EXPERIMENTAL INVESTIGATION OF SHOCK WAVES IN A PARTIALLY IONIZED DISCHARGE PLASMA

Yu. I. Chutov

Results are presented of an experimental investigation of shock waves in an argon discharge plasma.

It is shown that the shock wave width is appreciably greater than the particle mean free path in the plasma. The shock width is close to the value given by theory, accounting for electronic thermal conduction.

At the shock front a potential jump was recorded whose value is given by ambipolar diffusion of charged particles in the front.

At the shock front there is a considerable change in the concentration of charged particles, for a practically constant electron temperature. For strong shock this change is apparently due to thermal ionization at the front. For weak shock waves an appreciable part is played by supplementary ionization at the shock front, arising from energy liberated when the discharge current passes through the potential jump at the shock wave front.

The properties of shock waves in a partially ionized plasma differ appreciably from those of shock waves in a neutral gas. This difference is due to the tremendous difference between the mass of the electron and of heavy particles composing the plasma, and also by the existence of strong electrical forces arising in the plasma from a very small degree of charge separation. These special features of the plasma lead, for example, to the shock wave width in a partial ionized plasma (in contrast with that in a neutral gas) considerably in excess of the particle mean free path in the plasma in a number of cases [1].

In many cases a partially ionized plasma is not in thermodynamic equilibrium. It is well known [2] that in a thermodynamically nonequilibrium plasma there is difficulty in calculating, not only the shock wave structure, but also the plasma parameters behind the shock front.

A description is given below of an attempt to investigate shock waves experimentally in a partially ionized gaseous discharge plasma. The shock waves were generated using interaction between an impulsively moving plasma and an independently created fixed discharge plasma [3], in a similar way to that in electrical shock tubes, which use interaction between this type of plasma and a neutral gas [4, 5]. No reports of experiments of this kind have been published. Investigations of strong shocks at whose fronts ionization of an initially neutral gas occurs [6], clearly differ from the case considered of propagation of shock waves in a previously created plasma.

The following measurement units are assumed here: pressure p in mm Hg, temperature T in deg K, power p in $W \cdot cm^{-1}$ current strength i in A, charged particle concentration n in cm^{-3}, and speed in cm. sec^{-1}.

1. Technique and Experimental Results. The experiments were carried out in a cylindrical glass tube with an internal diameter of 16 mm (Fig. 1a), filled with argon at a pressure of 0.5 mm Hg. Located in the tube were two plane circular molybdenum electrodes A_1 and A_2 of diameter 14 mm, an annular nickel electrode K of width 1 cm and diameter 14 mm, and also four pairs of cylindrical tungsten probes Z_1-Z_4 of diameter 0.1 mm and length 3 mm. The probes were located symmetrically with respect to the tube axis, so that the distance between them was 10 mm. In some experiments probes of the same dimensions were

Kiev. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 11, no. 1, pp. 124-130, January-February, 1970. Original article submitted February 14, 1969.

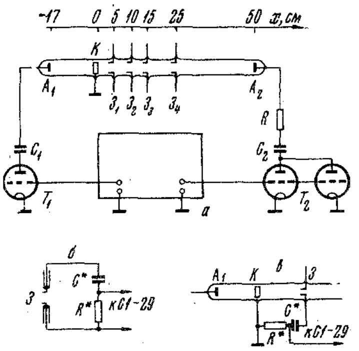

Fig. 1

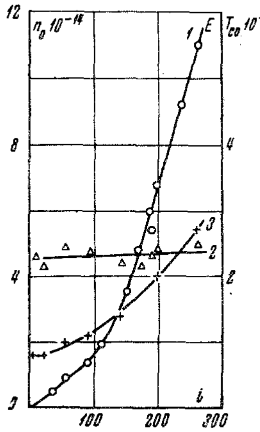

Fig. 2

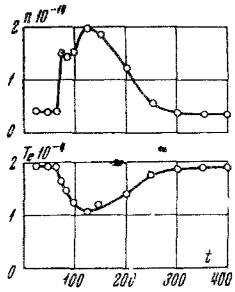

Fig. 3

used, at a distance x = 10 cm from the annulus K to the tube, as was done in [7], and capable of being moved along the tube radius.

A plasma pulse moving in the volume KA_2 was created by rapid discharge (duration 5-25 μsec) of a condensor C_1 of capacity 24 or 14 μF (V_1 = 3 kV) at electrodes K and A_1. The fixed gas-discharge plasma was created in volume KA_2 by a slow exponential discharge of a capacitor bank C_2 of capacity 100 or 200 μF (V_2 = 3 kV) through the ohmic resistor R of value 53 or 8 Ω, respectively. The minimum value of the quantity RC_2 is 1600 μsec, i.e., appreciably greater than the time in which the temperature of the neutral gas reaches equilibrium due to heat conduction (the maximum characteristic time of the slow discharge) $\tau_T \sim r^2/5.8\, a$, which is equal, in these experimental conditions, to 370 μsec (a is the thermal diffusivity, and r is the tube radius), i.e., the slow discharge is quasi-stationary.

The parameters of the fixed discharge plasma, as measured using probes Z_1-Z_4, are shown in Fig. 2 as a function of discharge current i. Curves 1 to 3 in Fig. 2 show, respectively, the variation in charged particle concentration n_0 cm^{-3}, the electron temperature T_{e0} deg K and the electric field strength E V/cm in the fixed plasma. The measurements of radial distributions of these parameters, made by means of the moving probes, show that in the conditions of this experiment there is a central region of almost constant parameters, of diameter about 1 cm.

Type TGI-400/16 hydrogen thyratrons were used as the switching elements in the discharge circuits. A special circuit (Fig. 1a) fired thyratrons T_1 (fast discharge) a controlled time after firing of thyratrons T_2 (onset of the slow discharge), so that the short-duration plasma moved in the motionless discharge plasma and interacted with it. Since the fixed plasma was created by an exponential discharge, change of the delay time τ altered the parameters of the fixed plasma, with which the impulsive moving plasma interacted.

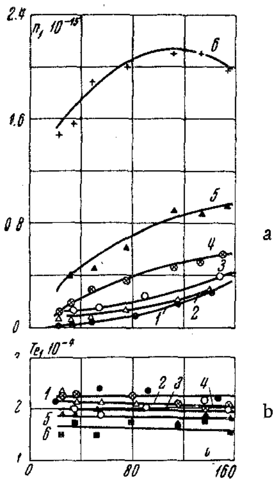

Fig. 4a, b

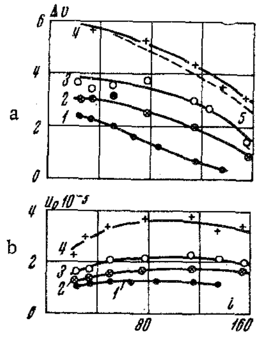

Fig. 5a, b

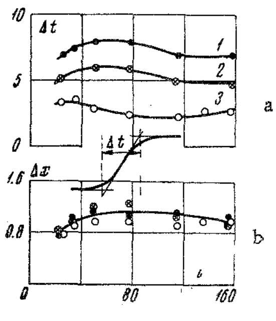

Fig. 6a, b

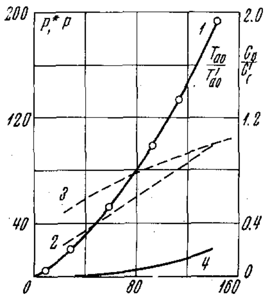

Fig. 7

A double probe method, with the usual processing of probe characteristics, was used to measure the plasma parameters in this work. The circuit used for switching the probes Z in order to obtain the probe characteristics is shown in Fig. 1b. A voltage source in the probe circuit was a condensor C* of capacitance 1300 μF, charged to the necessary voltage, while the probe current was determined by the voltage drop in the resistor R*, recorded on a type SI-29 storage oscillograph. The probe circuit potential was floating.

The use of probes to measure parameters of the moving plasma, in addition to the usual requirement that the ratio of the electron mean free path l_e to probe diameter ($l_e \sim 5 \cdot 10^{-2}$ cm [5] in the case examined for argon at $p_0 \sim 0.5$ mm Hg and $T_e \sim 2 \cdot 10^4$ °K, and $d = 10^{-2}$ cm) also presupposes no boundary layer on the probes. This postulate holds in the case considered, i.e., plasma flow behind the shock front. In fact, the maximum pressure p_{max} induced on a flat plate with a sharp edge, located parallel to the flow [8], does not exceed $p\ M^2R^{-1/2}$, where M, p, R are, respectively, the Mach number, the pressure, and the Reynold's number in the unperturbed stream. A similar relation will also hold on a probe located parallel to the flow. Since $M < 1$ for the plasma flow behind the shock wave, then $p_{max}/p < R^{-1/2}$. The Reynolds number behind the shock is given by the relation

$$R = \frac{\rho_1 u_1 L}{\eta_1} \approx \frac{\rho_0 u_0 L (\beta_0 - 1)}{\eta_0 \sqrt{T_{a1}/T_{a0}}} \approx \frac{\rho_0 c_0 L (\beta_0 - 1)}{\eta_0 \sqrt{2\gamma/\beta_0(\gamma+1)}}\ .$$

Here ρ, η, c are the density, viscosity, and sound speed, and the subscripts 1 and 0 refer, respectively, to the state behind and ahead of the shock; β_0 is the degree of compression of the plasma in the shock wave; u_0 is the shock wave speed; u_1 is the plasma speed behind the shock; and γ is the adiabatic exponent. For argon at initial pressure 0.5 mm Hg and $L \sim 0.3$ cm, $\beta_0 \sim 2$, we have $R \sim 100$. This means that the pressure induced in the probes can be neglected in the case considered, i.e., the boundary layer at the probe does not play an appreciable part.

The experimental results described below were obtained in the condition when the shock wave front was detached from the impulsive moving plasma, which acted as a hydrodynamic "piston." This separation is clearly seen in Fig. 3, which shows, by way of example, the variation with time of charged particle concentration n and electron temperature T_e, as measured by the double probe at x = 10 cm. The variation with time of n and T_e in the short-duration moving plasma were discussed in [3].

The double probe was used to measured charged particle concentration n_1 and electron temperature T_{e1} behind the shock for various values of the discharge current i. The results of these measurements are shown in Fig. 4, curves 2-6, for x = 15 cm. The parameter for these curves is the energy of condenser C_1, respectively 4, 9, 18, 24, and 63J. Curve 1 of Fig. 4a shows the variation of charged particle concentration in the fixed discharge plasma, and Curve 1 of Fig. 4b shows the variation of electron temperature there (i.e., the plasma parameters in front of the shock). It can be seen from Fig. 4 that a considerable increase in charged particle concentration is observed in the plasma at the shock front, occurring during practically constant electron temperature over the whole range of measurements.

Probes were also used to measure the potential jump occurring at the shock front due to charge separation [9]. The circuit for switching the probe in order to record the variation of its potential with time is shown in Fig. 1c. The condenser C*, of capacity 1300 μF, charged to the required potential, served here to compensate the potential differences arising in the fixed plasma between probe Z and annulus K, due to flow of discharge current. The variation of probe potential with time was recorded by a type SI-29 oscillograph, from the voltage drop in a fairly large resistor R*, usually 10 kΩ. The polarity of the potential jump at the shock wave front was such that the direction of the electric field arising at the front from this potential jump coincided with that of the shock wave motion. For the observed polarity of discharge current (Fig. 1a) the direction of the electric field at the shock front coincides also with that of the electric field in the fixed plasma.

The results of measurements of the potential jump ΔV at the shock front, for various values of i (x = 15 cm) are shown in Fig. 5a. Curves 1-4 were obtained with C_1 = 1, 2, 4, and 14 μF (V_1 = 3 kV). Figure 5b shows the shock wave propagation speed u_0, for the same conditions, as a function of the current i, obtained from measurement of the displacement of the beginning of the luminous section over a length of 2 cm.

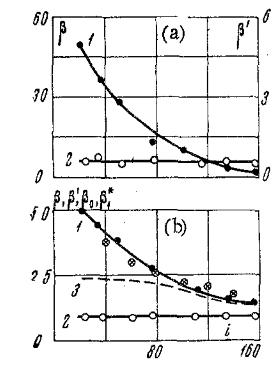

Fig. 8 a, b

The shock wave front width Δx was also investigated. It was determined from the measured rise time of the probe potential or of the probe saturation current at the front, Δt (Fig. 6) and from the shock wave speed u_0, using the relation $\Delta x = u_0 \Delta t$. The measured values of Δt are shown in Fig. 6a, where Curves 1, 2, and 3 were obtained for $C_1 = 2$, 4, and 14 μF (x = 15 cm). The calculated values of Δx are shown (as points, crosses, and circles, respectively) in Fig. 6b. It can be seen that Δx is 2-8 μsec, and varied by roughly a factor of four with the change of C_1, while Δx remained at the level of 1 cm, with a scatter of 20%. It should be noted that the measured times Δt are considerably greater than the quantity $1/\omega_{pi}$, equal to $5 \cdot 10^{-10}$ sec for argon with $n \sim 10^{14}$ cm^{-3} (ω_{pi} is the ion plasma frequency). This condition is required for nonstationary probe measurements [10].

The values of Δx obtained are several times larger than the length of the measuring probes, which was 0.3 cm in these experiments. The spatial separation of these probes was checked in a special way. For this purpose the probes were oriented, not along the axis, as in Fig. 1a, but along a radius, so that the total extent of the probe in the direction of motion of the shock wave was 10^{-2} cm. No difference in the measured values of Δx was observed for the two probe orientations.

2. Discussion of Experimental Results. Firstly, we note that behind the shock wave there is no stationary state, as is typical for an ideal shock tube (Fig. 3). This is because the plasma behind the shock front is decomposed by ambipolar diffusion of charged particles to the tube wall in a similar way to what occurs with a pulsed moving plasma [3, 11]. However, since the decay time (several tens of microseconds) is substantially greater than the growth time of the plasma parameters in the shock front, Δt (Fig. 6), we can assume that a quasi-stationary state is reached behind the shock front.

To calculate the plasma parameters behind the shock we must known the sound speed ahead of the shock. In these experimental conditions the sound speed in the fixed discharge plasma is given, to a first approximation [12], by the relation $c_0 = \sqrt{\gamma k T_{a0}/m_a}$, since the pressure of the charged component can be neglected. In fact, the maximum concentration of charged particles in the fixed plasma at $T_{e0} \sim 2 \cdot 10^4$ °K does not exceed $3.5 \cdot 10^{14}$ (Fig. 4) i.e., the ratio of the initial pressure of neutral argon, p_0, to the maximum electron pressure $p_{e0} = n_0 k T_{e0}$, is roughly 1. But heating of the neutral gas, which undoubtedly occurs with discharge currents of the order of 100 A, can be neglected as contributing to the pressure of the charged component in the total pressure of the fixed plasma.

The temperature of neutral argon in the fixed plasma T_{a0} was not measured in these experiments. However, taking into account the above-mentioned measurements of radial distribution of parameters of the fixed plasma, it is natural to postulate that the quantity T_{a0} varies very little in the central region of almost constant parameters. The relative variation of T_{a0} with change of discharge current can be estimated from the power balance in the discharge. Assuming that the energy obtained by the neutral gas is determined by elastic collisions with electrons, and that the energy lost by it is determined by the thermal conduction of the gas, this balance can be written in the form

$$P = \chi \frac{T_{a0} - T^*}{r^*} S^*$$

per unit length of column, where $T^* = 300°$ K is the tube wall temperature, χ is the thermal conductivity, and r^* and S^* are the effective geometric dimensions, which do not depend on the value of i, since the reative radial distribution of the parameters of the fixed plasma is conserved with change of i, as was shown by experiment. The value of the power P obtained by the neutral gas, calculated from the known n_0 and T_e (Fig. 2), are shown as Curve 4 of Fig. 7. In the calculations mean free path values averaged for a Maxwellian distribution [5] were used. It can be seen from Fig. 7 that the power P is much less than the total power P^*, expended in the discharge, which is shown as Curve 1 in Fig. 7. This means that practically all the power is expended in inelastic collisions.

Taking into account that $\chi \sim T_{a0}{}^{2/3}$ [13], and assuming $T_{a0} \gg T^*$, we obtain $T_{a0} \sim p^{0.6}$, and $c_0 \sim {}^{0.3}$. Curves 2 and 3 of Fig. 7 show the relative variation in the quantities $P^{0.6}$ and $P^{0.3}$, respectively, resulting from this calculation. With the assumptions made, these curves describe, respectively, the relative variation of T_{a0} and c_0 in the fixed discharge plasma.

The results of measured concentrations of charged particles behind the shock front (Fig. 4) can be examined in detail if they are reduced to the form of the ratio β of charged particle concentration behind the front, n_1, to the charged particle concentration ahead of the front, n_0. Figure 8, Curve 1 shows the variation of $\beta = n_1/n_0$ for two substantially different cases: a) $C_1 = 14\ \mu F$ (Curve 6 of Fig. 4), and b) $C_1 = 4\ \mu F$ (Curve 3 of Fig. 4). Figure 8a shows that the concentration of charged particles with $C_1 = 14\ \mu F$ varies by roughly a factor of 50, while the variation of the argon density in the shock wave cannot exceed 4. (The ideal gas approximation is used since the degree of ionization of the plasma is insignificant [2]). This means that there is additional ionization of argon in the shock front. Evidently, in this case there is thermal ionization of argon due to increase of temperature of the neutral gas [6]. In fact, the charged particle concentration, reaching a value here of $2 \cdot 10^{15}\ cm^{-3}$ (Fig. 4, Curve 6) corresponds to an equilibrium temperature of $T_a \sim 9400°$ K. Estimates from ideal gas formulas indicate that this temperature is reached by the shock propagating in argon with speed $(3\text{-}3.5) \cdot 10^5$ cm/sec (Fig. 5, Curve 4), if the gas ahead of the shock is heated to a temperature of $T_{a0} \sim 1000°$ K. The estimates carried out with the above power balance in the gaseous discharge show that this neutral gas temperature in the fixed discharge plasma is entirely possible.

For $C_1 = 4\ \mu F$ (Fig. 8b) thermal ionization at the front is impossible, since the shock speed is then reduced by a factor of two relative to the previous value (Fig. 5, Curve 3), which leads to a reduction of T_{a1} of roughly a factor of four, while the charged particle concentration behind the front corresponds then to $T_a \sim 8000°$ K. However, since $\beta \leqslant 5$, it is reasonable to compare the quantity β with the compression β_0 of neutral argon in the shock wave. The absolute values of Mach number M required to calculate β_0 are unknown, but the relative change of M can be obtained using measured values of the shock speed (Fig. 5b), and the calculated relative change of sound speed, c_0 (Fig. 7, Curve 3). By normalizing the compression β_0 to the experimentally measured value of β for a certain value of i, we can compare the relative change in β and β_0. The dotted curve 2 in Fig. 8b shows the calculated value of β_0 when normalized to the value of β, with i = 155 A. The figure shows that there is an appreciable discrepancy between β and β_0 which is conserved for any choice of the normalization point. Thus, plasma compression cannot produce the experimentally obtained variation in charged particle density in the shock front.

One cause of this discrepancy may be additional ionization of neutral gas due to the energy of the electron gas. Since the compression of electrons in the shock is slow (since the shock wave speed is much less than the random electron speed), the change taking place in the parameters of the electron gas will evidently follow a Poisson adiabat, as observed in [14]. With $\gamma = 5/3$, we obtain $(n^*/n_0)^{0.67} = \beta_0^{0.67} = T_{e1}^*/T_{e0}$ from the Poisson adiabat, i.e., along with variation in electron concentration at the front there must also be a variation in electron temperature. However, the experiment shows (Fig. 8, Curve 3) that $\beta' = T_{e1}/T_{e0} \sim 1$. In the case considered this means that the electrons in some way lose part of their energy, equal to $n^*(kT_{e1} - kT_{e0})$. Assuming that all this energy goes into additional ionization at the shock wave front, the ratio of charged particle density on the two sides of the front can be written in the form

$$\beta^* = \frac{n_1^*}{n_0} = \frac{1}{n_0}\left[n^* + \frac{n^*(kT_{e1}^* - kT_{e0})}{E_i}\right] = \beta_0\left[1 + \frac{kT_{e0}}{E_i}(\beta_0^{0.67} - 1)\right].$$

where $E_i = 15.7$ eV is the argon ionization energy. The maximum value of β_0 is 4, and therefore, β^* will be altogether 32% greater than the compression of neutral gas, which is much less than the observed discrepancy in the experiment (Fig. 8b, Curves 2 and 1).

However, for a shock wave in a discharge plasma a mechanism for additional ionization at the front can arise from Joule energy liberated when the discharge current passes through the potential jump ΔV at the front (Fig. 5a). Assuming that all this energy goes to ionization (and such an assumption is reasonable, since almost all of the power expended in the discharge in the experiment, as was seen above, goes to inelastic losses), the number of additional ionization events at the front can be written in the form

$$\Delta n = \frac{i\,\Delta V\,\Delta t}{S\,\Delta x\,E_i} = \frac{i\,\Delta V}{S\,E_i u_0}\ .$$

where S is the shock wave area. Then the charged particle density ratio on the two sides of the front can be represented in the form $\beta_1^* = (\Delta n + n_0)/n_0$. The results of calculating β_1^* for $C_1 = 4\ \mu F$, shown by crosses in Fig. 8b, are in good agreement with experimental values of β. It is important here to note that the shock wave width Δx (see Fig. 6) is greater than the electron mean free path with respect to ionization, equal to 0.17 cm in argon at a pressure of 0.5 mm Hg, and the ionization crosses section is $q_i \sim 3 \cdot 10^{-16}$ cm^2 [15]. In addition, the growth time Δt for the plasma parameters at the front exceeds the mean time between ionizing collisions, equal to $1.7 \cdot 10^{-9}$ sec for $T_e \sim 2 \cdot 10^4$ °K.

The appearance of a potential jump at the shock wave front is due to the appreciable ambipolar diffusion of charged particles here. In fact, the electric field under ambipolar diffusion can be written in the form

$$E = \frac{1}{n}\frac{dn}{dx}\frac{D_e - D_i}{\mu_e + \mu_i} \approx \frac{1}{n}\frac{dn}{dx}\frac{kT_e}{e}.$$

Here D_e and D_i are diffusion coefficients, and μ_e, μ_i are mobilities for electrons and ions, respectively. Integration along the front with T_e = const yields

$$e\Delta V = kT_e \ln (n_1 / n_0) = kT_e \ln \beta$$

As an example, the dotted curve in Fig. 5 gives results of a calculation of ΔV for $C_1 = 14$ μF with $T_e \sim 2 \cdot 10^4$ °K. The value of β here was taken from Fig. 8a. It can be seen from Fig. 5 that the calculated values are in good agreement with the experimental.

In conclusion we discuss the shock wave front thickness $\Delta x \sim 1$ cm (Fig. 6b), which is appreciably greater than the width of the viscous density jump [9], since the argon atomic mean free path at pressure 0.5 mm Hg is $1.55 \cdot 10^{-2}$ cm [16]. The large shock front thickness in the case considered is responsible for the diffusive potential jump and the additional ionization at the shock wave front. The cause of this broadening of the front appears to be electron heat conduction. In fact, as was shown theoretically in [1], allowance for electron heat conduction gives the result that the width of the front of a weak shock wave is of the order of $l_{e1}/\in$(l_{e1}, the electron mean free path behind the front, while $\in = \sqrt{m_e/m_i}$). In the case considered the electron mean free path ahead of the front l_{e0} is $2.4 \cdot 10^{-2}$ cm [5], while $l_{e0}/\in \sim 6.5$ cm. Allowance for compression of neutral gas in the shock, which reduces the electron mean path behind the shock several times, gives the result that $l_{e1}/\in$ is very close to the experimentally determined shock front width Δx (Fig. 6b). This also means that Δx in the case considered is determined by electron heat conduction.

In conclusion the author wishes to thank N. D. Morgulis for supervision of the work, E. Ya. Kogan for useful discussions, L. S. Simonenko for assistance in conducting the experiment, and V. G. Zykov and B. P. Il'enko (of the Physics and Engineering Institute of the Academy of Sciences of the Ukranian SSR) for the delay time circuit shown.

LITERATURE CITED

1. M. Y. Jaffrin, "Shock structure in a partially ionized gas," Phys. Fluids., vol. 8, no. 4, 1965.
2. B. Ahlborn and M. Salvat, "Calculations of shock front parameters in a plasma," Zt. Naturforschung, vol. 22 (A), no. 2, 1967.
3. Yu. I. Chutov, "Interaction of a pulsed moving plasma with a fixed quasi-stationary discharge plasma," Ukr. fiz. zhurn., 14, no. 3, 1969.
4. Yu. V. Makarov and E. K. Chekalin, Physical Processes in Electromagnetic Shock Tubes [in Russian], Atomizdat, Moscow, 1968.
5. R. C. Fowler, "Electrons as a hydrodynamical fluid," in: Advances in Electronics and Electron Phys., Acad. Press, New York-London, vol. 20, 1964.
6. R. A. Gross, "Strong ionizing shock waves," Rev. Modern Phys., vol. 37, no. 4, 1965.
7. Yu. I. Chutov, Investigation of the nature of a moving plasma generated in an electric shock tube, Ukr. fiz. zh, 12, no. 7, 1967.
8. N. I. Yushchenkova, A. A. Pomerantsev, and V. I. Nemchenko, "Influence of real gas effects on the hypersonic rarefied flow near the sharp leading edge of a thin plate," Internat. J. Heat and Mass Transfer, vol. 10, no. 1, 1967.
9. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena [in Russian], Nauka, Moscow, pp. 50-54, 316, 1966.
10. Plasma Diagnostics [in Russian], Mir, Moscow, p. 153, 1967.

11. Yu. I. Chutov, "Experimental study of the interaction of an argon plasma set in motion instantaneously with a transverse magnetic field," Magnitnaya gidrodinamika [Magnetohydrodynamics], no. 2, 1968.
12. B. Ahlborn, "Approximate calculation of the speed of sound in a plasma," Phys. Fluids, vol. 9, no. 9, 1966.
13. E. Hayess, D. Venzke, and K. Wojaczek, "Die Neutralgastemperatur in der Argon-Mitteldruckentladung, Beiträge Plasma Physik, vol. 7, no. 6, 1957.
14. Yu. I. Chutov, "Reflection of a pulsed moving plasma at a metal surface," Ukr. fiz. zh., 13, no. 6, 1968.
15. I. MacDaniel, Collision Processes in Ionized Gases [Russian translation], Mir, Moscow, p. 209, 1967.
16. Concise Handbook of Physics and Engineering, Vol. 1 [in Russian], Fizmatgiz, Moscow, p. 331, 1960.