ISSN 0027-1349, Moscow University Physics Bulletin, 2017, Vol. 72, No. 3, pp. 294–300. © Allerton Press, Inc., 2017.
Original Russian Text © V.M. Shibkov, L.V. Shibkova, A.A. Logunov, 2017, published in Vestnik Moskovskogo Universiteta, Seriya 3: Fizika, Astronomiya, 2017, No. 3, pp. 76–82.

CHEMICAL PHYSICS, PHYSICAL KINETICS, AND PLASMA PHYSICS

The Electron Temperature in the Plasma of a DC Discharge Created in a Supersonic Airflow

V. M. Shibkov*, L. V. Shibkova, and A. A. Logunov
Department of Physics, Moscow State University, Moscow, 119991 Russia
** e-mail: shibkov@phys.msu.ru*
Received June 2, 2016; in final form, September 23, 2016

Abstract—The plasma parameters of a pulsating DC discharge created in a supersonic airflow with a Mach number of $M = 2$ are determined. It is revealed that along with the intense bands of CN and the molecular nitrogen ion, as well as the spectral lines of atomic oxygen, nitrogen, hydrogen and copper, an intense continuous spectrum is observed in the spectrum of the gas-discharge plasma radiation, which is caused by the deceleration of electrons on ions. The dependences of the electron temperature on the discharge current and longitudinal coordinates are determined. It was revealed that the studied plasma is nonequilibrium, with the electron temperature being much higher than the gas temperature.

Keywords: supersonic airflow, pulsating discharge, low-temperature plasma, bremsstrahlung, electron temperature.

DOI: 10.3103/S0027134917030109

For the advancement of modern aviation, it is necessary to search for and develop new effective methods that would make it possible to control the gas flow characteristics near an aircraft surface, reduce surface friction, delay the laminar–turbulent transition, control the flow separation, reduce the ignition time and control the burning process of supersonic flows of fuel in a ramjet engine. One of the new methods for solving these problems is the use of various types of gas discharge. Thus, a new trend in plasma physics, namely, supersonic plasma aerodynamics [1], is now strongly developing. In order to improve the aerodynamic characteristics of aircraft, it is proposed to create plasma formations in front of them and on their bearing surfaces. The use a nonequilibrium gas-discharge plasma has been proposed for reduction of the fuel ignition time in a ramjet engine. One of the problems that must be solved when creating a modern high-speed aircraft is the effective, stable, and controlled burning of hydrocarbon fuel in a supersonic airflow taking the variable parameters of the environment during flight into account. In various research institutes, intensive experimental and theoretical investigations are carried out in the framework of supersonic plasma-stimulated burning of a fuel mixture. Nevertheless, the experimental investigations devoted to studying the various mechanisms connected with the fast volumetric ignition and burning stabilization of the high-speed flows of hydrocarbon fuel have been insufficient. The search for the optimal type of electrical discharge and desired optimal mode of plasma creating continues [2–28].

Different types of self-maintained gas discharges, namely, the free localized discharge generated by the focused beam of electromagnetic radiation and the microwave discharge generated by a surface wave on a dielectric body streamlined by a supersonic airflow, as well as the pulse transverse and longitudinal surface and volumetric electrode discharges have been experimentally tested [2, 6, 10–25]. As self-maintained microwave discharges exist at high values of a reduced electric field, the quantity of generated active particles they produce is more than that in the plasma of an electrode discharge. This greatly affects the kinetics of the processes that involve active radicals and, consequently, decreases the induction time, which is very promising to initiate the ignition of supersonic flows of gaseous fuel.

The ignition of a supersonic propane–air flow using microwave discharges for different values of the gas pressure, exposure duration, power, mixture composition, etc., has been investigated in a number of works (see [6] and cited literature). A high voltage nanosecond discharge was used in [3, 4] for ignition, which evolves as the high-speed wave of ionization and generates highly excited plasma in the discharge gap at the characteristic time scales of tens of nanoseconds. The possibility of using a high-voltage nanosecond discharge generated in the pulse-periodic regime with a pulse repetition rate of up to 50 kHz to ignite subsonic air–hydrocarbon flows was investigated in

[5]. The problems associated with using a gas-discharge plasma to ignite air–hydrocarbon fuels were discussed in [7–9]. In addition, great attention is paid to the influence of active particles on the ignition mechanism in literature.

Different degrees of gas ionization are achieved for different discharges with the same consumed specific power. The input electric energy is distributed in a variety of ways by the internal degrees of freedom of molecular gas. This distribution strongly depends on the reduced electric field, which, in turn, is determined by the electrodynamics of the discharge. The experiments in [24, 25] revealed that pulse-periodic electrode discharge resulted in ignition only when the pulse duration was more than 150 μs. The ignition of supersonic flow of propane–air mixtures using freely localized microwave discharge was carried out when the pulse duration equaled $\tau \approx 25$ μs and the ignition using the surface microwave discharge occurred almost without delay immediately after turning on the microwave energy. Self-maintained microwave discharges exist at high values of the reduced electric field [24]. In this case, a large number of active particles is generated, which has a strong affect on the kinetics of the processes that involve active radicals and decreases the induction time. The results obtained in [24, 25] visually confirmed the fact that at high values of a reduced electric field rapid gas heating occurs at the rate of 10^7–10^8 K/s and a high degree of dissociation of molecules of ~50% in the microwave plasma discharge. Finally, this promotes rapid fuel ignition.

To optimize the burning of gaseous and liquid fuels under supersonic airflows it is necessary to know the parameters of the plasma used for the ignition and stabilization of the burning of hydrocarbon fuels. The parameters of self-maintained microwave discharges have been well studied [14–25]; this work is devoted to research on the parameters of the insufficiently known DC discharge pulsating in a supersonic flow, which is essentially a nonstationary discharge generated using a DC voltage source.

The test bench includes a vacuum chamber, a high-pressure air receiver, a system for generating a supersonic flow, a rectangular wind tunnel with an attached air duct, the high-voltage power supply to create the gas-discharge plasma, the synchronization system, and diagnostic equipment. The basis of the experimental apparatus is a pumped metallic cylindrical pressure chamber with an inner diameter of 1 m and a length of 3 m. The wind tunnel was placed inside the pressure chamber. The supersonic flow in the wind tunnel was created by filling the pressure chamber with air through a specially shaped Laval nozzle. To prevent thermal choking a tunnel with a variable section was used; the ratio of the output section to the input section equals $S_2/S_1 = 12$. The longitudinal length of the tunnel was 50 cm.

A pulsating discharge generated by a DC voltage source with the voltage $U = 1$–5 kV was generated between two electrodes that are well covered by the airflow, the sections of which were a thin elongated diamond with smooth tops (the maximum thickness of the electrodes did not exceed 1 mm and the width was no more than 5 mm). The electrodes were mounted inside an expanding wind tunnel. The experiments were performed in an open pressure chamber at atmospheric air pressure with a cold ($T = 200$ K) supersonic airflow under the following parameters: the duration of the existence of the supersonic flow was $\tau = 3$ s; the Mach number of the flow was $M = 2$, the discharge current was varied within 2–18 A; the mass air flow rate per second was 100 g/s and the mass propane flow rate per second was 4.2 g/s; the duration of the discharge current pulse was $\tau = 2$ s. The discharge under is a thin plasma channel with a diameter of the order of 1 mm, which is elongated by a flow along its propagation. When supplying the voltage to the electrodes the breakdown of air occurs between them. The thus-created plasma channel slides on the electrodes in the direction of the high-speed air flow and then it is fixed on the tips of the electrodes and the plasma loop begins to stretch down along the flow. When it reaches its maximum length, when the voltage on the discharge gap begins to exceed a critical value, a new breakdown occurs between electrodes, the discharge loop is broken, and the process of extension of the plasma loop down along the flow is periodically repeated. Therefore, the DC discharge that is formed in the airflow in principle is a nonstationary pulsating discharge.

The emission spectrum of the discharge plasma was recorded using a digital dual-channel AvaSpec-2048-2-DT spectrograph from the Avantes BV company. Averaging was performed for the exposure time $\tau = 20$ ms, the frame repetition rate was 20 Hz, i.e., for one start with a duration of $t = 2$ s up to 40 spectra are consistently recorded. Figure 1 shows the overview of the plasma emission spectrum of a discharge pulsating in a supersonic airflow recorded at a distance of $z = 1$ cm from the tips of electrodes when the discharge current $i = 16$ A. At first, the correction of the recorded spectrum was carried out taking the coefficient of spectral sensitivity of the spectrograph into account. The absolute sensitivity of the spectrograph was calibrated using a tungsten band lamp. As the hot tungsten lamp does not radiate as a blackbody, when determining the coefficient of spectral sensitivity of the spectrograph the fact was taken into account that at a fixed temperature of tungsten the difference of the intensity of its radiation of the blackbody radiation spectrum changes when the wavelength of radiation changes [29–32]. One distinctive feature of the plasma radiation is that along with intense bands of CN and molecular nitrogen ion, as well as the spectral lines of atomic oxygen, nitrogen, hydrogen, and copper in the spectrum, a powerful continuum is observed.

The gas temperature in the discharge was determined by the bands of CN and the molecular nitrogen ion. For this the model distributions were calculated of the rotational levels of molecular bands of CN and N_2^+ at different gas temperatures taking the instrument function of the spectral device and various effects into account, leading to the broadening of the spectral lines in the plasma of the discharge (Doppler broadening, Stark broadening, broadening due to the effects of pressure, i.e., when a collision with air molecules, etc.). Further, the experimentally obtained spectrum was compared with the data of mathematical modeling. The gas temperature was assumed equal to the temperature, at which the best coincidence of the calculated data with the experimental results occurred. It was revealed that the gas temperature near the electrodes varies within 300–900 K.

The atomic lines of hydrogen H_α and H_β also were recorded in the emission spectrum. The electron density n_e in the plasma of the channel discharge was measured by Stark broadening of the H_β line of the hydrogen Balmer series [29, 33]. It was revealed that with an increase in the discharge current from 2 to 18 A the electron density increases from 3×10^{14} to 3×10^{16} cm^{-3}. The obtained amount corresponds well with the electron density calculated by the formula $i = en_e v_{dr} S$, where i is the discharge current and e is the electron charge. The drift velocity v_{dr} was calculated via the value of the electric field strength in the plasma, which was determined by the measured voltage drop U on the discharge; the length l and cross-sectional area S of the discharge channel was recorded using a VideoSprint high-speed digital video camera that makes it possible to record the discharge with a frame-repetition rate up to 50 kHz at the exposure time of each frame equal to 2 μs. The total length of the plasma channel that forms the discharge loop increases in the experiment from 60 mm with a 2-A current to 120 mm when the discharge current is 18 A. It should also be noted that the channel length varies in time synchronously with the voltage drop on the discharge. In this case, the electrical field strength during the discharge propagation process remains almost constant over time and decreases with an increase in the discharge current. Reducing the electric field strength leads to a decrease in the drift velocity of electrons and consequently to increasing the electron density.

The strong lines of atomic oxygen radiation, as well as the lines of atomic nitrogen that occur as a result of effective dissociation of the molecules of oxygen and nitrogen in the plasma at high values of the electron density were recorded in the long-wave spectrum range $\lambda = 600$–800 nm. The intensive dissociation of molecules is the source of the formation of radicals and active excited particles in the plasma, which promotes the acceleration of chain reactions that provide rapid ignition of hydrocarbon fuel and maintains its stationary burning in the supersonic airflow.

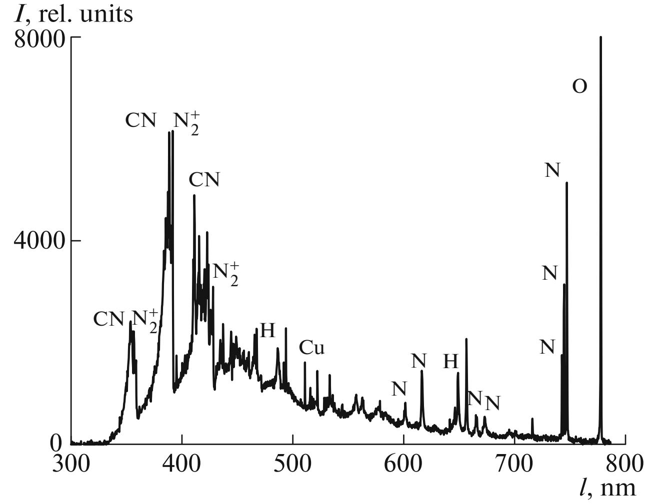

Fig. 1. An overview of the plasma-emission spectrum recorded at the distance $z = 1$ cm from the electrodes; a pulsating discharge produced in supersonic airflow by a DC voltage source.

The nature of the continuous spectrum recorded in the experiment (Fig. 1) can be associated either with the electron deceleration effects on ions or atoms, or with the recombination spectrum, or it will be determined by the radiation of heated metal microparticles that fall into the discharge region owing to their ablation from the surface of electrodes. The estimates reveal that during the experiment the bremsstrahlung spectrum intensity that occurs during the interaction of electrons with ions prevails over the spectrum associated with the deceleration of electrons on atoms. The recombination spectrum nonmonotonically depends on the wavelength, whereas the experimentally measured continuous spectrum has a monotonous dependence on λ. The recorded molecular bands and spectral lines do not bear any relationship to the edges of the series of the recombination spectrum.

The electron temperature measurement is performed by comparing the recorded spectrum with the bremsstrahlung spectrum calculated by the following formula at various temperatures of electrons [34]:

$$I_\lambda = C_1 \frac{n_e n^+}{\lambda^2 T_e^{1/2}} \exp\left\{-\frac{hc}{\lambda k T_e}\right\} d\lambda, \quad (1)$$

where C_1 is a constant, n_e and n^+ are the densities of electrons and positive ions; λ is the emission wavelength; h and k are the Planck and Boltzmann constants; c is the speed of light; and T_e is the electron temperature. It is assumed in the calculations that the distribution of electrons by energy is a Maxwellian distribution function that does not contradict the experiment conditions, namely, high values of the electron density and low values of the reduced electric field.

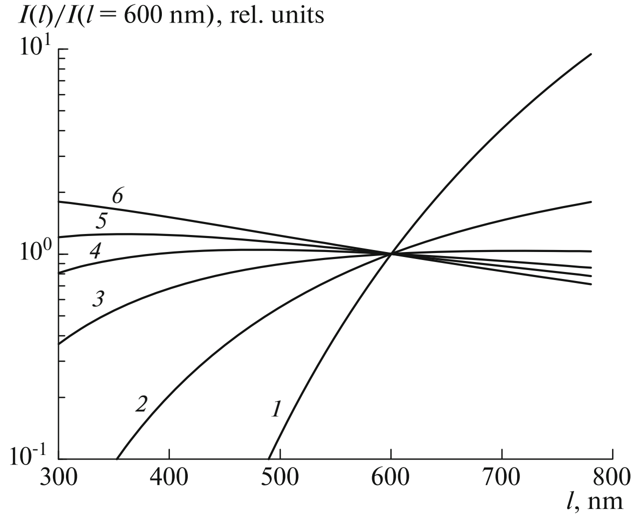

Fig. 2. The dependences of the calculated intensities of the bremsstrahlung spectrum normalized per unit when λ = 600 nm, on the emission wavelength at various electron temperatures T_e: (*1*), 2000 K; (*2*), 5000 K; (*3*), 10 000 K; (*4*), 15 000 K; (*5*), 20 000 K; (*6*), 30 000 K.

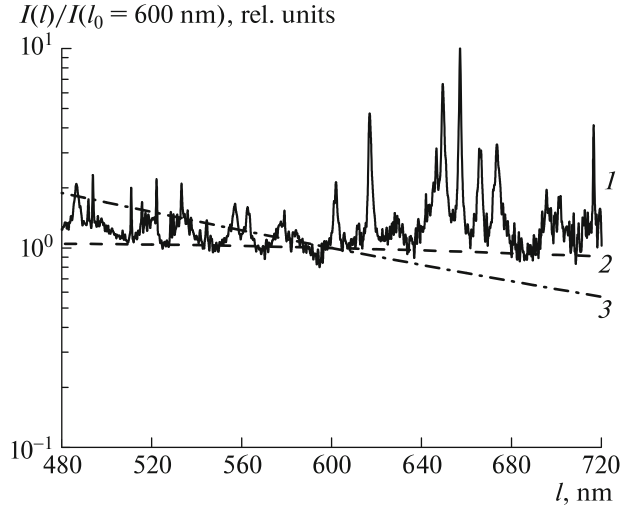

Fig. 3. The comparison of the experimentally measured (*1*) emission spectrum of the pulsating discharge in the airflow with the bremsstrahlung spectrum when T_e = 15 000 K (dashed curve *2*) and the Planck spectrum at T_g = 15 000 K (dashed-dotted curve *3*).

Figure 2 presents a nomogram of the dependences of bremsstrahlung spectrum intensities calculated by formula (1), normalized per unit when $\lambda = 600$ nm, on the emission wavelength at various electron temperatures. It is seen that at low electron temperatures of $T_e < 10000$ K the intensity of the spectrum normalized per unit in the range of $400 < \lambda < 800$ nm rises with an increase in the emission wavelength, while at higher $T_e > 10000$ K the spectrum intensity decreases with an increase in the wavelength. This fact makes it possible to easily evaluate the temperature of electrons in the appearance of bremsstrahlung spectrum.

The uninterrupted continuum associated with the thermal radiation from the surface of the microparticles heated in the discharge can be compared with the blackbody spectrum. The dependence of the blackbody brightness $b_{\lambda,T}$ on the wavelength is defined by the Planck formula [30, 34]:

$$b_{\lambda,T} = \frac{C_2}{\lambda^5}\frac{1}{\exp\left\{\frac{hc}{\lambda kT}\right\}-1}, \tag{2}$$

where T is the temperature of the body surface and C_2 is a constant.

By comparing the experimentally recorded spectrum recalculated taking the spectral sensitivity of the spectrograph [30–32] with the bremsstrahlung or Planck spectra computed by Eqs. (1) and (2) into account, one can define its nature and, accordingly, the electron temperature or the surface temperature of radiating hot particles that arise in the plasma as a result of their ablation from the surfaces of the electrodes.

Figure 3 illustrated the comparison of the normalized per unit experimentally measured spectrum of pulsating discharge in the airflow at a wavelength of 600 nm (curve *1*) recomputed taking the coefficient of the spectral sensitivity of the spectrograph with the bremsstrahlung spectrum when T_e = 15 000 K (dashed curve *2*) and Planck spectrum when T_g = 15 000 K (dash dot curve *3*) into account. The test conditions were as follows: the Mach number of the supersonic flow is $M = 2$, the discharge current is $i = 16$ A, the mass airflow rate per second is 100 g/s, the distance from the tips of electrodes is $z = 1$ cm. It is seen that there is a good agreement of the experimental measured spectrum with the bremsstrahlung spectrum when T_e = 15 000 K, whereas the behavior of the thermal radiation does not correspond to the experiment results. Similar measurements were carried out with different values of the discharge current and distances along the flow from the tips of the electrodes. The results are presented in Fig. 4. It is seen that the electron temperature measured by the bremsstrahlung spectrum increases from 10 000 K to 15 000 K with an increase in the discharge current from 2 to 16 A, while with an increase in the distance from the electrodes from 0 to 5 cm the electron temperature decreases from 15 000 K to 8000 K.

An addition to the supersonic airflow, a small amount of propane substantially changes the discharge parameters. Figure 5 gives a comparison of the normalized per unit experimentally measured spectrum of pulsating discharge at a wavelength of 600 nm in the propane–airflow with the bremsstrahlung spectrum when T_e = 5000 K (dashed curve *2*) and the Planck spectrum with T_e = 5000 K (dash dot curve *3*).

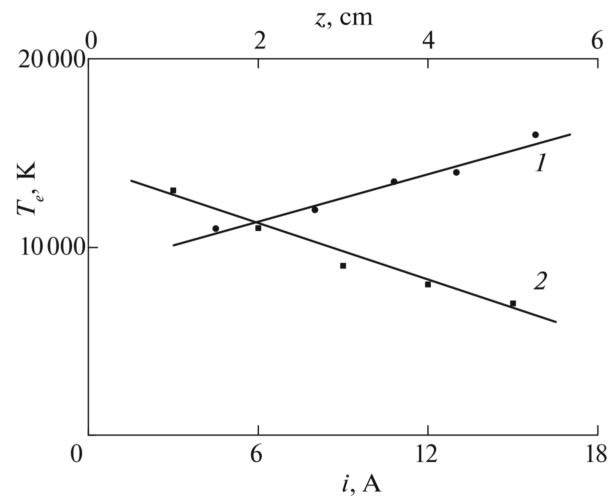

Fig. 4. The dependences of the electron temperature on the discharge current, measured at the distance of $z = 1$ cm from the electrodes (straight line *1*) and on the longitudinal coordinate z at discharge current $i = 10.8$ A (straight line *2*).

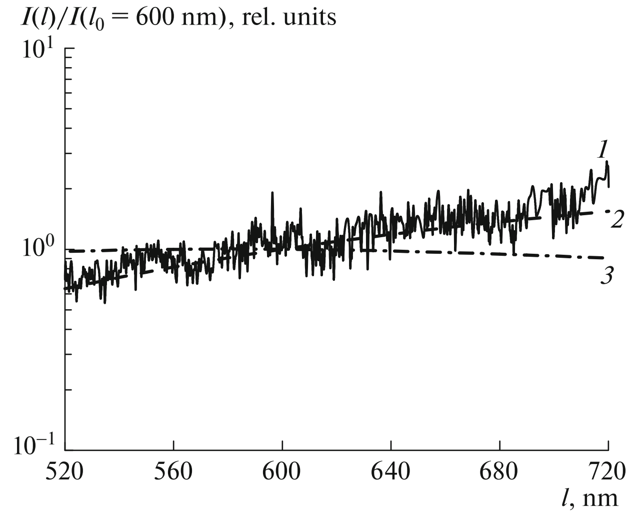

Fig. 5. A comparison of the measured emission spectrum of the pulsating discharge in the propane–air flow (*1*) with the bremsstrahlung spectrum when $T_e = 5000$ K (dashed curve *2*) and the Planck spectrum at $T_g = 5000$ K (dash dot curve *3*).

The test conditions were as follows: the Mach number of the supersonic flow is $M = 2$, the discharge current is $i = 4.5$ A, the mass airflow rate per second is 100 g/s, the mass propane flow rate per second is 4.2 g/s, and the distance from the tips of the electrodes is $z = 1$ cm. It is seen that the electron temperature in the gas-discharge plasma generated in the propane-air flow is considerably lower than the electron temperature in the supersonic airflow.

Copper atom lines with the wavelengths $\lambda = 510.5$, 515.3, and 521.8 nm also occur in the spectrum (see Fig. 1). Copper vapor appears in the plasma due to ablation from the electrode surface streamlined by the supersonic airflow during flow through them of the electric current and formation at the electrode tips of the cathode and anode. The temperature of the distribution on the energy levels of populations of excited copper atoms was defined by the relative intensities of these lines. Because the role of radiation processes sharply decreases with the approach to the continuous spectrum edge (at the larger main quantum numbers n the oscillator strength f is proportional to n^{-3}), the intensity of the radiation processes decreases with a decrease in the binding energy. The intensity of the impact processes that involve electrons, conversely, sharply increases (the sections of the first and the second kinds of interactions of electrons with the excited atoms are proportional to n^4). This makes it possible to split the energy interval into two region [35]. In the first region, where the binding energy ε_b is less then ε_R, the impact processes dominate, in the second region, where $\varepsilon_b > \varepsilon_R$, the excitation of the levels is carried out by electron impact and suppression occurs due to radiation. Then for small binding energies the distribution of the excited atoms that are in equilibrium with the electrons will be close to the distribution of electrons according to their energies, i.e., in these conditions one can estimate the electron temperature using the temperature of the distribution of atoms according to the excitation states measured by the relative intensities of the spectral lines. For this, it is necessary to use the spectral lines for which the condition [35]

$$\varepsilon_b < \varepsilon_R = \left(-\frac{n_e}{4.5\times10^{13}}\right)^{1/4}\frac{1}{T_e^{1/2}}, \quad (3)$$

is met, where the dimension of the electrons density is cm^{-3} and the dimension of the electron temperature and binding energy is eV.

It should be noted that during the experiment, at high values of electron densities $n_e \sim 10^{14}$–10^{16} cm^{-3} and electron temperature on the order of $T_e = 1$ eV the distribution function of the populations of copper levels according to the excitation states should be identical to the distribution function of the electrons according to energy, i.e., the temperature of distribution according to the levels of copper atoms is close to the electron temperature. Figure 6 presents the temperatures T_{Cu} of the population distribution of excited copper atoms. The temperature T_{Cu} was measured by the relative intensities of the different pairs of spectral lines of copper: $I_1/I_3(1)$ and $I_1/I_2(2)$, where I_1 is the line intensity with the wavelength $\lambda_1 = 510.5$ nm, I_2 is the line intensity with the wavelength $\lambda_2 = 515.3$ nm, and I_3 is the line intensity with the wavelength $\lambda_3 = 521.8$ nm. It is seen that the temperature of distribution of copper atoms is within 1.0–1.5 eV, which is

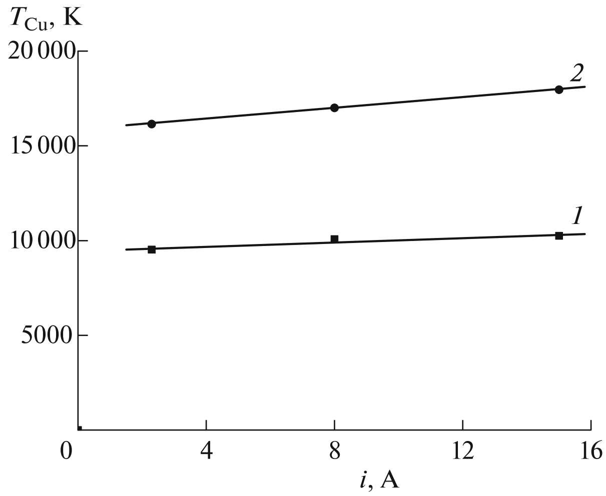

Fig. 6. The temperature of the population distribution of the excited copper atoms at different discharge currents at the distance $z = 1$ cm from the electrodes.

close to the electron temperature measured by the bremsstrahlung spectrum.

It should be noted that the wavelengths of the copper lines used for measuring the excitation temperature differ from each other slightly and are located in the spectral range where the sensitivity of the spectral device is high and the spectral sensitivity coefficient is lightly varies with the wavelength. This makes it possible to measure the electron temperature quite simply without using the labor-intensive method of measurement of electron temperature according to the absolute intensity of the continuous spectrum. However, this method is much less accurate and is used here only in order to estimate the order of magnitude of the electron temperature.

CONCLUSIONS

The pulsating DC discharge created in the supersonic airflow with the Mach number $M = 2$ was investigated. It was revealed that the electron temperature measured by the bremsstrahlung spectrum increased from 10 000 K up to 15 000 K with an increase in the discharge current from 2 to 18 A, while with an increase in the distance from the electrodes from 0 to 5 cm the electron temperature decreased from 15 000 K to 8000K. The gas temperature in these conditions varied within 300–900 K. Upon adding propane to the airflow the electron temperature decreased sharply to 5000 K.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (no. 14-02-00514-a).

REFERENCES

1. D. Van Wie, presented at *10th Weakly Ionized Gas Workshop, Reno, Nevada, 2008.*
2. R. S. Konstantinovskii, V. M. Shibkov, and L. V. Shibkova, Kinet. Catal. **46**, 775 (2005).
3. S. M. Starikovskaya, J. Phys. D **39**, R265 (2006).
4. A. Y. Starikovskii, N. B. Anikin, I. N. Kosarev, et al., J. Propul. Power **24**, 1182 (2008).
5. I. V. Adamovich, W. R. Lempert, J. W. Rich, and Y. G. Utkin, J. Propul. Power **24**, 1198 (2008).
6. V. M. Shibkov, A. F. Aleksandrov, V. A. Chernikov, et al., J. Propul. Power **25**, 123 (2009). doi 10.2514/1.24803
7. I. A. Kossyi, in *Proc. 45th AIAA Aerospace Sciences Meeting and Exhibition, Reno, Nevada, 2007*, p. AIAA-2007-0429.
8. S. Yu. Kazantsev, I. G. Kononov, I. A. Kossyi, N. M. Tarasova, and K. N. Firsov, Plasma Phys. Rep. **35**, 251 (2009).
9. N. L. Aleksandrov, S. V. Kindysheva, E. N. Kukaev, S. M. Starikovskaya, and A. Yu. Starikovskii, Plasma Phys. Rep. **35**, 867 (2009).
10. P. V. Kopyl, O. S. Surkont, V. M. Shibkov, and L. V. Shibkova, Plasma Phys. Rep. **38**, 503 (2012).
11. A. P. Ershov, O. S. Surkont, I. B. Timofeev, V. M. Shibkov, and V. A. Chernikov, High Temp. **42**, 516 (2004).
12. A. P. Ershov, O. S. Surkont, I. B. Timofeev, V. M. Shibkov, and V. A. Chernikov, High Temp. **42**, 667 (2004).
13. A. P. Ershov, A. V. Kalinin, O. S. Surkont, I. B. Timofeev, V. M. Shibkov, and V. A. Chernikov, High Temp. **42**, 865 (2004).
14. V. M. Shibkov, A. F. Aleksandrov, A. P. Ershov, I. B. Timofeev, V. A. Chernikov, and L. V. Shibkova, Plasma Phys. Rep. **31**, 795 (2005).
15. V. M. Shibkov, A. P. Ershov, V. A. Chernikov, and L. V. Shibkova, Tech. Phys. **50**, 455 (2005).
16. V. M. Shibkov, S. A. Dvinin, A. P. Ershov, and L. V. Shibkova, Tech. Phys. **50**, 462 (2005).
17. A. F. Aleksandrov, V. M. Shibkov, and L. V. Shibkova, Moscow Univ. Phys. Bull. **63**, 365 (2008). doi 10.3103/S0027134908050135
18. A. F. Aleksandrov, V. M. Shibkov, and L. V. Shibkova, Moscow Univ. Phys. Bull. **63**, 433 (2008). doi 10.3103/S0027134908060179
19. V. M. Shibkov, L. V. Shibkova, and A. A. Karachev, High Temp. **47**, 620 (2009).
20. A. F. Aleksandrov, V. M. Shibkov, and L. V. Shibkova, High Temp. **48**, 611 (2010).
21. V. M. Shibkov, L. V. Shibkova, V. G. Gromov, A. A. Karachev, and R. S. Konstantinovskii, High Temp. **49**, 155 (2011).
22. V. M. Shibkov and L. V. Shibkova, Tech. Phys. **54**, 1467 (2009).
23. V. M. Shibkov and L. V. Shibkova, Tech. Phys. **55**, 58 (2010).
24. L. V. Shibkova, Doctoral Dissertation in Mathematics and Physics (Joint Inst. for High Temperatures, Russian Academy of Sciences, Moscow, 2007).

25. R. S. Konstantinovskii, Candidate's Dissertation in Mathematics and Physics (Moscow State Univ., Moscow, 2011).

26. V. I. Alferov and A. S. Bushmin, J. Exp. Theor. Phys. **17**, 1190 (1963).

27. V. I. Alferov, A. S. Bushmin, and B. V. Kalachev, J. Exp. Theor. Phys. **24**, 859 (1966).

28. V. I. Alfyorov, Fluid Dyn. **39**, 988 (2004).

29. *Plasma Diagnostics*, Ed. by W. Lochte-Holtgreven (Wiley, New York, 1968).

30. V. I. Malyshev, *Introduction to Experimental Spectroscopy* (Nauka, Moscow, 1979).

31. A. S. Zarin, A. A. Kuzovnikov, and V. M. Shibkov, *Freely Localized Microwave Discharge in Air* (Neft' i Gaz, Moscow, 1996).

32. L. V. Shibkova and V. M. Shibkov, *Discharge in Mixtures of Inert Gases* (Fizmatlit, Moscow, 2005).

33. H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic Press, New York, 1974).

34. Yu. P. Raizer, *Gas Discharge Physics* (Nauka, Moscow, 1987).

35. L. M. Biberman, V. S. Vorob'ev, and I. T. Yakubov, *Kinetics of Nonequilibrium Low-Temperature Plasma* (Nauka, Moscow, 1982).

Translated by M. Kromin