OBTAINING HIGH GAS TEMPERATURES IN AN ELECTRODELESS HIGH-FREQUENCY DISCHARGE

(REVIEW)

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One of the earliest references to the high-frequency electrodeless discharge dates from 1884, when Hittorf reported [1] that the residual gas in a vacuum tube placed in a solenoid begins to glow as soon as a high-frequency current is passed through the solenoid. Hittorf attributed this effect to the action of the magnetic field of the solenoid on the gas and expressed the opinion that the current in the discharge was inductive in character. The same effect was observed by Lehrmann [2], who attributed the luminescence of the gas to the action of the electric field created by the turns of the solenoid.

A detailed study of the phenomenon did not begin until 1926-1927 when Thomson [3, 4] showed that the magnetic field of the solenoid was basically responsible for the discharge. Thomson proposed a theory of the electrodeless discharge and, in particular, established a breakdown criterion.

Thomson experimentally confirmed the inductive nature of the electrodeless discharge.

Later, Thomson's experiments were questioned by Townsend and Donaldson [5]. These authors assumed that the discharge was caused by the electric field of the solenoid and asserted that the geometry of this field controlled the ring shape of the discharge.

The debate between Thomson and Townsend led to the investigation of the electrodeless discharge by numerous investigators. Between 1929 and 1934 the problem received the attention of MacKinnon [6], Knipp [7], Smith [8], Brasefield [9], Mierdel [10], and many others.

MacKinnon's article put an end to the dispute between Thomson [4] and Townsend-Donaldson [5]. MacKinnon was able to show that while Thomson had obtained a high-frequency H-mode ring discharge caused by the variable magnetic field, Townsend and Donaldson had obtained a similar high-frequency discharge, whose inductive nature was masked by the E-mode discharge caused by the electric field of the solenoid. MacKinnon repeated the Thomson and Townsend-Donaldson experiments and showed that in the experimental apparatus of the latter conditions facilitating the appearance of a E-mode discharge had been accidentally created.

The experiments of Brasefield [9] and Mierdel [10] were devoted to a quantitative verification of Thomson's theory [4] of the origin of the high-frequency discharge.

Data were obtained for a series of gases: O_2, N_2, N, Ar, Ne, He.

The relations between pressure and breakdown voltage obtained in these experiments confirmed Thomson's theoretical conclusions.

A qualitatively new stage in the investigation of the electrodeless discharge began with the work of Babat [11]. Babat was the first to demonstrate the possibility of introducing hundreds of kilowatts of power into a gas stream at atmospheric pressure by an inductive electrodeless method. His basic experimental parameters were as follows: discharge tube diameter 60-400 mm, tube oscillator frequency f = 3-62 MHz, gas pressure p = 0.01-760 mm Hg; the gas was air. A discharge was created both with and without a gas flow.

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Unfortunately, in this apparatus the discharge channel, made of glass and quartz, did not have reliable thermal shielding and at high powers was instantaneously destroyed.

Babat turned his attention to the effect of the aerodynamic characteristics on the stability of an electrodeless discharge in a gas flow and also detected the important phenomenon of separation (constriction) of the electrodeless discharge from the walls of the discharge tube as the pressure increased.

This article [11] presents simple formulas for estimating the electrical parameters of the radio-frequency circuit, the solenoid, and the electrodeless discharge. It remains the only description of possible applications of electrodeless discharges with polygonal (sectional) inductors.

Babat's work attracted the attention of foreign specialists and in 1947 a more detailed account was published abroad [12].

Attempts to use the electrodeless discharge for purposes of ultraviolet vacuum spectroscopy were described by Birkhoff [13], who examined the question of the different types of electrodeless high-frequency discharges. Birkhoff used a 2-kW tube oscillator with a frequency f = 22.5-61.5 MHz and a discharge tube 22 mm in diameter.

Strauss [14] investigated the effect of various gases on the electrodeless discharge. He employed He, Ar, Kr, Ne, Xe, N_2, O_2 and mercury and iodine vapor. The tube oscillator produces 1.3 kW at a frequency of 4-8 MHz. Strauss obtained the pressure dependence of the striking potential of the electrodeless discharge.

Cabannes [15] made an extensive investigation of the electrodeless discharge in Ar, He, Xe, Kr on the pressure interval $5 \cdot 10^{-2}$-$1 \cdot 10^{2}$ mm Hg. The discharge power was 0.15-1.2 kW, the diameter of the discharge tube 30-45 mm, and the tube oscillator frequency varied from 1 to 2.9 MHz. The experimental relations for the pressure dependence of the breakdown voltage are in good agreement with the results of [9]. It was shown that the discharge geometry depends on the pressure and that at pressures below 1 mm Hg the heat transfer mechanism is determined by the diffusion of electrons and their recombination at the walls and at pressures exceeding 10 mm Hg by heat conduction. The electron densities measured by the probe and spectral methods were of the same order of magnitude.

Romig [16] made a theoretical analysis of the behavior of the various aerodynamic discharge parameters in a supersonic low-density air stream with allowance for diffusion processes. The necessary conditions for maintaining a steady-state discharge were obtained as a function of the maximum of the electron density and the electric field.

Eckert [17, 18] has made certain analytical studies of a ring discharge at low pressures. In [17] he examined the use of the Schottky theory (positive discharge column) to describe a high-frequency discharge for the case in which the collision frequency exceeds the field frequency. In [18] he described the transition from free to ambipolar diffusion in a steady-state high-frequency discharge and showed that for a hydrogen discharge in a field with solenoidal geometry this transition is unstable.

Soshnikov and Trekhov [19-21] have made a theoretical study of a high-frequency high-pressure (p = 1 atm) vortex discharge created in a cylindrical solenoid of infinite length. The problem is formulated on the assumption of thermodynamic equilibrium. With these assumptions Maxwell's equations and the heat transfer equation are written with allowance for radiative losses and solved numerically for an arbitrarily specified magnetic field strength and temperature on the discharge axis. The results of the calculations are presented in the form of curves representing the radial distributions of the electric E(r) and magnetic H(r) field strengths, current density I(r), and temperature T(r) for argon and air on the temperature interval 6000-14,000°K and field frequencies 1.5-100 MHz. The integral characteristics of the discharge: total discharge power, radiation power, inductive reactance, and resistance of the plasma are tabulated for each calculation regime [19-21].

Gruzdev, Rovinskii, and Sobolev [22] investigated the analogous problem for a dense plasma, when the discharge geometry is determined by heat conduction. Local thermodynamic equilibrium, when all the transport coefficients are functions of temperature and pressure, is assumed. The starting system of equations is written with the following assumptions: the field exciting the discharge is homogeneous along the discharge axis, the plasma is stationary, the pressure is atmospheric and constant, the frequency of the electromagnetic field is much greater than the characteristic reciprocal relaxation time of the plasma, radiation is neglected:

$$-\frac{\partial H}{\partial r}=\frac{4\pi}{c}\sigma E, \quad \frac{1}{r}\frac{\partial}{\partial r}rE=-\frac{\omega}{c}\frac{\partial H}{\partial \tau}, \qquad \frac{1}{r}\frac{\partial}{\partial r}r\lambda\frac{\partial T}{\partial \tau}+\frac{\sigma}{2\pi}\int_0^{2\pi}E^2(\tau)\,d\tau=0$$

Here, H and E are the magnetic and electric field strengths, λ is the thermal conductivity, σ is the electrical conductivity, and T is temperature.

The boundary value problem is solved by the method of successive approximations. The boundary conditions at the walls of the discharge chamber are obtained from physical considerations. The first approximation, when the electrical conductivity of the plasma is assumed to be a step function of temperature, permits a qualitative investigation of the phenomena associated with the induced discharge. The second approximation is used for numerical calculations of the discharge power and separation of the discharge from the channel walls in argon. The radial distributions of magnetic and electric field strengths and current density are obtained.

Rovinskii and Sobolev [23] have examined the choice of the optimal frequency range of a stationary induced discharge, basing the analysis on the relations obtained in [22]. The optimality criterion is identified with the condition most favorable for obtaining a given maximum temperature in the discharge. Estimates [23] show that the frequencies of the order of several MHz or more encountered in practice do not correspond to optimal conditions.

A reduction in working frequency is associated with an increase in skin depth and a more uniform occupation of the central zone of the discharge by the plasma. The electric field strength decreases in proportion to the frequency, which causes a deterioration in the discharge conditions. In this case two solenoids were used: a high-frequency initiating solenoid operating at 3.8 MHz and a low-frequency working solenoid operating at 280 kHz [24].

Raizer [25] has proposed an approximate theory of the high-frequency high-pressure (p = 1 atm) electrodeless discharge in a gas stream. He begins by considering the qualitative picture of an electrodeless high-frequency discharge with allowance for the fact that the formation of the discharge geometry is importantly affected not only by heat conduction but also by the nature of the gas flow. In particular, he deals with a tangential supply of gas to the discharge chamber, which is of special practical importance. This produces a slow eddying motion in the axial region, and most of the gas flows along the walls of the discharge channel. This flow protects the walls of the channel from the heat of the plasma and helps to stabilize the discharge.

Estimates for a frequency of 15 MHz show that the skin depth, within which Joule heat is released, is much less than the discharge radius. This makes it possible to consider a plane model of the discharge front. By the discharge front we understand the isotherm T_0, where R_0 is the temperature value corresponding to the conventional abrupt change in electrical conductivity σ. It is assumed that at $T < T_0$ the electrical conductivity is negligibly small and there is almost no release of Joule heat. The discharge front is treated in the same way as a combustion front. On the basis of Maxwell's equation and the energy-balance equation

$$\rho_0 u c_p \frac{dT}{dx}=-\frac{dJ}{dx}+\sigma\langle E^2\rangle, \quad J=-\varkappa\frac{dT}{dx}, \qquad -\frac{dH}{dx}=\frac{4\pi}{c}\sigma E, \quad \frac{dE}{\partial x}=\frac{i\omega}{c}H$$

it is possible to formulate the conditions at the front and obtain relations for the region of existence of the discharge and its velocity in relation to the cold gas flowing into the discharge region along the normal to the front: here, c_p is the specific heat at constant pressure, $\varkappa$ is the thermal conductivity, ρ_0 is the density of the cold gas, < > denotes averaging with respect to time, and u is the normal velocity of the gas. This velocity is determined by the thermal diffusivity of the gas at the end temperature.

Like the flame front in burners, the discharge front is inclined with respect to the direction of flow. Numerical estimates for discharges in air and argon have been based on the proposed model. The frequency of 15 MHz and the other parameters are those of an existing plasma generator at the Institute of Applied Mechanics of the USSR Academy of Sciences. These estimates give values of 9000-10,000°K obtained by Buevich et al. [26].

Mironer and Hushfar [27] have examined certain questions relating to the release of high-frequency energy in a stream of dense moving plasma.

In the theoretical part of their work they analyze the case of a one-dimensional flow of ionized gas in a chamber of constant cross section at atmospheric pressure. It is assumed that beyond the zone of inductive energy release the flow becomes supersonic. The effect of heat release on the hydrodynamic flow parameters is investigated.

The effect of frequency on the energy distribution in the plasma flow is then discussed in relation to an electrodeless high-frequency discharge. The analysis is based on the analogy between the heating of a gas and the well-understood heating of a solid conductor in the electromagnetic field of a solenoid.

The theoretical part of the work is approximate and idealized in character and there is no attempt to give a detailed description of the state of the flow in the discharge.

Freeman and Chase [28] investigated the energy transfer mechanism and the operating characteristics of the thermal high-frequency plasma generator. The physical processes in the discharge and the electrical characteristics of the power source, obtained experimentally, are considered independently. In the theoretical part of this study the Maxwell equation and the energy-balance equation for a plasma in an infinitely long solenoid are written without allowance for radiation at constant atmospheric pressure. The discharge channel is simulated by two concentric zones with an electrical conductivity jump at the zone boundary. The central zone is assumed to be conductive with constant conductivity, while the opposite applies to the outer zone. The principle of minimum entropy production of the thermodynamics of irreversible processes is used to obtain relations that make it possible to calculate the magnetic field strength, the heat flux potential, and the effective discharge radius. The rate of increase of entropy in the discharge is expressed in terms of the heat removed from the discharge by radial heat conduction at constant channel radius. The analytical relations obtained permit the numerical determination of the characteristic curves: dependence of the magnetic field strength on the power of the discharge in nitrogen and argon for a series of frequencies at fixed channel radius. The separation of the discharge from the walls and the heat flux density are investigated in relation to the power released in argon, oxygen, and nitrogen.

In the second half of this study the theoretical conclusions are used for an experimental determination of the region of stable existence of the discharge and to establish the optimal relation between the power source and the discharge parameters.

The experimental investigations of Sherman and McCoy [29] have shown that as the gas flow through the discharge channel increases, the minimum electric field strength grows more slowly than would be the case if it increased according to a linear law.

Having examined existing methods of measuring the current in high-voltage high-frequency circuits, Penfold and Warder [30] proposed a convenient method of measuring the current in a tank circuit from the voltage drop at the inductance.

Rovinskii et al. [31] investigated the separation of a high-frequency electrodeless discharge from the walls in stationary Ar and Xe on the pressure interval 10^{-2}-760 mm Hg, establishing the existence of three pressure regions: a low-pressure region $p < 1$ mm Hg, a transition region $p \approx 1$-250 mm Hg, and a high-pressure region $p > 250$ mm Hg, with distinct characteristics depending on the mechanism of formation of the discharge. For high-pressure regions the authors confirm the conclusion of [15] to the effect that heat conduction is the principal mechanism determining separation of the plasma from the discharge chamber walls.

Smelyanskii et al. [32] investigated the separation of a discharge from the walls in a flow with a tangential gas supply to the discharge channel at atmospheric pressure. It is shown that the discharge radius decreases with increase in the gas flow rate and is 0.4-0.8 of the tube radius. Under these conditions separation is determined by heat conduction and convective heat transfer.

There have been a number of studies concerned with the use of optical methods of measuring temperatures in an electrodeless high-frequency discharge [26, 33-46]. These studies differ chiefly with respect to the experimental conditions. Accordingly, we have tabulated the principal results of Soviet and foreign investigators published since 1961. From the table it may be concluded that for an argon plasma at discharge powers of 2-24 kW on the frequency range 2-26 MHz the temperature varies on average over the interval 8000-11,000°K. Reed's results [33] form an exception. In this case the temperature is exaggerated, since the Larenz method was unjustifiably used and the 7635 Å line of argon, which is subject to reabsorption, was selected for the pyrometric measurements. Spectroscopic studies of an air plasma are described in

TABLE 1

Gas	p, atm	d, mm	N, kW	f,MHz	$T_e \cdot 10^{-3}$, °K	$n_e \cdot 10^{-16}$, cm^{-3}	G, liters/min	
$A_2 + O_2$	1	25.4	3.08	4	18.9		2.8—12.3	[33]
A_r	1	25.4	2.55		8		45	[34]
A_r	1	25	9.5	3—10	13		30	[35]
		30			9.5	0.88	12	
A_r	1	22	2—3	26	9.6	0.96	4	[36]
		16			9.75	1.2	2.5	
A_r	1	30	5.9	15—25	11		51	[37]
A_r	10	30	0.6	10	9	2		[38]
A_r	1	15—45	5	0.3—33	10.5		30—160	[39]
A_r	1	60	24	2	9.75	1.25	49	[40]
A_r	1	30		5.8	10.5		40	[41]
A_r	1	50.8	6	4.5	9.5	4.5		[42]
A_r	1	72	7.2	11.5	9.3	0.82		[43]
X_e	1	72	9.21	11.5	7.86	1.9		[43]
A_r	1	23	6	5.1	9	1	20	[44]
A_r	1	60	5.9	17	8.2	0.16	6.7	[45]
Air	1	100	18	4	7.1	0.05	30	[46]
Air	1	60	27	17.5	9.8		113	[26]

[26, 46]. The spread of the tabulated temperatures can be attributed to differences in the specific power level in the discharge and instrumental errors in the measurements.

The thermal action of a high-frequency plasma flame on bodies with flat and cylindrical surfaces has shown [34, 47, 48] that the specific heat fluxes reach the order of 1 kW/cm^2. These measurements were made on continuous-flow water calorimeters made of copper. The mean plasma flow velocity was 20-50 m/sec [34, 47]. Short-wave power oscillators were used as a source of high-frequency electrical energy. The efficiency of the process and the quality of the plasma obtained depend on the correct choice of oscillator tank circuit parameters and the coordination of the oscillator and the discharge [49-52].

The efficiency (ratio of discharge power to power input) is a measure of the quality of plasma production in an electrodeless high-frequency discharge. In [33, 31, 53-59] it was shown that for modern equipment the efficiency is on the order of 36-60%, reaching 70-80% in pulsed devices.

In most cases the channel of the discharge chamber is made of quartz glass and protected by water-cooling or hydrodynamic separation of the discharge from the channel walls. In [60] Mironer describes a method of shielding the walls based on the use of a copper water-cooled tube with a notch oriented normal to the induced currents and sealed with a heat-resistant dielectric. The discharge channel used by Donskoi et al. [61] is based on a similar principle: the walls of the cylindrical channel are assembled from copper water-cooled tubes with a gap filled with dielectric.

In 1942 Babat [11] predicted that the high-frequency electrodeless discharge would find extensive application in electrochemistry. Today the high-frequency electrodeless plasma torch has become a working tool of the physicist, chemist, and metallurgist for heating gases to high temperatures without contamination. The use of high-frequency plasma in a stream of argon, hydrogen, and other gases for obtaining heat-resistant oxides and growing crystals of refractory materials of the sapphire and ruby type has become a reality [62-65].

In discharges of this kind particles of chromium, tantalum, tungsten, aluminum, magnesium oxide, and certain uranium alloys can be successfully spheroidized [35]. The particles obtained are distinguished by the sterility of their chemical composition, their regular shape (spherical), and the possibility of varying their dimensions over the range from 50 to 700μ. The electrodeless discharge is used in spectral analysis [66], where the atomized sample can be introduced into the plasma jet in the powdered, gaseous, or liquid starting state. The principal advantage of this technique is the absence of contamination and the large useful plasma volume. The use of discharges for creating high-intensity pulsed light sources is of undoubted interest [57]. In spectroscopy the electrodeless discharge is used as a light source for Raman scattering [67] and as a radiation source for the vacuum ultraviolet [68].

The absence of contamination and other potential advantages of the electrodeless high-frequency discharge make it suitable for use in aerodynamic research [69, 70]. Chuan [69] has described the plasma heating of a supersonic (M = 3.5) air stream at a static pressure of 0.4 mm Hg and a temperature of 900°C. The discharge system consisted of a glass Laval nozzle going over into a cylindrical channel surrounded by an inductor and a magnetic coil creating a longitudinal field of 1000 gauss used to reduce the ambipolar diffusion of electrons to the walls.

The plasma tunnel described by Carswell [70] consists of compressed gas cylinders, forechambers, a supersonic nozzle, a test section, a booster tank, and a system of vacuum pumps. The gas is heated by an electrodeless high-frequency discharge with a capacitive coupling on the supersonic section of the nozzle. Carswell used various quartz nozzles with exit diameters of about 20 mm at Mach numbers M = 2. The static pressure in the supersonic flow was varied from 0.1 to 10 mm Hg.

The electron temperature at the nozzle exit reached 65,000°K, whereas the gas temperature was 750°K, which coincides with the results of [71], in which the electron temperature in a high-frequency discharge plasma was measured at low pressures. Probe measurements gave the radial electron distributions (maximum value $n_e = 1.5 \cdot 10^{13}$ cm^{-3}) at the exit of the supersonic nozzle, which for the given conditions corresponds to a degree of ionization of 0.04%. The discharge power was 1 kW at a field frequency of 13.56 MHz.

Although most of the experiments were conducted with argon, certain experiments of direct interest to the aerodynamicist were conducted with air and nitrogen. The same apparatus was used to investigate the interaction of centimeter waves (10-25 GHz) with a supersonic plasma flow at various angles of incidence of the radio waves. A number of investigations were devoted to recombination processes in the flow when additives are introduced. Carswell [70] notes that the principle of his apparatus can be extended to much larger systems.

Vermeulen, Boddie, and Wierum [72] have examined the interaction of an electrodeless discharge with a thermal plasma obtained in a dc arc plasma generator from two standpoints: as a means of increasing the specific impulse of an electrothermal engine and as a means of controlling the flow parameter distribution.

In a dc arc plasma generator under optimal conditions it is possible to obtain a stable and minimally contaminated plasma flow, which, after expanding in a nozzle, is heated by an electrodeless high-frequency discharge, which leads to an increase in the specific impulse of the system. It is known that the most important criterion for estimating the quality of experimental aerodynamic plasma devices is the uniform distribution of the flow parameters. This relates primarily to the obtaining of a flow with a flat profile of the radial temperature distribution. A corresponding adjustment was obtained by supplying high-frequency power to the previously obtained plasma. It was shown that it is possible not only to regulate, but also to raise somewhat the temperature profiles of the flow.

Buevich and Yakushin [73, 74] have used plasma flows obtained in electrodeless high-frequency heating devices to investigate the effect of high temperatures and heat fluxes on thermoplastics.

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