THE INFLUENCE OF RADIATION ON THE TEMPERATURE PROFILE OF AN INDUCED DISCHARGE IN ARGON AT ATMOSPHERIC PRESSURE

V. N. Soshnikov, E. S. Trekhov,
A. F. Fomenko, and Yu. m. Khoshev

UDC 537.527

This study presents a quantitative evaluation of the influence of radiation upon the parameters of a long induced discharge in argon at atmospheric pressure. Radiation heat transfer in the optically transparent (in plasma layers with thickness of the order of several centimeters) and reabsorption spectral intervals is examined. Experimental error produced by inaccurate knowledge of the transfer and optical characteristics of the plasma is evaluated. The effect of convection on radial temperature profile is evaluated.

The temperature profile of an electrodeless induced discharge is determined by the spacial distribution of Jouleian energy, loss of this energy from the discharge, and redistribution within the discharge due to the processes of thermal conductivity, light radiation, and convection. Despite the significant number of works on this subject (cf. [1-4]), until the present there has been no detailed presentation concerning the influence of the individual processes upon the temperature profile and other parameters of an induced discharge [5-7].

The authors of [5] reached the conclusion that radiation has no significant effect upon the parameters of the discharge, and that in calculation of the discharge radiation could be neglected. The appearance of an axial dip in the radial temperature distribution is determined, in such a case, solely by the presence of planar heat emission. However, the calculations of the same authors [8] show that the axial dip in radial temperature profile produced by axial heat emission within the central portion of the tube does not exceed $\sim 100°K$ even at $l \geqslant 2\rho_0$, where l is the length of the inductor, and ρ_0 is the radius of the discharge tube. Moreover, in [9] it was noted that an axial dip was produced less frequently in gasses possessing higher radiation capabilities.

Yet the authors of [7] feel that in calculation of discharge parameters it is absolutely necessary to consider not only radiation losses in the optically transparent (in layers with thickness 1-10 cm) spectral intervals, but also radiation transfer in the reabsorption spectral intervals. In fact, the degree of influence which radiation transfer has upon axial dip has yet to be clarified [1]; the possibility of levelling the temperature profile by this mechanism was not excluded in [6], either.

This study will present an analysis of the effect of loss of optically transparent radiation and redistribution of reabsorption radiation on the radial temperature distribution in an induced discharge in argon at atmospheric pressure. In view of the great complications produced by consideration of the finite length of the discharge [8] and passage of gas through the discharge chamber [10, 11] calculations were conducted for the much simpler case of an infinitely long discharge in thermal equilibrium in a nonmoving plasma. The results of calculations were compared with the experimental data of [1].

Calculations without Radiation. In the majority of calculation studies, plasma radiation has been neglected. Without considering the validity of such an approach for the meantime, we will examine the numerical results of calculations of the discharge equations of [12-16] with no consideration of radiation, in

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 35-43, November-December, 1971. Original article submitted February 22, 1971.

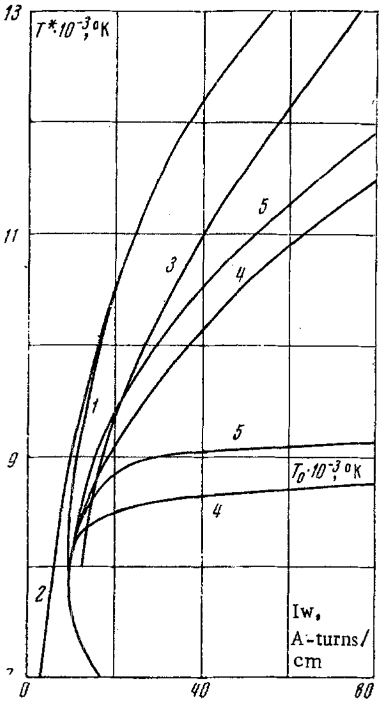

Fig. 1

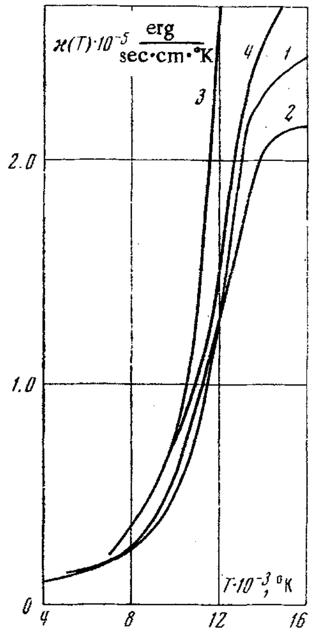

Fig. 2

order to clarify the peculiarities of discharge behavior unconnected with radiation. Simultaneously, we will compare the calculations accomplished in this study with the results of [17], which were further developed in the works of R. E. Rovinski and A. P. Sobolev [18, 19].

Figure 1 shows the relationship between maximum temperature T* and number of ampere-turns per unit inductor length Iw, obtained by numerical calculations with the discharge equations of [12-16], with radiation power equal to zero, and the same relationship from the formula proposed by Rovinski and Sobolev in [17-19],

$$\int_0^{T^*} \varkappa(T)\,\sigma(T)\,dT = 2\,(Iw/2)^2 \qquad (1)$$

$\varkappa$(T) and σ(T) are the thermal and electrical conductivities, respectively, just as in [16]. Equation (1) is a definite integral of the equations for the electromagnetic field and energy balance within the plasma for $H^2(0) \ll H^2(\rho_0)$, where H is the magnetic field intensity. Calculations were performed for argon at $\rho_0 = 1.5$ cm and $f = 10$ MHz. Curve 1 is the calculation of [12-16] with initial data from [16], neglecting radiation; curve 2 is the calculation of [19] with data from [16]; curve 3 is the calculation of [19] with data from [20]; curve 4 is the calculation of [12-16] with data from [16], considering radiation, the relative radiation power being the same as in [16]; curve 5 is the calculation of [12-16], with data from [16], but with radiation power decreased by a factor of two as compared with [16]. The calculations performed in this study agree well with Eq. (1) for $T \geq 9000$°K*. At the same time we note that the condition for the validity of Eq. (1), $\beta \equiv 2\rho_0^2/\delta^2 \gg 1$, (where δ is the skin layer thickness corresponding to maximum temperature), as introduced in [17], is not completely accurate. The skin layer thickness Δ, corresponding to a drop in the magnetic field by a factor of e, is strongly dependent on the radial temperature profile, and can differ significantly from δ, as calculated from maximum temperature. Thus even at $T = 7200$°K $\beta \simeq 10 \gg 1$.

If radiation is neglected, the maximum temperature is attained on the axis of the discharge; the axial dip in radial temperature profile is absent.

*The disagreement noted earlier [21] in the data of numerical calculations neglecting radiation from [17-19], as was clarified later, was explained by the use in [17-19] of amplitude values for ampere-turns, instead of the generally employed rms effective values over time.

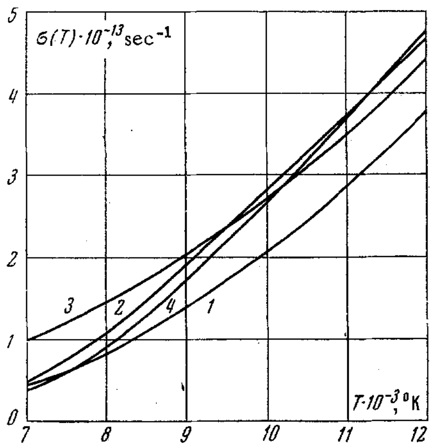

Fig. 3

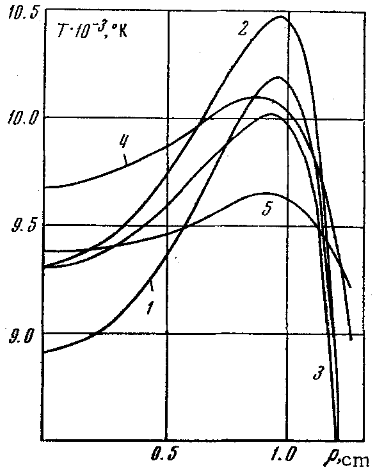

Fig. 4

At $\Delta \sim \rho_0$ the number of ampere-turns passes through a minimum, the existence of which follows from very basic reasons [16]. In this region Eq. (1) is not valid. We note that the minimum value of Iw is significantly dependent on the radius of the discharge chamber, the frequency of the excitation field, and the nature of the plasma-forming gas [16]..

Selection of Basic Data. In Fig. 1 the dependence of maximum temperature on ampere-turns, proposed in [19], is presented. Its marked difference from the dependence as calculated in the present study, using the same Eq. (1), is due solely to the use in [19] of data on electrical and thermal conductivity differing from that employed in [12-16].

In [19] the experimental data of Emmons [20] were employed. In [12-16] the calculated data of [12-14] and [22], presented in [16], were used.

The calculated data of Krinberg [22] and Devoto [23] on thermal conductivity agree well with each other over the entire temperature range. The corresponding curves of thermal conductivity as a function of temperature are presented in Fig. 2. Curve 1 is the calculation of [22], curve 2 is the calculation of [23], curve 4 is the calculation of [24], which agrees within the limits of 30-50% error with the experiment conducted in the same study, while curve 3 is the experiment of [20]. The data from the experiments of [20] and [24] differ significantly for T > 10,000°K. Below 10,000°K, the experimental data of [20] are evidently less reliable than calculated values, since they were obtained at the limit of the measurement range with the points obtained being widely scattered [20].

Inasmuch as experimental data on electrical conductivity are ambiguous and require further refinement, the calculated values for electrical conductivity coefficients for argon plasma at atmospheric pressure [12-14] presented in Fig. 3 were employed. Curve 1 is the calculation of [12-14] (results presented in [16] with consideration of electron-electron collisions), curve 2 is the calculation of [12-14] (without consideration of electron-electron collisions), curve 3 is the experimental data of [20], and curve 4, the calculation of [23]. The data of [12-14] agree with Devoto's results [23] with accuracy up to the coefficient employed in [12-14], with consideration of interelectron collisions [25].

Calculation of Radiation Loss. Due to the fact that the first excited level of the atom is high ($I_1 = 11.5$ eV for an ionization potential of $I^* = 15.8$ eV, the argon plasma radiation at atmospheric pressure in layers with thickness of the order of several centimeters is divided into a completely transparent component, corresponding to free-to-bound and free-to-free transitions to the excited levels of the atoms, and free-to-free transitions in the fields of neutral and ionized atoms ($\lambda \geq 2000$ Å), and a strongly reabsorbed component: an ionization continuum ($\lambda \leq 790$ Å) [26, 27], and lines corresponding to transitions to the fundamental level of the atom (790 Å $\leq \lambda \leq$ 1066 Å). Due to the shortness of the path length, the strongly reabsorbed radiation will be found to be in equilibrium with the matter in a first approximation.

The power level of the transparent radiation exiting completely from the discharge plasma can be found by using the results of a calculation of the degree of blackness of a hemisphere with radius R at various temperatures [28]. In [12-16] the transition between the degree of blackness of a hemisphere ε

TABLE 1

Curve No. (see Fig. 5)	T_0, °K	T^*, °K	$\varphi(T)$, W/cm³ [16]	div F (0), W/cm³
1	8500	8800	11	+0.030
2	8600	9500	13.5	−0.080
3	8660	10700	15.5	−0.75
4	8700	12500	17.5	−2.90
5	9600	10100	90	+0.096
6	9300	10400	53	−0.44

with radius R = 0.1 cm to the radiation power per unit plasma volume φ(T) is accomplished with the formula

$$\varphi(T) = \frac{4\varepsilon}{R}\sigma T^4$$

(σ is the Stefan-Boltzmann constant), obtained in the supposition of an optically thin hemisphere. However, in [12-16] the data of [28] were employed for total blackness, including therein the reabsorbed segments. To exclude these from consideration, as was indicated in [1], the data on radiation power in [12-16] must be reduced by a factor of approximately two [28]. We note that the calculated data of [28] agree well with the experimental data of [20, 24, 29].

Figure 1 presents the dependence of maximum temperature T* and axial temperature T_0 on ampere-turns, as calculated with the data on radiation power both as originally given in [12-16] and with the level reduced by a factor of 2. At low temperatures (in this case at T < 8000°K) radiation exerts practically no influence on the temperature profile, the maximum temperature is attained directly at the discharge axis, and coincides with the temperature as calculated with no consideration of radiation. As temperature increases, radiation begins to play an ever greater role, and a dip near the axis is formed in the radial temperature profile, which increases as the number of ampere-turns per unit inductor length is increased. This is illustrated in Fig. 1 by the branching of the curves of maximum and axial temperature versus ampere-turns at Iw for $\Delta \sim \rho_0$ (the lower branch in Fig. 1 is the axial temperature; the higher, the maximum).

The condition that $\Delta \ll \rho_0$, employed in [1], indicates a significant radiation loss. In view of the absence of ohmic energy losses in the large-volume internal regions of the discharge, radiation losses must determine the temperature characteristics of the discharge to a significant degree. Thus, in particular, for the mode examined in [1, 2] ρ_0 = 1.3 cm, f = 9 MHz, Iw = 40 A · turn/cm, Fig. 4 presents the radial temperature profile in induced argon discharges at atmospheric pressure. Curve 1 is a calculation in accordance with [12-16], with original data of [16]; curve 2 is the calculation of [12-16] with radiation power decreased by a factor of two [16], $\varkappa$(T) and σ(T) from [16]; curve 3 is the calculation of [12-16] with radiation power reduced by a factor of two [16], $\varkappa$(T) and σ(T) from [20]; curve 4 is the ionization temperature, measured by the absolute intensity of the continuous argon plasma spectrum [1]; and curve 5 is the temperature of the population of a series of Ar I levels from the $3p^5 5p$ configuration, measured by absolute intensity of the lines. The calculations conducted in this study, with consideration of optically transparent radiation loss, give a maximum temperature T = 10,000-10,500°K (depending on the data taken for the optical properties of the plasma), which agrees well with the experimental value (9800 ± 400°K). At the same time, calculations without consideration of radiation with the same data for electrical conductivity σ(T) and thermal conductivity $\varkappa$(T) of the plasma give T = 12,200°K (see Fig. 1).

As has already been noted, the error in computational results for the discharge temperature characteristics, produced by inaccurate values for the plasma transfer characteristics, is great in the case of calculation without consideration of radiation, and attains, as follows from Fig. 1, values of hundreds and thousands of degrees. When the effect of radiation is considered, the error is reduced. In fact, we assume that the use of lowered values for σ(T) and $\varkappa$(T) must lead to an increase in the calculated temperature value; however, at the same time radiation losses are increased, which leads to a temperature decrease. Thus, for example, a change in the data for $\varkappa$(T) and σ(T) which, in calculations without consideration of radiation, leads to a change in calculated temperature of 1200°K (Fig. 1), in calculations with consideration of radiation produces a temperature change of only 200°K (Fig. 4). Data on the radiation peculiarities of argon are known to an accuracy of tens of percents. As an illustration of the error introduced by this fact, Fig. 4 presents calculated temperature profiles based on radiation power, distinguished by a factor of 2 (error ≤ 500°K).

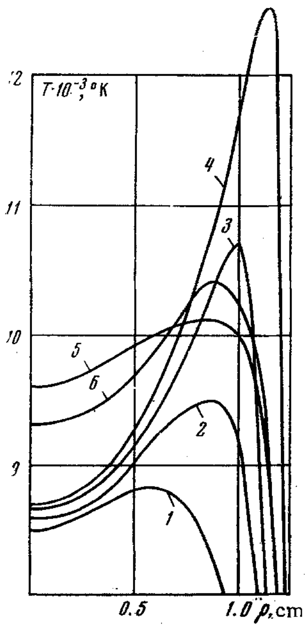

Fig. 5

As follows from Fig. 4, calculation with the data of Emmons [20] produces better agreement with experimental data with respect to both the relative contour and the absolute values of temperature. Nevertheless, there remains approximately a twofold increase in the calculated value of the axial temperature drop, as compared to experimental data.

Radiation Transfer. The evaluations presented in [1] as an approximation of radiative thermal conductivity indicated that radiation transfer in the strongly reabsorbed ionization continuum and the central portions of the argon resonance lines at $T \sim 10{,}000°K$ is insignificant. For a final explanation of the role of radiation transfer it is necessary to examine radiation transfer in the further regions of the spectrum, which correspond to transitions to the unexcited state of the atom. The divergence of the radiant flux in the spectral lines along the axis of a long cylindrical volume of plasma in thermal equilibrium is equal to

$$\operatorname{div} F(0) = 4\pi B_{\nu_0}(0)\, S(0) - 2\pi \int_0^\infty d\nu \int_0^R \rho d\rho \int_{-\infty}^{\infty} dz\, k_\nu(\rho)\, k_\nu(0)\, B_\nu(\rho)\, (\rho^2 + z^2)^{-1} \exp\left(-\frac{\sqrt{\rho^2 + z^2}}{\rho} \int_0^\rho k_\nu(\rho)\, d\rho\right) \tag{2}$$

where $S(\rho) \equiv \int_0^\infty k_\nu(\rho) d\nu$ is the complete absorption within a line; ρ and z are the radial and axial co-ordinates; $k_\nu(\rho)$ is the spectral absorption index; $B_{\nu_0}(\rho)$ is the Planck function, calculated for one steradian, ν_0 is the transition frequency; and R is the cyclinder radius.

With the change of variables

$$\rho^2 + z^2 = \rho^2 \sin^{-2}\vartheta, \qquad dz = -\rho \sin^{-2}\vartheta d\vartheta$$

integrating in Eq. (2) over ρ by parts, assuming that on the walls

$$T(R) = B_{\nu_0}(R) = 0$$

we obtain

$$\operatorname{div} F(0) = -4\pi \int_0^{\pi/2} \sin\vartheta d\vartheta \int_0^\infty k_\nu(0)\, d\nu \int_0^R \frac{\partial B_{\nu_0}(\rho)}{\partial \rho} \exp\left(-\sin^{-1}\vartheta \int_0^\rho k_\nu(\rho')\, d\rho'\right) d\rho \tag{3}$$

It follows from Eq. (3) that in flows where always $\partial T/\partial\rho < 0$, the radiant flux divergence is negative, i.e., the radiant energy departs from the axial points of the flow. In induced discharges, where portions exist with $\partial T/\partial\rho > 0$, there may appear a radiant energy flow toward the axis.

On the axis of the discharge, $\partial T/\partial\rho = 0$, $dB_{\nu_0}/\partial\rho = 0$, so that integration in Eq. (3) leads to some $\rho^* \ll \Delta l$, where Δl is the characteristic length for change in the parameters of the discharge in the axial region. Considering that for strongly reabsorbed resonance lines in argon the condition is fulfilled that $k_0^{-1} \sim 10^{-5}$ cm $\ll \rho^* \ll \Delta l \sim 0.1$ cm, with a great degree of accuracy one may substitute in Eq. (3) for the true absorption contour in the line the asymptotic expression for the further regions of the lines. In this process, neither Doppler widening nor shift in the lines plays a role in the integration of Eq. (3), since they change the line contour significantly only near the center of the line.

For a line with dispersion wings

$$k_\nu(\rho) \approx \pi^{-1} S(\rho) \Delta\nu(\rho) (\nu - \nu_0)^{-2} \tag{4}$$

we have

$$\operatorname{div} F(0) = -\pi^{3/2} \frac{\Gamma(5/4)}{\Gamma(7/4)} \frac{W(0, R)}{R} \int_0^1 \left(\int_0^\xi S_*(\xi')\, \Delta\nu_*(\xi')\, d\xi'\right)^{-1/2} \frac{\partial B_{\nu_0}(\xi)}{\partial \xi} d\xi \tag{5}$$

where $\Gamma(\varkappa)$ is the Gamma function, $\Delta\nu(\rho)$ is the shock half-width, and W is the equivalent width of the dispersion line in a layer of thickness R (in sec^{-1})

$$S_*(\xi) \equiv S(\xi)/S(0),\ \Delta\nu_*(\xi) \equiv \Delta\nu(\xi)/\Delta\nu(0),\ \xi \equiv \rho/R$$
$$W(0, R) \equiv 2(S(0)\,\Delta\nu(0)\,R)^{1/2}$$

We note that Eq. (5) can also be obtained from more complex formulas, presented in [30] (with an accuracy equivalent to the factor, omitted in [30], which is close to unity).

Analogously, one may obtain an expression for the divergence of the radiant flux in the strongly reabsorbed lines with the dispersion form of the further wings in the case of spherical symmetry:

$$\operatorname{div} F(0) = -2\pi \frac{W(0, R)}{R} \int_0^1 \left(\int_0^\xi S_*(\xi')\,\Delta\nu_*(\xi')\,d\xi' \right)^{-1/2} \frac{\partial B_{\nu_0}(\xi)}{\partial \xi}\,d\xi \qquad (6)$$

From Eqs. (5), (6) there follows a law of similarity: for a change in radius of the plasma volume, while preserving the relative temperature profile (the flux not disturbing the relationship $k_0^{-1} \ll \Delta l$)

$$\frac{\operatorname{div} F_{R_1}(0)}{\operatorname{div} F_{R_2}(0)} = \frac{W(0, R_1)\,R_2}{W(0, R_2)\,R_1} = \sqrt{\frac{R_2}{R_1}}$$

We note that the regions where $\partial B_{\nu_0}(\xi)/\partial\xi = 0$, in general produce no contribution to Eqs. (5, 6).

Data on the widening of argon resonance lines, widened basically by electrons, has been taken from [31]:

$$\Delta\nu(\rho) \approx CN_e(\rho)$$

where $\Delta\nu(\rho)$ is in sec^{-1}, N_e is the electron concentration, $C = 1.3 \cdot 10^{-7}\ sec^{-1} \cdot cm^3$.

The oscillator absorption power was taken as equal to 0.2 and 0.05 for the lines Ar I 1049 Å and 1067 Å respectively [32–34]. Of all the lines related to transitions to the fundamental state, these are the most important.

Calculated results for the radiant flux divergence in the argon resonance lines for various temperature profiles according to Eq. (5) are presented in Table 1. The corresponding radial temperature distributions for which the radiant flux divergence was calculated in the Ar I resonance lines at the axial point of the discharge div F(0) are presented in Fig. 5. The digits indicate the numbers of the profiles data for which are presented in Table 1. Curve 5 is the experimental result of [1]. Radiant transfer proves to be insignificant up to temperature transitions of several thousand degrees.

Under experimental conditions, within the argon discharge spectrum, there is often observed an intense brightness in the lines of atomic hydrogen, present in the plasma as a minor impurity. The lines of the Balmer series are clear, and energy transfer can take place only in lines of the Lyman series. Calculation of radiation transfer in the most intense line L_α was conducted with the same Eq. (2), using the contour tabulated in [31]. The final formula for calculation of radiant flux divergence in a line on the axis of a discharge in argon at atmospheric pressure with a small admixture of atomic hydrogen then has the form

$$\operatorname{div} F_{L_\alpha}(0) = -9.75 \frac{S^{1/2}(0)\,N_e^{1/3}(0)}{R^{1/2}} \int_0^1 \left(\int_0^\xi S_*(\xi')\,N_{e*}^{2/3}(\xi')\,d\xi' \right)^{-1/2} \frac{\partial B_{\nu_0}(\xi)}{\partial \xi}\,d\xi$$

where $N_{e*}(\xi) \equiv N_e(\xi)/N_e(0)$, $S(\xi)$ is the complete absorption in the line, and N_e is the electron concentration per cm^3. The formula is valid for a discharge radius $\rho_0 \simeq$ 1–2 cm and temperatures of the order of 10,000°K.

Evaluations for the case of a molar concentration of atomic hydrogen in argon of ~1% indicate that radiant transfer in the hydrogen lines is small, and cannot lead to a noticable change in the radial temperature profile under the conditions of the experiment [1].

The Effect of Convection. Inasmuch as experimental temperature profiles have a less sharply defined temperature drop at the center than is predicted by the theory of [12–16], and radiation transfer plays no significant role under these conditions, some other mechanism of temperature equalization in the induced discharge must exist. It is natural to assume that the cause of this equalization is convection, especially when

$$\varkappa \Delta T / (\Delta\rho)^2 \leqslant c_p v \rho_m \Delta T / \Delta\rho$$

where the coefficient of thermal conductivity $\varkappa \approx 4 \cdot 10^4$ erg/cm · sec · deg, the thermal capacity $c_p \simeq 0.2$ cal/g · deg, argon density $\rho_m \approx 5.3 \cdot 10^{-5}$ g/cm^3 (T ~ 9500°K), the characteristic radial length $\Delta\rho \sim 1$ cm [1], which leads to convective flow velocities $V \gtrsim 10^2$ cm/sec. Such velocities are attainable and have been observed even in low power carbon arcs of small dimensions [35].

LITERATURE CITED

1. E. S. Trekhov, A. F. Fomenko, and Yu. M. Khoshev, "The temperature profile in the plasma column of an induced discharge in argon at atmospheric pressure," Teplofiz. Vys. Temp., 8, No. 4 (1970).
2. E. S. Trekhov, A. F. Fomenko, and Yu. M. Khoshev, "Temperature characteristics of a channel-less induced discharge in air at atmospheric pressure," Teplofiz. Vys. Temp., 9, No. 2 (1971).
3. Yu. P. Raizer, "A high-pressure, high-frequency discharge in an electrodeless plasmatron," Usp. Fiz. Nauk, 99, No. 4 (1969).
4. M. I. Yakushin, "Attainment of high gas temperatures in an electrodeless high-frequency discharge (survey)," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 3 (1969).
5. R. E. Rovinski and A. P. Sobolev, "Letter to the editor," Teplofiz. Vys. Temp., 6, No. 3 (1968).
6. V. N. Soshnikov, E. S. Trekhov, and Yu. M. Khoshev, "Calculation of parameters in turbulent discharges," Teplofiz. Vys. Temp., 6, No. 3 (1968).
7. Yu. Yu. Abramov and A. P. Napartovich, "Letter to the editor," Teplofiz. Vys. Temp., 7, No. 4 (1969).
8. R. E. Rovinski and A. P. Sobolev, "Analysis of two-dimensional effects in the theory of an induced discharge," in: Physics, Technology and Applications of Low-temperature Plasma [in Russian], Alma-Ata (1970), p. 732.
9. R. E. Rovinski, V. A. Gruzdev, T. M. Gutenmakher, and A. P. Sobolev, "Determination of temperature in a stationary high-frequency induced discharge," Teplofiz. Vys. Temp., 5, No. 4 (1967).
10. Yu. P. Raizer, "A high-pressure, high-frequency discharge in a gas stream as a slow burning process," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 3 (1968).
11. V. N. Soshnikov, E. S. Trekhov, and Yu. M. Khoshev, "A turbulent discharge in argon at atmospheric pressure," in: Physics of a Gas Discharge Plasma [in Russian], Atomizdat, Moscow (1968).
12. V. N. Soshnikov and E. S. Trekhov, "The theory of a high-frequency turbulent discharge under high pressure. I," Teplofiz. Vys. Temp., 4, No. 2 (1966).
13. V. N. Soshnikov and E. S. Trekhov, "The theory of a high-frequency turbulent discharge under high pressure. II," Teplofiz. Vys. Temp., 4, No. 3 (1966).
14. V. N. Soshnikov and E. S. Trekhov, "The theory of a high-frequency turbulent discharge under high pressure in air and argon. III," Teplofiz. Vys. Temp., 5, No. 3 (1967).
15. V. N. Soshnikov, E. S. Trekhov, and Yu. M. Khoshev, "Calculation of turbulent discharge parameters," Teplofiz. Vys. Temp., 6, No. 3, (1968).
16. V. N. Soshnikov, E. S. Trekhov, and Yu. M. Khoshev, "Theory of a turbulent discharge (skin effect) in air and argon at atmospheric pressure," in: Gasseous Discharge Plasma Physics, 1st Ed. [in Russian], Atomizdat, Moscow (1968).
17. V. A. Gruzdev, R. E. Rovinski, and A. P. Sobolev, "An approximate solution to the problem of a stationary high-frequency induced discharge in a closed volume," Zh. Prikl. Mekh. i Tekh. Fiz., No. 1 (1967).
18. R. E. Rovinski and A. P. Sobolev, "The optimum frequency range for a high-frequency induced discharge," Teplofiz. Vys. Temp., 6, No. 2 (1968).
19. R. E. Rovinski and A. P. Sobolev, "Calculation of induced high-frequency discharge parameters under high pressure," Teplofiz. Vys. Temp., 7, No. 2 (1969).
20. H. W. Emmons, "Arc measurement of high-temperature gas transport properties," Phys. Fluids, 10, No. 6 (1967).
21. V. N. Soshnikov, E. S. Trekhov, A. F. Fomenko, and Yu. M. Khoshev, "The influence of radiation on the temperature profile of an induced discharge in argon at atmospheric pressure," in: Physics, Technology, and Applications of Low-temperature Plasma [in Russian], Alma-Ata (1970).
22. I. A. Krinberg, "Calculation of the thermal conductivity of certain gases in the temperature range 1,000-20,000°K at atmospheric pressure," Teplofiz. Vys. Temp., 3, No. 4 (1965).
23. R. S. Devoto, "Transport coefficients of partially ionized argon," Phys. Fluids, 10, No. 2 (1967).
24. É. I. Asinovski and A. V. Kirillin, "Experimental determination of the thermal conductivity coefficient of an argon plasma," in: Low-temperature Plasma [Russian translation], Mir, Moscow (1967).

25. B. L. Ginzburg and A. V. Gurevich, "Nonlinear phenomena in a plasma situated in an alternating electromagnetic field," Usp. Fiz. Nauk, 70, No. 2, (1960); 70, No. 3 (1960).
26. Po Lee and G. L. Weissler, "Absorption cross section of helium and argon in the extreme ultraviolet," Phys. Rev., 99, No. 2 (1955).
27. N. Wainfan, W. C. Walker, and G. L. Weissler, "Photoionization efficiencies and cross sections in O_2, N_2, CO_2, Ar, H_2O, H_2, and CH_4," Phys. Rev., 99, No. 2 (1955).
28. I. G. Yakubov, "Energy radiated by an argon plasma in spectral lines," Opt. i Spektr., 19, No. 4 (1965).
29. D. L. Evans and R. S. Tankin, "Measurement of emission and absorption of radiation by an argon plasma," Phys. Fluids, 10, No. 6 (1967).
30. É. I. Asinovski, E. V. Drokhanova, A. V. Kirillin, and A. N. Lagar'kov, "An experimental and theoretical study of the coefficient of thermal conductivity and complete radiation of nitrogen plasma," Teplofiz. Vys. Temp., 5, No. 5 (1967).
31. G. Grim, Plasma Spectroscopy [in Russian], Atomizdat, Moscow (1969).
32. R. S. Knox, "Excited-state wave functions, excitation energies, and oscillator strengths for argon ($3p^5 4s$)," Phys. Rev., 110, No. 2 (1958).
33. P. F. Gruzdev, "Oscillator strengths of lines of the sharp series in the atomic spectra of elements of the II group," Opt. i Spektr., 22, No. 2 (1967).
34. G. M. Lawrence, "Radiance lifetimes in the resonance series of Ar I," Phys. Rev., 175, No. 1 (1968).
35. V. Finkelburg and G. Mekker, Electrical Arcs and a Thermal Plasma [Russian translation], Izd. Inostr. Lit., Moscow (1961).