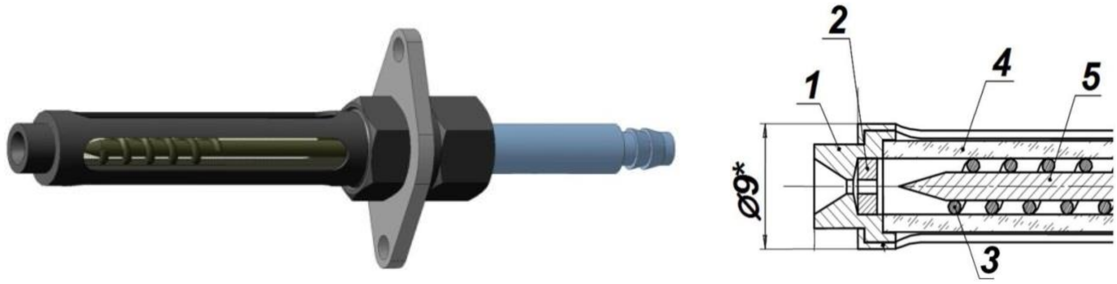

Figure 1. Arcjet electrothermal model [6] and its fragment. 1 – nozzle, 2 – anode, 3 – swirler of gas flow, 4 – tube made of quartz glass, 5 – cathode; In the figure on the left, an aperture measuring 5 × 50 mm for optical registrations is clearly visible in the micro-motor wall.

The interelectrode distance between the cathode 5 and the edge of the annular anode 2 is 3 ÷ 5 mm. The material of the electrodes is tungsten. Buffer gas argon is fed into the cavity through a swirler under pressure (1.03–1.08) × 101.3 × 10^3 Pa.

Power was provided by the standard power supply unit «Tetrix 230». The discharge current was measured by a shunt with a resistance of 1 Ohm, and the voltage on the discharge with the help of an ohmic divider 11.9 / 43.8 kΩ with the help of the oscillograph "RIGOL DS 2202". The design of the discharge power supply unit did not provide for a voltage change, therefore the discharge parameters were estimated at the current I_R = 3.8 – 4.2 A and the corresponding voltage drop U_R = 16.8 ÷ 19.0 V.

The working temperature of the quartz tube wall (420 – 450 K) and the outer wall of the nozzle (900-1100 K) was recorded by chromel-alumelium thermocouples.

Spectral measurements were carried out using a five-channel modular calibrated radiometric complex «Ava-Spec-ULS204L-5-RM», whose spectral range was 235 – 815 nm, the optical resolution in the range 296 – 400 nm was 0.07 nm, in the range of 605 – 815 nm not less than 0.15 nm. For simultaneous use of five channels, a 25 mm focusing collimating lens with an SMA adapter was used. The dynamic range of changes in the intensities of the spectral lines reached 60,000. The exposure could vary from 50 ms to 1 min. This ensured the possibility of recording the spectrum in a linear regime of the intensity changes of the spectral lines under study. We investigated the emission spectrum of a discharge through the wall of a quartz tube at an angle of 90 ° to the axis of the micromotor. To observe the glow of the total discharge in the transverse direction relative to the motor housing, the radiation was output to the spectrograph from the aperture. We also analyzed the spectra of the axial radiation of the nozzle of the micromotor model.

The distance between the aperture and the collimation lens was 110 mm, when measuring the longitudinal radiation of the nozzle, the distance to the nozzle was 420 mm. Optical measurements were carried out after the resistojet model was released to the stationary mode of operation.
The laboratory room temperature was 20 ° C.

IOP Conf. Series: Journal of Physics: Conf. Series **944** (2018) 012040 doi:10.1088/1742-6596/944/1/012040

3. Experimental results

With the operating parameters of the power supply unit, measurements were made and the discharge current density was calculated for a known diameter of the positive discharge column d = 0.5…1.0 mm. The current density j = (121-538.5) A / cm^2 found the electron concentration of the arc discharge.

The necessary drift velocity of electrons V_d can be obtained from the consideration that electrons in the gas gap L_e = 0.3 ... 0.5 cm move in an argon atmosphere. The argon concentration is $N_{Ar} = P_{Ar} / kT = 2.45 \times 10^{19}$ cm^{-3}.

It is known that the mobility of electrons depends on the strength of the electric field, and in a number of cases leads to a specific instability of the gas-discharge plasma. Taking into account the dependence of the drift electrons velocity in argon on the reduced electric field strength [7] E / N_{Ar} = 0.18 – 0.3Td in the approximation of low electron density, the sought value is V_d = (3 ... 6) × 10^5 cm s^{-1}. The current density of the arc discharge j = en_eV_d = (121 ... 538.5) A / cm^2 makes it possible to estimate the electron concentration ne = (1.2 ... 5.6) × 10^{15} cm^{-3}.

The flow of electrons under the action of an external electric field excites the gas discharge plasma. The flow of charged particles heats the electrodes to a very high temperature and, judging by the erosion of the cathode, reaches the melting point of tungsten $T_W \approx 3700$ K, which makes it possible to estimate the concentration of tungsten atoms from the saturated vapor pressure [8].

The concentration of tungsten vapor corresponding to the vapor pressure $P_w = 5 \times 10^{-2}$mm. Hg (6.67 Pa) at T_w = 3655 K is n_w 1.32 × 10^{14} cm^{-3}.

In Fig. 2 shows the emission spectrum of an arc discharge plasma of the *resistojet model*.

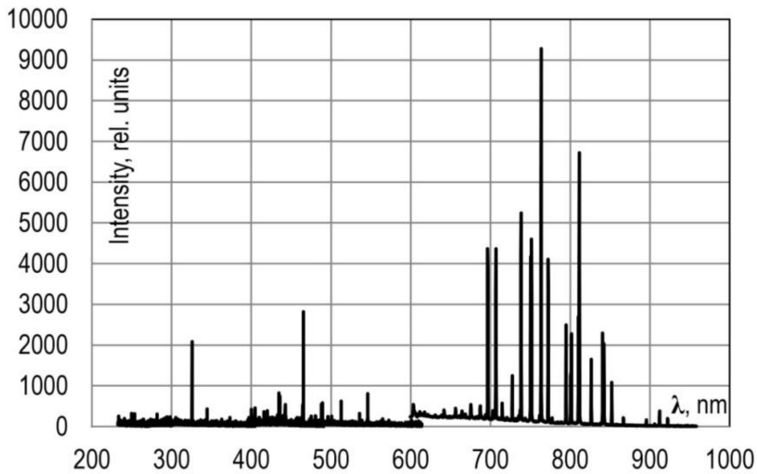

Figure 2.The discharge radiation spectrum observed through the nozzle.

Figure 2 clearly shows a number of spectral lines in the visible range (462 ... 547) nm, which belong to tungsten atoms (Table 1).

All the noticeable spectral lines in Fig. 3 refer to the lines of argon (Table 2).

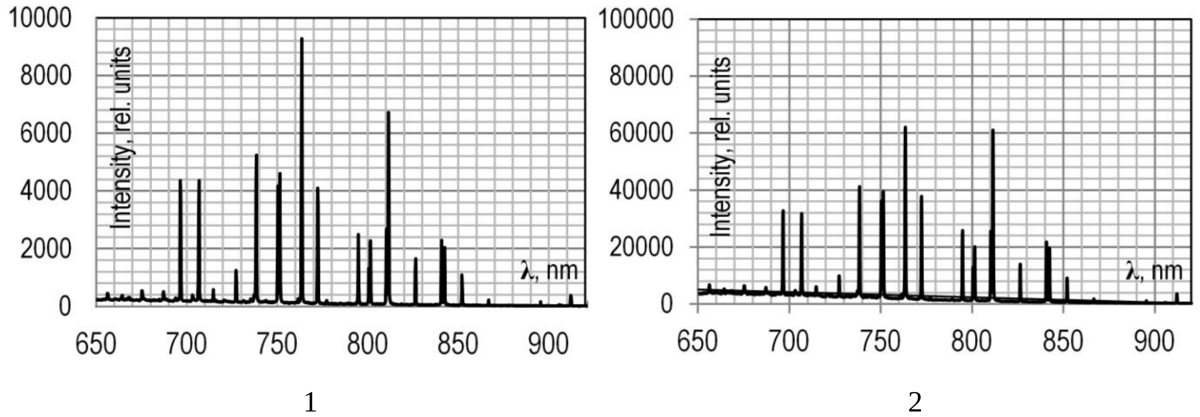

Figure 3. The spectral region (667 ... 930) nm (1) – taken through the nozzle and (2) – through the aperture.

From the comparison of Fig. 3 (positions 1 – 2) it can be seen that the intensity of emission lines from the nozzle in the 650 ... 850 nm range, compared to radiation through the aperture, decreased by almost an order of magnitude due to the increase in the distance to the registrar.

Table 1. Atomic tungsten spectrum.

№	*λ_{tab}, nm [10]*	*λ_1, nm (aperture)*	*λ_2, nm (nozzle)*
1	462.055	462.0	462.0
2	464.256	464.2	464.2
3	465.987	465.2	465.2
4	487.828	487.8	487.8
5	489.244	489.2	
6	500.616		500.7
7	513.0	512.6	
8	546.9	546.0	

Table 2. Atomic argon spectrum.
Registration of spectrum 1 is performed through an aperture, spectrum 2 through a nozzle

№	*λ_{tab}, nm*[9]	*λ_1, nm (aperture)*	*λ_2, nm (nozzle)*	*Paschen'transition [11]*	L→ S *transition* [11]
1	696.543	696.4	696.4	$^1P_1 \to {}^3P_2$ $2p_2 \to 1s_5$	$4p'^2[1/2]_1 \to 4s^2[3/2]_2$
2	706.722	706.7	706.7	$^3P_2 \to {}^3P_2$ $2p_3 \to 1s_5$	$4p'^2[3/2]_2 \to 4s^2[3/2]_2$
3	714.704	714.6		$^3P_1 \to {}^3P_2$ $2p_4 \to 1s_5$	$4p'^2[3/2]_1 \to 4s^2[3/2]_2$
4	727.294	727.2		$^1P_1 \to {}^3P_1$ $2p_2 \to 1s_4$	$4p'^2[1/2]_1 \to 4s^2[3/2]_1$
5	738.398	738.4	738.4	$^3P_2 \to {}^3P_1$ $2p_3 \to 1s_4$	$4p'^2[3/2]_2 \to 4s^2[3/2]_1$
6	750.387	750.3	750.3	$^1S_0 \to {}^1P_1$ $2p_1 \to 1s_2$	$4p'^2[1/2]_0 \to 4s'^2[1/2]_1$
7	751.465	751.3	751.3	$^3P_0 \to {}^3P_1$ $2p_5 \to 1s_4$	$4p^2[1/2]_0 \to 4s^2[3/2]_1$
8	763,511	763.5	763.5	$^3D_2 \to {}^3P_2$ $2p_6 \to 1s_5$	$4p^2[3/2]_2 \to 4s^2[3/2]_2$
9	772,376	772.3	772.3	$^3D_1 \to {}^3P_2$ $2p_7 \to 1s_5$	$4p^2[3/2]_1 \to 4s^2[3/2]_2$
10	794.815	794.8	794.6	$^3P_1 \to {}^3P_0$ $2p_4 \to 1s_3$	$4p'^2[3/2]_1 \to 4s'^2[1/2]_0$
11	800,616	800.6	800.4	$^3D_2 \to {}^3P_1$ $2p_6 \to 1s_4$	$4p^2[3/2]_2 \to 4s^2[3/2]_1$
12	801,479	801.3	801.3	$^3D_2 \to {}^3P_2$ $2p_8 \to 1s_5$	$4p^2[5/2]_2 \to 4s^2[3/2]_2$
13	810.369	810.3	810.2	$^3D_1 \to {}^3P_1$ $2p_7 \to 1s_4$	$4p^2[3/2]_1 \to 4s^2[3/2]_1$
14	811.531	811.4	811.4	$^3D_3 \to {}^3P_2$ $2p_9 \to 1s_5$	$4p^2[5/2]_3 \to 4s^2[3/2]_2$
15	826.452	826.4	826.4	$^3P_1 \to {}^1P_1$ $2p_2 \to 1s_2$	$4p'^2[1/2]_1 \to 4s'^2[1/2]_1$
16	840.821	840.7	840.7	$^3P_2 \to {}^1P_1$ $2p_3 \to 1s_2$	$4p'^2[3/2]_2 \to 4s'^2[1/2]_1$
17	842,465	842.4	842.4	$^3D_2 \to {}^3P_1$ $2p_8 \to 1s_4$	$4p^2[5/2]_2 \to 4s^2[3/2]_1$
18	852.144	851.9	851.9	$^3P_1 \to {}^1P_1$ $2p_4 \to 1s_2$	$4p'^2[3/2]_1 \to 4s'^2[1/2]_1$

IOP Conf. Series: Journal of Physics: Conf. Series **944** (2018) 012040 doi:10.1088/1742-6596/944/1/012040

4. Results and discussion

In the arc discharge of the resistojet model, the pressure of saturated tungsten vapors is four orders of magnitude less than the argon pressure. Therefore, argon has a decisive influence on the drift velocity of the electrons V_d and on the thermal conductivity of the plasma, and the role of tungsten with a small ionization potential (E_W = 7.98 eV) reduces to the formation of the ne concentration and the T_e temperature of the electrons.

According to the calculations, the discharge plasma of anresistojet is a multicomponent argon-tungsten plasma having several local temperatures.

The concentration of argon is much greater than the concentration of tungsten vapor and electron concentration, so the width of the radiation contour could be determined, basically, by elastic collisions of argon atoms with each other and with electrons. However, the calculations of the electron temperature based on the shock broadening of the radiation contours of argon atoms in the range 696 ... 852 nm do not allow one to unequivocally state the shock excitation of heavy-particle atoms of the plasma in question.

The emission lines of tungsten provide a white glow discharge, observed through the aperture. The appearance of tungsten atoms in the plasma volume, on the one hand, is not unexpected, since tungsten is part of the structural parts, but, on the other hand, it is a signal of the erosion of structural elements. [12]

At the same time, a strong absorption of the longwave wing of the contour of the intense tungsten line is observed at λ = 465.987 nm. If this effect is determined by self-absorption, then by the parameters of the "tail" of this line (at λ = 465.2 nm) recorded through the nozzle of the engine, it is possible to estimate the consumption of tungsten. Probably, the absence of tungsten lines in the spectrum of the nozzle at λ = 489.2 nm, 513.0 nm and 546.9 nm can also be explained by self-absorption.

It was noted that the spectrum of argon passed through the aperture lost several lines: λ = 714.704 nm, 727.294 nm, 866.794 nm, 912.296 nm, 922.450 nm. This phenomenon was explained in [11] by the high rate of quenching of excited states of argon by nitrogen molecules from the surrounding nozzle of the air medium.

When comparing the wavelengths of argon lines λ = 794.815 nm, 800.616 nm and 810.369 nm, (Table 2), the radiation from the nozzle relative to radiation from the discharge chamber shows that the lines have a Doppler shift of wavelengths.

The confirmation of this shift is found in the fact that the velocities of the argon atoms in the chamber are more chaotic than in the gas jet directed from the nozzle, mainly with an axial velocity.

5. Conclusions

The discharge plasma of the arcjet model is a multicomponent argon-tungsten plasma having several local temperatures.

The discharge glow spectrum observed through the aperture of the discharge chamber is a consequence of the excitation of tungsten and argon atoms. In the spectrum observed through the nozzle of the discharge chamber, a strong absorption of the longwave wing of the contour of the intense tungsten line was observed at λ = 465.987 nm. The registration of partial self-absorption of this tungsten line, observed through the nozzle of the engine, makes it possible to estimate the magnitude of the erosion of the structural elements of the plasma device.

Under the considered excitation regime of the resistojet model in the discharge between the spectral lines of argon atoms at λ = 794.815 nm, 800.616 nm and 810.369 nm, an offset is observed when radiation passes through the discharge chamber nozzle. The marked shift, according to the Doppler effect, can be used to find the velocity of the gas jet outflow.

For more complete representation of the mechanisms of excitation of the DETMD discharge, additional studies are needed.

6. References

[1] Mazouffre S 2016 Electric propulsion for satellites and spacecraft: established technologies and novel approaches *Plasma Sources Sci. Technol* **25** pp 1–27
[2] El'yashevich M A 1962 *Atomic and Molecular Spectroscopy* (Moscow) [in Russian].
[3] Brinkman E A Electron densities and temperatures 1997 *J. Appl. Phis* **81** (3) pp 1093–1098
[4] Bijie Yang 2014 Quanhua Sun. Numerical Analysis of the Plasma Flow in an Arcjet Thruster *AIP Conference Proceedings* Vol 1628 pp 1132–1138
[5] Landau L D, Lifshitz E M 1987 *Fluid Mechanics* vol 6 Butterworth–Heinemann. ISBN 978-0-08-033933-7
[6] Blinov V N., Ruban V I. et al. 2016 Design features and experimental researches of an arcjet thruster for small satellite *Dynamics of Systems, Mechanisms and Machines (Dynamics)*
[7] Smirnov B M 2009 Modeling of gas discharge plasma *Physics – Uspekhi* vol 52 pp 559–571
[8] Rosebury Fred 1964 *Handbook of Electron Tube and Vacuum Techniques* (Massachusetts) p 456
[9] Frish S E 1963 *Optical spectra of atoms (*Moscow) p 640
[10] Zaĭdel'A N, Prokof'ev V K, S M Raĭskiĭ et al. 1977 *Tables of Spectral Lines* (Moscow: Nauka)
[11] Cullen P J, Milosavljevic V **2015** Spectroscopic characterization of a radio-frequency argon plasma jet discharge in ambient air *Prog. Theor. Exp. Phys*. 063J01
[12] Smirnov Yu M 2009 Electron impact excitation cross-section of tungsten atom *High temperature* Vol 47 pp 13–21

Acknowledgments
The work was supported by the Russian Foundation for Basic Research, grant No. 15-08-00726.