# EFFICIENCY OF GAS HEATING IN A SUBDIVIDED PLASMOTRON WITH A CONSTRICTED CHANNEL

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The thermal efficiency of gas heating was studied in a plasmotron as a function of the pressure in the subdivided plasmotron channel produced with a nozzle-diaphragm. An estimated function was obtained (3) for calculating the thermal efficiency of plasmotrons of similar construction.

In the design of plasma heaters one must solve several problems, often independent of their intended purpose, including:

1) determination of the thermal efficiency or the efficiency of the thermal consumption of electrical power supplied for the heating of gas in the plasmotron;

2) a study of the electrical characteristics of the plasmotrons;

3) regulation of the discharge velocity of the plasma streams through changes in the geometry of the gas channel;

4) gas-dynamic and thermal diagnostics of the plasma streams.

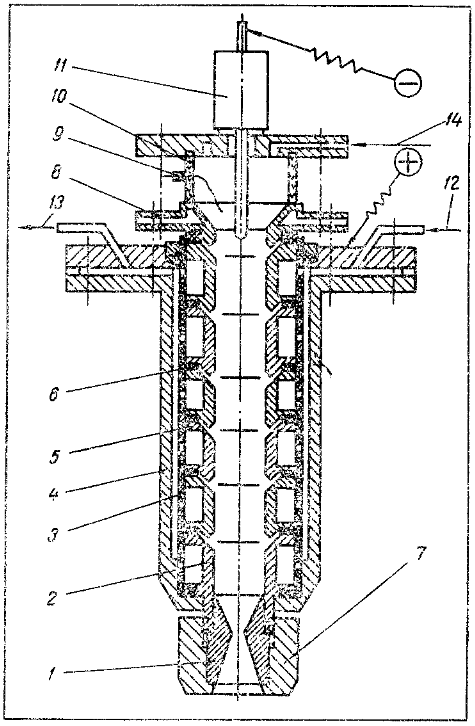


Fig. 1. Subdivided plasmotron with power of up to 100 kW: 1) nozzle with critical cross section diameter of 4, 8, 12, and 16 mm; 2) anode section; 3) cylinder insulator; 4) casing; 5) intermediate sections; 6) intersectional insulators; 7) outer nut; 8) auxiliary anode; 9) initiating electrode; 10) quartz insertion; 11) cathode holder with cathode; 12) cooling water inlet to each section; 13) water outlet; 14) inlet of plasma-generating argon.

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TABLE 1. Initial Experimental Results

| $d_n$, mm | $\Gamma_d$ | UI, kV | $\eta$, % | G, g/sec | $H_n$, kJ/kg | $T_n$, °K | $P_c$, N/m$^2$ | $T_c$, °K | $\rho_c$, kg/m$^3$ | $w_c$, m/sec | $a$, m/sec | $\mu_c \cdot 10^5$, N·sec/m$^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 1,00 | 40,5 | 40,5 | 0,62 | 26500 | 11300 | $6,34 \cdot 10^3$ | 5780 | 5,25 | 375 | 1420 | 21,0 |
| 20 | 1,00 | 39,9 | 52,4 | 1,18 | 17700 | 10800 | $9,33 \cdot 10^3$ | 5530 | 8,07 | 465 | 130 | 20,0 |
| 20 | 1,00 | 40,5 | 59,3 | 1,84 | 13050 | 10350 | $1,23 \cdot 10^4$ | 5300 | 11,10 | 529 | 1360 | 19,0 |
| 20 | 1,00 | 38,8 | 65,3 | 3,40 | 7450 | 9700 | $1,83 \cdot 10^4$ | 4980 | 17,60 | 615 | 1320 | 18,0 |
| 16 | 1,25 | 37,8 | 43,4 | 1,16 | 14000 | 10300 | $9,86 \cdot 10^3$ | 5280 | 8,95 | 413 | 1360 | 19,0 |
| 16 | 1,25 | 37,4 | 53,9 | 1,78 | 11300 | 10100 | $1,31 \cdot 10^4$ | 5180 | 12,10 | 469 | 1340 | 18,5 |
| 16 | 1,25 | 37,7 | 58,5 | 2,50 | 8780 | 9700 | $1,69 \cdot 10^4$ | 4980 | 16,30 | 489 | 1320 | 16,3 |
| 16 | 1,25 | 39,2 | 61,1 | 3,37 | 7100 | 9300 | $2,12 \cdot 10^4$ | 4780 | 21,20 | 506 | 1290 | 21,2 |
| 8 | 2,50 | 40,5 | 17,3 | 0,79 | 8800 | 9950 | $2,16 \cdot 10^4$ | 5100 | 20,4 | 124 | 1330 | 18,0 |
| 8 | 2,50 | 44,5 | 25,3 | 1,40 | 7700 | 9600 | $3,54 \cdot 10^4$ | 4930 | 34,4 | 130 | 1310 | 17,5 |
| 8 | 2,50 | 40,4 | 27,6 | 2,10 | 5320 | 8800 | $4,76 \cdot 10^4$ | 4525 | 50,4 | 133 | 1260 | 17,0 |
| 8 | 2,50 | 39,8 | 28,3 | 2,32 | 4850 | 8450 | $5,26 \cdot 10^4$ | 4350 | 56,0 | 132 | 1250 | 17,0 |
| 4 | 5,00 | 44,0 | 10,1 | 3,71 | 1200 | 2400 | $4,8 \cdot 10^4$ | 1340 | 171,4 | 69 | 684 | 6,5 |
| 4 | 5,00 | 46,8 | 6,0 | 2,88 | 970 | 2000 | $4,9 \cdot 10^4$ | 1140 | 206,0 | 44 | 630 | 6,0 |
| 4 | 5,00 | 44,1 | 7,2 | 1,64 | 1930 | 3860 | $5,0 \cdot 10^4$ | 2070 | 116,0 | 45 | 850 | 9,5 |
| 4 | 5,00 | 14,6 | 8,8 | 1,04 | 1240 | 2480 | $5,1 \cdot 10^4$ | 1380 | 178,0 | 18 | 694 | 6,5 |

We made a study of the efficiency of gas heating in relation to the constriction of the subdivided plasmotron channel by nozzle-diaphragms. Subdivided plasmotrons have a number of advantages over plasmotrons having a short arc. These are: the possibility of building a long enough arc column increasing the time the heating gas remains in the channel, the presence of rising volt–ampere characteristics, since the isolated sections are a system of interelectrode insertions confining the arc, etc.

The energetic possibilities of such plasmotrons were examined earlier [1, 2]. The considerable effect of pressure on the plasmotron efficiency was noted, i. e., on the efficiency of the heat exchange between the plasma stream within the channel and the channel walls and anode. It is interesting to determine the dependence of the heating efficiency of the gas in the channel on the degree of constriction of the discharge cross section of the channel outlet.

The channel constrictions consist of geometrical nozzles with different diameters of the critical cross section in accordance with the necessity of obtaining the desired supersonic high-enthalpy gas currents.

A six-section plasmotron with a channel diameter of 20 mm and section height of 20 mm was used as the subject of the study. Nozzle inserts of different constrictions, having diameters of the critical cross section of 16, 12, 8, and 4 mm, were tightly fitted in the anode section and secured with an outer nut (Fig. 1).

The plasma stream discharged into a vacuum chamber having a diameter of 800 mm and height of 1500 mm in which the pressure was maintained from $2 \cdot 10^2$ to $6.6 \cdot 10^3$ N/m$^2$ depending on the given system. In this case the pressure in the channel was $1.3 \cdot 10^3$–$1.3 \cdot 10^5$ N/m$^2$. The discharge rate of the plasma-generating gas (argon) lay in the interval of 0.2–3.5 g/sec. In the experiments the heat fluxes through each section of the plasma channel were measured including the cathode apparatus. For this the temperature of the cooling water at the inlet and outlet of each section and its flow rate were recorded, allowing the calculation of the heat flux in each element, as well as the current strength, the voltage on the arc, and the discharge rate of the plasma-generating gas. The thermal power of the plasma stream at the nozzle outlet relative to the electrical power supplied to the arc characterizes the thermal efficiency of gas heating or the efficiency of the plasma apparatus.

The average mass temperature of the stream at the nozzle outlet Tn was determined according to the specific enthalpy at the outlet of the stream from the plasmotron using the tabular data of [3].

Cooling of the nozzles fastened to the anode section was accomplished mainly by thermal conduction through the anode section which is cooled by water and partly by radiation from the outer nut. The thermal power of the radiation by the outer nut was determined analytically and experimentally. In the extreme case it was ~1.5% of the thermal power extracted from the anode by the cooling water. This allowed one to consider the nozzle and outer nut as elements of the plasmotron. The initial experimental data are presented in Table 1.

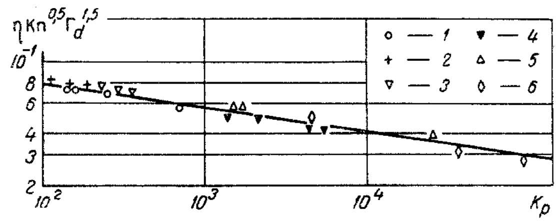


Fig. 2. Experimental data of correlation values: 1) $\Gamma_d$ = 1.00; 2) 1.25; 3) 1.65; 4) 2.50; 5) 2.50; 6) 5.00.

It is known that the thermal efficiency of the plasmotron depends in a complex way on the electrical and hydrodynamic parameters of its operation. Treatment of the experimental results in similarity criteria gives a dependence for different forms of plasmotron construction in the form [4, 5]

$$\eta = f(\mathrm{Re}\ K_e,\ \Gamma_g, \ldots). \tag{1}$$

Not pretending to any strict and broad correlation of the experimental data, for which another series of experiments must be carried out in the future, attempts were made by analogy with [2, 4] to obtain a calculated dependence in criterional form for a plasmotron with subdivided channel terminating in a nozzle with a critical cross section. For this it is assumed that during flow of the stream in the channel for low pressures in a sliding system the intensity of heat exchange between the plasma stream and the channel walls, characterized by the St criterion, depends on the Knudsen criterion ($\mathrm{Kn} = \mathrm{M}/\sqrt{\mathrm{Re}}$) [6, 7] which usually takes into account the pressure in the plasmotron channel. However, as the initial calculations showed, this was not sufficient and it was necessary to introduce the criterion of geometrical similarity $\Gamma_d = d_c/d_n$, characterizing the narrowing of the channel due to its constriction by the critical cross section of the nozzle, which also evidently takes into account the pressure factor. The Joule heat effect which is prominent in the channel can be taken into account by the energetic criterion $K_p$, which is to some extent analogous to the criterion $K_e$ and represents a measure of the ratio of the electrical energy supplied to the arc to the kinetic energy of the stream.

The use of the Knudsen criterion allows one to dispense with the Reynolds criterion. Thus, the experimental results were successfully approximated by the function

$$\eta = F(\mathrm{Kn},\ K_p,\ \Gamma_d). \tag{2}$$

The expression of the experimental results in the criterional form in the given case has several advantages, since with the similarity criteria one can clearly present a picture of the physical interaction of concurrent values (force, current, etc.).

The experimental results of the table, analyzed with the goal of obtaining an estimated formula for $\Gamma_l = l/d_c = 6$, gave a formula for estimating the efficiency $\eta$:

$$\eta = 0.17\ \mathrm{Kn}^{-0.5} K_p^{-0.15} \Gamma_d^{-1.5}, \qquad 10^{-4} < \mathrm{Kn} < 2 \cdot 10^{-2};\ 1 < \Gamma_d < 5;\ 5 \cdot 10 < K_p < 5 \cdot 10^4. \tag{3}$$

For a determination of the temperature at the calculated similarity criteria the mathematical mean of the gas temperatures at the channel inlet and nozzle outlet was chosen. The latter was obtained in experiments with a reduction of the heat balance and equalled practically half the temperature of the gas (plasma) at the nozzle outlet ($T_c = 0.5T_n$). However, the temperature at the nozzle outlet of the plasmotron ($T_n$) can itself be determined. Therefore with the presentation of the data in the criterional form, as in the calculation of heat exchange apparatus, this temperature can be assigned preliminarily and later corrected in the results of the calculation.

The tables of experimental data can be used for a preliminary choice in a calculation determining the temperature in analogous constructions, taking into account the ratio $\Gamma_d = d_c/d_n$, where $T_n$ = 9500-1000°K for $\Gamma_d$ = 1-2 and $T_n$ = 2500°K for $\Gamma_d$ = 2-5.

The temperature $T_c$ found was used in an evaluation of the thermophysical parameters of the medium in the subdivided plasmotron channel for the calculation of the similarity criteria.

The mathematical mean of the pressures in the cathode chamber and beyond the nozzle in the vacuum chamber was taken as the pressure $P_c$ determined in the channel.

A curve constructed from the experimental data is presented in Fig. 2. The scatter of the experimental points, except for several exceptions, is ±5% from the average value so that Eq. (3) can be used for an approximate evaluation of the efficiency of similar subdivided plasma heaters.

## NOTATION

| | |
|---|---|
| $T_n$ and $T_c$ | are the temperature at nozzle outlet and temperature determined in channel, °K; |
| $\rho_c$ | is the density, $kg/m^3$; |
| $w_c$ | is the stream velocity in channel, m/sec; |
| $P_c$ | is the pressure in channel, $N/m^2$; |
| g | is the acceleration of gravity, m/sec; |
| $d_c$, $d_n$ | are the diameter of channel and diameter of critical cross section of nozzle, m; |
| $l$ | is the length of channel, m; |
| $a$ | is the speed of sound, m/sec; |
| $\mu_c$ | is the dynamic viscosity of stream, $N \cdot sec/m^2$; |
| G | is the discharge rate of gas, g/sec; |
| I | is the current strength, A; |
| U | is the voltage, V; |
| $H_n$ | is the enthalpy of stream, J/kg; |
| $\sigma$ | is the electrical conductance, $1/ohm \cdot m$; |
| $Re = w_c d_c \rho_c / \mu_c$; | |
| $Kn = M/\sqrt{Re}$; | |
| $M = w_c / a$; | |
| $\Gamma_d = d_c/d_n$; | |
| $\Gamma_l = l d_c$ | is the parametric criteria of geometric similarity; |
| $\Gamma_g$ | is a parametric criterion in Eq. (1); |
| $K_p = UIgd^4$ and $\rho_c^2/G^3$ | are the energetic criteria; |
| $\eta = H_n/UI$; | |
| $K_e = I^2/H_n g d_c \sigma$ | is the energetic criteria of (1). |

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