A HYDROGEN PLASMATRON OF 1 MW POWER

R. Ya. Zakharin and A. V. Pustogarov

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A plasmatron design is analyzed for producing hydrogen plasma at a mean-mass temperature above 4000°K with a rather high efficiency.

Plasmatrons operating on hydrogen can be classified into those for industrial, electric rocket propulsion, and plasma research applications. From the practical viewpoint, of considerable interest would be industrial plasmatrons operating at a mean-mass temperature of $T_{m.m}$ = 4000-4500°K and a pressure of 1-5 atm • abs for about 300 h. Such devices are desirable for use in plasma chemistry applications. Meanwhile there are available industrial hydrogen plasmatrons of various designs.

The three-phase plasmatron [1] with wearing carbon electrodes 70 mm in diameter was used for producing acetylene. Its basic parameters, along with those of other plasmatrons, are listed in Table 1.

For heating methane, the plasmatron in [2] was used with face-type copper electrodes and magnetic arc stabilization. The feasibility of operating this device on pure hydrogen has not been proved experimentally.

The arc of the plasmatron in [3], with a lanthanum-plated tungsten cathode pressed flush into an externally cooled copper housing and with a tubular copper anode (10 or 20 mm in diameter, 100 or 200 mm long), was gas stabilized. The results of 12 min tests at an arc current I_a = 900 A, erosion rates $\bar{G} = 3.4 \cdot 10^{-7}$ g/C for the copper anode and $\bar{G} = 6.2 \cdot 10^{-8}$ g/C for the tungsten cathode are presented.

A plasmatron with bilateral gas discharge was studied in [4]. This one had copper electrodes protected by graphite retainers. Arc stabilization was achieved by means of two metallic diaphragms (8 mm in diameter) and a whirled gas stream.

For heating hydrogen, a plasmatron was developed in [5] with a lanthanum-plated tungsten rod cathode (10 mm in diameter, 70 mm long) and a copper anode (30, 40, or 50 mm in diameter). A magnetic field of up to 1 kG was produced by a solenoid. At an arc current I_a = 400 A the cathode eroded at a rate $\bar{G} = 3 \cdot 10^{-7}$ g/C. Increasing the anode diameter from 30 to 50 mm raised the plasmatron voltage at I_a = 600 A from 280 to 420 V. Increasing the external magnetic field from 0.4 to 1.0 kG reduced the efficiency from 70 to 40%.

Of all designs considered here for the achievement of a high-power hydrogen plasmatron, most promising is the one with a long tungsten thermocathode, a copper anode, and a whirled arc.

In this study the authors have tested a plasmatron of such a design with a copper capability of 1 MW.

TABLE 1. Parameters of Hydrogen Plasmatrons

Arc current, A	Arc voltage, V	Plasmatron power, kW	Gas flow rate, g/sec	Pressure, atm. abs	Mean mass gas temperature • 10^{-3}, °K	Arc stabilization	Thermal efficiency	Published source
—	—	$2,5—3,5 \cdot 10^5$	16—19	1	3—4	Gas	—	[1]
—	—	$2,3 \cdot 10^3$	100 (CH_4)	—	—	Magnetic	0,8	[4]
300—900	—	~350	0,3—1,5	1	3—4	Gas	0,6—0,8	[3]
200—700	400—600	~350	0,5—4	1	—	Gas	—	[4]
300—800	—	~350	0,3—1,5	1	3,5—4	Magnetic	0,4—0,8	[5]
400—1400	800—600	$\sim 1 \cdot 10^3$	5—15	3—6	2,0—5,5	Magnetic	0,8—0,85	This study

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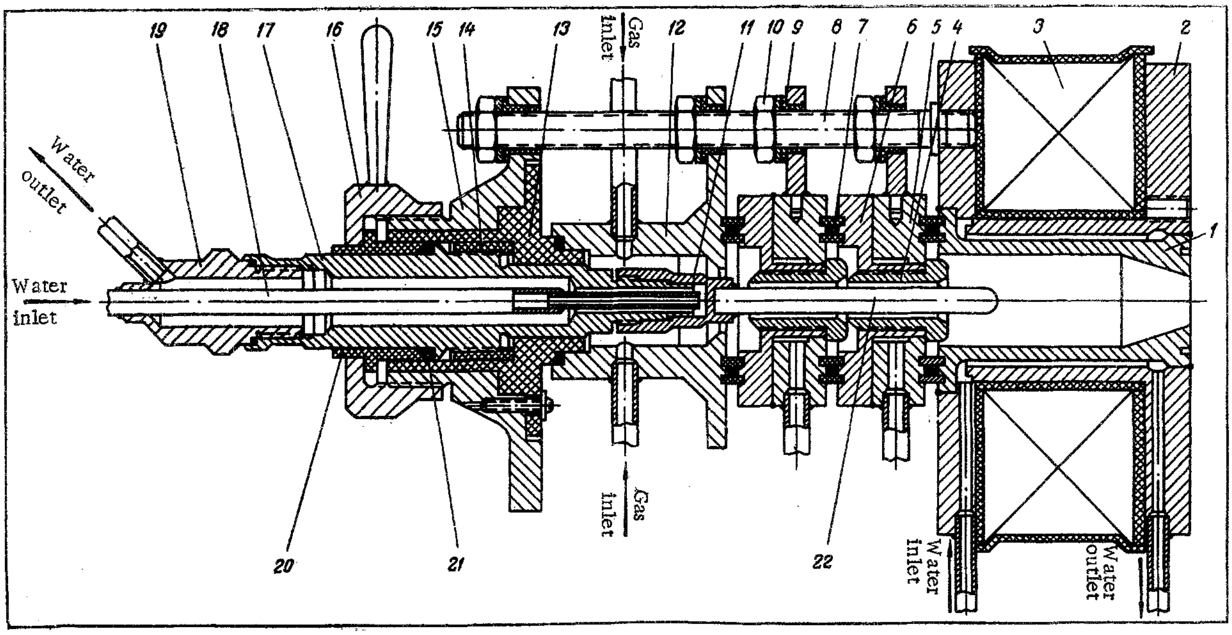

Fig. 1. Construction of the plasmatron: 1) anode (MZ); 2) anode housing (Kh19N10T); 3) solenoid; 4) interchangeable sleeve (MZ); 5, 6) housing of the intermediate segment (Kh18N10T); 7) insulator; 8) pin; 9) sleeve (Textolite); 10) nut; 11) bushing; 12) flange fitting for gas supply; 13) tail spindle (Textolite); 14) colar (Textolite); 15) housing; 16) cover nut; 17) cathode housing; 18) tube; 19) stem; 20) sleeve (Textolite); 21) seal (rubber); 22) thermocathode.

Structurally, the plasmatron consists of a cathode, an electrically insulated intermediate segment, and an anode (Fig. 1). The thermocathode 22 (grade VL-10 lanthanum-plated tungsten, 10 mm in diameter and 70-80 mm long) was soldered into a copper bushing 11 and fastened into a steel housing 17. The position of the thermocathode relative to the anode can be smoothly adjusted by means of a threaded coupling between the housing 17 and the collar 14.

The electrically insulated intermediate segment includes a housing 15, a tail spindle 13, a flange fitting for gas supply 12, and spacers. These cooled spacers are made up of a steel body 5, 6 and an interchangeable copper sleeve 4 by means of which the duct section for the gas flow can be varied. By changing the number of spacers, it is possible to vary the length of the thermocathode 22.

The anode consists of a steel housing 2 and a copper sleeve 1 with an inside diameter 38 mm and a 5 mm thickness. The cooling gap is 2 mm wide. A cooler was connected to the anode, and a supercritical nozzle behind for maintaining the excess pressure in the chamber and for measuring the gas flow rate.

For shifting the arcing spot on the anode, a solenoid 3 has been wound around the latter with a magnetic field as shown in Fig. 2.

All plasmatron components are held together, through an electrically insulating seal 7, by means of three pins 8 also electrically insulated from the rest by Textolite sleeves 9.

The plasmatron is water-cooled, the cathode and the intermediate spacers cooled sequentially.

An arc discharge between the center thermocathode and the anode is initiated by means of a fuse wire. The anode and the solenoid are supplied from separate direct-current sources [6].

During the experiment we measured the flow rate and the temperature rise of the water, the gas flow rate, the solenoid current, and the plasmatron voltage and current. The mean-mass gas temperature was determined from the heat balance.

The plasmatron was tested over the following range of parameter values: arc current I_a = 0.4 to 1.4 kA, hydrogen flow rate G = 5 to 15 g/sec, solenoid current I_s = 20 to 30 A, pressure in the discharge chamber P = 3 to 6 atm • abs.

The plasmatron performance parameters are shown in Fig. 3 as functions of the arc current. For comparison, the volt–ampere characteristic of the plasmatron in [5] (d = 40 mm, P = 1 atm • abs, G = 1.5

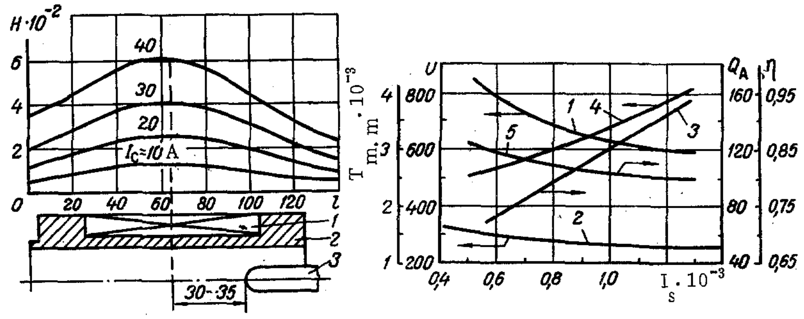

Fig. 2. Axial field of the solenoid: 1) solenoid; 2) anode; 3) thermocathode. Magnetic field H (G), distance *l* (mm).

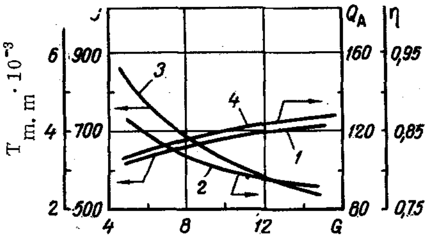

Fig. 3. Plasmatron performance parameters as functions of the arc current (I_s = 30 A, P = 3-6 atm·abs): volt–ampere characteristics (1 and 2 according to [5]), heat losses in the anode Q_A kW (3), mean-mass temperature $T_{m.m}$°K (4), thermal efficiency η (5).

g/sec) has also been plotted here. At I_a = 1 kA, the firing voltages are 630 and 270 V respectively. The higher firing voltage is explained by the excess pressure in the discharge chamber. By analogy with the plasmatron in [7], with the voltage–pressure characteristic $U \sim P^{0.56}$, one can estimate the plasmatron voltage at 1 atm abs. instead of 6 atm abs.; such an estimate has yielded approximately 260 V.

The electric parameters of the plasmatron with a ballast resistance R_b = 1.155 Ω and at a pressure P = 6 atm abs. fluctuated as follows: ΔU = ±30%, ΔI = ±25%.

Owing to the measurement imprecision, it was impossible to pick up the heat losses in the cathode and in the intermediate segment. Since heat was transmitted to the intermediate segment only by radiation from the arc column, hence the radiative losses from such a hydrogen arc was negligible.

In order to explain the absence of heat losses in the cathode, it is necessary to consider the heat balance at the cathode and, without analyzing the mechanism of heat transmission through the cathode fall, to express it as

$$Q_w = Q_{\Delta U} + Q_J + Q_{rad} - Q_{rc} - Q_{conv}, \tag{1}$$

with Q_w denoting the heat carried away by the cooling water, $Q_{\Delta U}$ the heat supplied to the cathode from the arcing spot, Q_J the Joule heat generated in the cathode, Q_{rad} the heat lost by radiation from the arc column to the cathode, Q_{rc} the heat radiated by the cathode, and Q_{conv} the heat carried away from the cathode by convection.

Since the radiation loss from the arc column is negligible, i.e., $Q_{rad} \approx 0$ and because $Q_w \approx 0$, hence the heat balance at the cathode is

$$Q_{\Delta U} + Q_J \simeq Q_{rc} + Q_{conv}. \tag{2}$$

It follows from (2) that the heat coming to the cathode is dissipated by radiation and convection.

The thermal efficiency of a plasmatron is determined by the heat losses in the anode:

$$\eta = \frac{I_s U - Q_A}{I_s U} = 1 - \frac{\Delta U_A}{U}. \tag{3}$$

The heat losses in the anode Q_A increase linearly with the arc current. The voltage equivalent of losses is ΔU_A = 120 V. As a consequence of the dropping volt–ampere characteristic, and increase in the current causes the thermal efficiency of the plasmatron to drop from 86 to 80% and the mean-mass temperature of hydrogen to rise from 2500 to 4000°K.

When the hydrogen flow rate is increased (Fig. 4), the plasmatron voltage rises on account of the higher rate of heat transfer from the arc column to the oncoming cold gas, as this results in a higher electric field intensity.

Because radiation from the arc column is negligible, the heat losses in the anode are determined by dissipation from the arcing spot and by convection from the whirled gas stream. Dissipation from the arcing spot does not vary with an increasing gas flow rate and, therefore, the heat losses in the anode are reduced because of a smaller convective component, as a result of a lower mean-mass gas temperature. The thermal efficiency of the plasmatron increases with an increasing gas flow rate, because of the reduced heat losses in the anode and because of the higher voltage.

A variation in the magnitude of the magnetic field, within the test range, does not significantly affect the plasmatron performance parameters.

During 6 min tests at $I_a = 800$ A, $G = 10$ g/sec, $P = 6$ atm abs., and $I_s = 30$ A the tungsten thermocathode after the test revealed that erosion had occurred beginning at the end surface. The entire end surface bore traces of fusion and fine arcing pits. We also noted a bright region at a distance 8.0-8.5 mm from the end. An examination of cathode specimens in helium indicated a temperature $T \sim 1000$°K at the boundary of this region at an arc current $I_a = 50$-250 A. Furthermore, a study of cathode specimens has also shown that for a narrow range of arc current levels there is an optimum cathode geometry which yields an erosion rate reduced to $\bar{G} \simeq 10^{-7}$-10^{-8} g/C.

With the pressure in the plasmatron chamber raised to 10-15 atm abs. and the arc current increased to 2-3 kA, the electric power of the plasmatron can be increased to 2-3 MW and 30-40 g of hydrogen can be heated to 3000-4000°K at a thermal efficiency of 70-80%.

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