EXPERIMENTAL INVESTIGATION OF ENERGY CHARACTERISTICS AND HEAT TRANSFER OF SHF DISCHARGE

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The energy characteristics of two constructions of SHF plasmatrons, waveguide type and resonator type, are determined by the calorimetric method and the heat transfer of the plasma of SHF discharge in air, carbon dioxide, and helium is investigated. The results of the investigation of heat transfer are presented in the form of criterial dependences.

Super-high-frequency (SHF) discharge as well as high-frequency discharge can be obtained in a wide range of pressures from thousandths of mm Hg to tens of atmospheres. The range of power is also wide and at present varies from a few tens of watts to several kilowatts.

The high stability of the SHF discharges and the energy density in them, the simplicity of feeding energy to the plasma and providing radiation protection, and the high coefficient of transfer of energy to the plasma have attracted the attention of investigators to the SHF discharge as a convenient agent for use in industrial processes. However, unlike high-frequency discharge, SHF discharge at atmospheric pressure has begun to be investigated rather recently. Several publications [1-4] can be enumerated in which mainly the constructions of plasmatrons are described or some results of spectral measurements of SHF discharge are given.

We have attempted to determine the energy characteristics of SHF plasmatrons of most extensively used constructions, using different gases and to obtain data on the possibility of using SHF discharge in some industrial scheme or other from the point of view of power indices of the discharge.

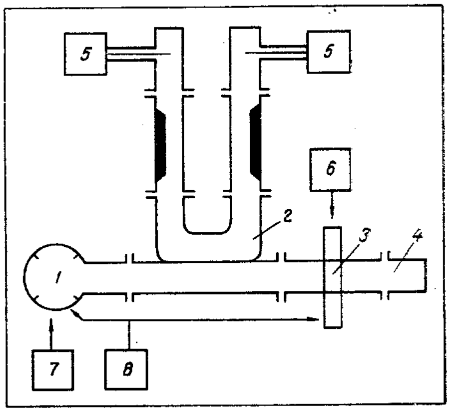

Fig. 1. Schematic diagram of the equipment: 1) SHF oscillator; 2) directional coupler; 3) plasmatron; 4) matched water load; 5) microwave power meter; 6) gas supply system; 7) electric supply system; 8) water supply system.

Two SHF oscillators were used for the investigation of SHF discharge: one with 2.5 kW power and the other with 5 kW. The oscillatory power of both was regulated by measuring the anode voltage of the oscillators, up to 250 W for the first and to 1.5 kW for the second. The energy of the oscillators was fed through a waveguide (Fig. 1) to the discharge gap where the discharge was initiated. The discharge was investigated in waveguide and resonator plasmatrons (Fig. 2). The incident and reflected power was measured with an IMM-6 microwavemeter with calibrating directional coupler. The error in the power measurement was not more than 5% SHF; the power absorbed in the water load (transmitted power P_t) was measured from the flow rate of water and the temperature drop at the entrance and exit of the load.

In the waveguide plasmatron the discharge was initiated by an H_{10} wave, in the resonator type plasmatron by E_{020} wave. The discharge was in the form of a cylindrical rod of 5 to 40 mm diameter and 50 to 350 mm length depending on the

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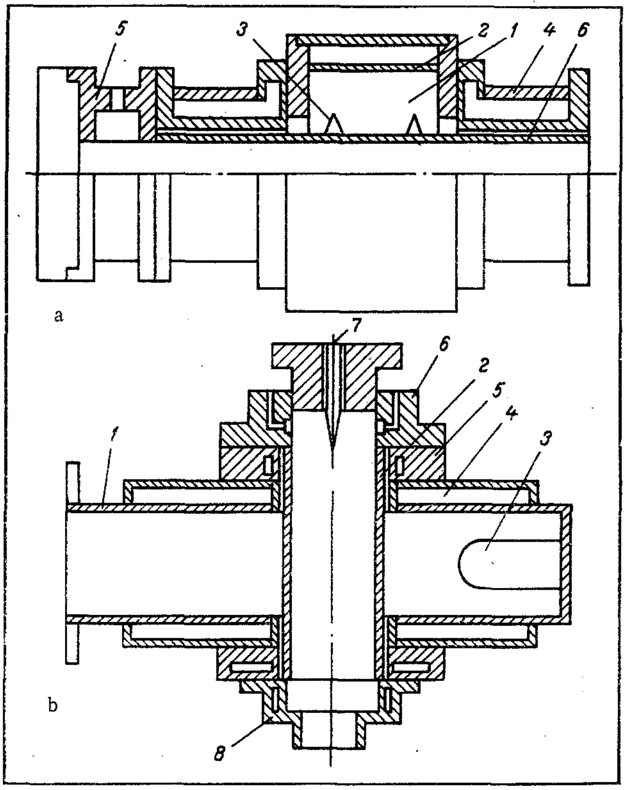

Fig. 2. SHF plasmatron: a) resonator type [1) resonator; 2) waveguide slot antenna; 3) slit; 4) outer tube; 5) gas ring; 6) quartz tube]; b) waveguide type with water load [1) waveguide; 2) quartz tube; 3) matched water load; 4) waveguide frame; 5) flange; 6) gas ring; 7) device for igniting discharge; 8) outer tube].

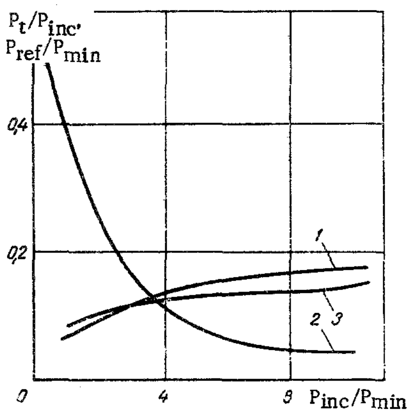

Fig. 3. Dependence of relative magnitude of transmitted and reflected power on P_{inc}/P_{min}: 1, 2) for waveguide construction; 3) for resonator type construction; 1, 3) P_{ref}/P_{inc}; 2) P_t/P_{inc} $-P_{inc} = 2.4$ kW.

nature of the gas, its flow rate, the diameter of the quartz tube, and the incident power.

The gas from the cylinders was fed to the discharge tangentially; its flow rate varied in the range 0.2-1.5 g/sec for air, 0.3-1.8 g/sec for carbon dioxide, and 0.02-0.2 g/sec for helium. The flow rate was measured by RS-5 rotameters.

In order to analyze the energy characteristics of the SHF discharge we measured the quantities that enable one to form the complete energy balance of the oscillator. For operation under a load the energy balance is written in the form

$$P_{a_0} + P_h = P_{cool} + P_d + P_{ref} + P_t, \tag{1}$$

where P_{cool} is considered for operation of the oscillator with matched load.

Of maximum interest is the utilization coefficient of the oscillatory power of the oscillator

$$\eta_{osc} = \frac{P_d}{P_{a_0} - P_{cool}}. \tag{2}$$

For an oscillator loaded to a resonator type plasmatron η_{osc} varied from 0.85 to 0.95, while for the waveguide plasmatron it was equal to 0.7-0.85 for large diameters of tubes $d/a \geq 0.4$ and 0.4-0.6 for small tube diameters.

TABLE 1. Criterial Dependences for Heat Transfer in SHF Plasmatrons

	Waveguide	Resonator
Air	$St = 0{,}22\,Re^{-0{,}18}\left(\frac{l}{d}\right)^{-0{,}6}$	$St = 0{,}19\,Re^{-0{,}12}\left(\frac{l}{d}\right)^{-0{,}6}$
CO_2	$St = 0{,}35\,Re^{-0{,}2}\left(\frac{l}{d}\right)^{-0{,}66}$	$St = 0{,}35\,Re^{-0{,}18}\left(\frac{l}{d}\right)^{-0{,}66}$
Helium	$St = 0{,}54\,Re^{-0{,}26}\left(\frac{l}{d}\right)^{-0{,}8}$	$St = 0{,}52\,Re^{-0{,}22}\left(\frac{l}{d}\right)^{-0{,}72}$

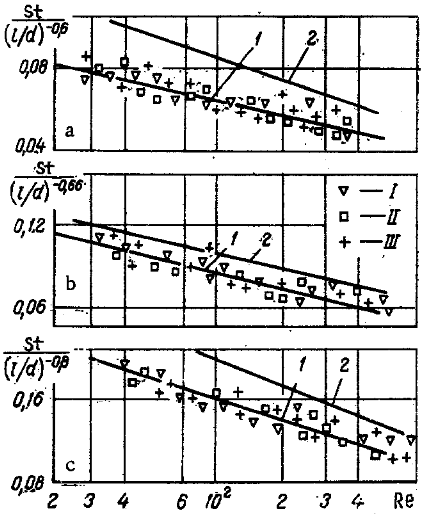

Fig. 4. Generalized characteristics of heat transfer to the wall of the discharge tube: a) air; b) carbon dioxide; c) helium; I) l/d = 0.05; II) 1.5; III) 2.2; 1) for resonator construction; 2) for waveguide. For a and b, values of Re · 10.

The efficiency of the anode circuit of the oscillators was also estimated from the measurements for the two types of oscillators during the variation of their oscillatory power. In the rated regime for operation with matched load the maximum value of the efficiency did not exceed η_a = 0.55, where

$$\eta_a = \frac{P_{a_0} - P_{cool}}{P_{a_0}}. \qquad (3)$$

The efficiency of gas heating, representing the ratio of the power derived from the plasma jet beyond the discharge region to the power absorbed in the discharge

$$\eta_d = \frac{P'_d}{P_d},$$

was η_d = 0.8-0.85 for air, η_d = 0.7-0.8 for carbon dioxide, and η_d = 0.2-0.25 for helium.

The minimum values of the incident power for such flow rates, which will still sustain the plasma filament at the center of the quartz tube for both plasmatron constructions, were determined experimentally. The quenching of the discharge with the decrease of power is apparently related to the decrease of the discharge temperature below the ionization temperature.

The magnitude of the power reflected from the discharge and the power absorbed in the discharge depends primarily on the radius of the discharge, which in turn depends on the diameter of the discharge tube and the amount of the incident power.

The dependences of P_{ref}/P_{inc} and P_t/P_{inc} on the quantity P_{inc}/P_{min} are shown in Fig. 3. The reflected power P_{ref} increases monotonically with the radius of the discharge and the incident power for the waveguide construction; the power absorbed in the water load increases sharply with the decrease of the radius of the discharge tube.

Quartz tubes with 20, 30, 40, and 50 mm diameter with wall thickness of 1.5-2 mm were investigated.

For the resonator type plasmatron a change of the mode of operation, change of the tube diameters, and the replacement of the plasma-forming gas do not result in large changes of the reflected power.

In the investigation of the heat transport phenomena at the wall of the discharge channel it must be noted that the basic form of transport at the wall of the quartz tube is the transport caused by molecular and turbulent thermal conductivity, since energy transport by radiation from the discharge is a small quantity of the order of 3-5%. From a generalization of the experimental results on heat transport at the wall of the discharge channel we make use of Stratton's criterion, which is expressed in terms of enthalpy in the following way:

$$St = \frac{H_a - H_{ex}}{H_a - H_w}\,\frac{d}{4l}. \qquad (4)$$

Stratton's criterion can be expressed in terms of quantities that are directly measured in the experiment:

$$\mathrm{St} = \frac{P_{\mathrm{f}}}{P_{\mathrm{inc}} - P_{\mathrm{ref}} - P_{\mathrm{t}}} \frac{d}{4l}. \tag{5}$$

For this purpose in the waveguide construction of the plasmatron, the surface of the waveguide feeding energy is made water-cooled, while in the resonator type plasmatron, the side walls of the resonator are cooled.

The temperature drops were measured in all elements of the plasmatron in the stationary regime by mercury thermometers and thermocouples; besides, in order to check the heat balance special experiments were conducted with a water-cooled quartz calorimeter to determine the heat content of the discharge jet.

The intensity of heat transfer from the discharge to the wall and from the supplied gas flow to the discharge is determined by the gas dynamic equations. As a criterion for argument arbitrarily characterizing the state of the turbulence in the flow, we take Reynolds number

$$\mathrm{Re} = \frac{v\rho d}{\mu}. \tag{6}$$

The diameter and the length of the discharge region, the amount of the power supplied, and also the ratio of the azimuthal and axial velocities of the gas affect the heat transport to the wall of the discharge chamber.

Therefore

$$\mathrm{St} = f\left(\mathrm{Re},\ \frac{v_r}{v_z},\ \frac{l}{d};\ k_{\mathrm{e}}\right), \tag{7}$$

where k_e is an energy criterion representing the ratio of the total supplied energy to the initial enthalpy of the gas.

The relative heat transfer to the wall decreases with the increase of the flow rate of the gas; this is apparently due to better reflection of the jet; at the same time the ratio of the azimuthal to axial velocities does not affect the nature of heat transfer in the investigated region.

The results of these investigations on the heat transfer of SHF discharge with the wall are generalized by the dependences shown in Table 1.

The difference in the generalizations for the two types of constructions is probably caused by the nonsymmetric supply of energy to the discharge in the waveguide construction of the plasmatron and by the difference in the lengths of the discharge tubes.

The approximating dependences for the two constructions of plasmatron are shown in Fig. 4 by the continuous lines.

The generalization of the experimental results for these gases by a single criterial dependence using Prandtl number was not possible.

Perhaps there exists some other mechanism which affects the heat transfer of SHF discharge with the wall of the discharge tube.

NOTATION

P_{a_0} is the power spent in the anode circuit of the magnetron;
P_h is the power spent in filament heating;
P_{cool} is the power spent in cooling the anode;
P_d is the power consumed by the discharge;
P_{ref} is the power reflected from the discharge;
P_t is the power transmitted through the discharge and absorbed in the water load;
P_f is the power spent for heating the plasmatron frame;
ρ is the gas density;
v is the gas velocity;
μ is the gas viscosity.
H_W is the enthalpy of the gas in the boundary layer;

H_{ex} is the enthalpy of the gas at the exit;
H_a is the conventional gas enthalpy determined from the SHF power supplied to the discharge;
d is the inner diameter of the quartz tube;
a is the dimension of the wide wall of the waveguide, a = 90 mm;
l is the length of the discharge region;
b is the dimension of the narrow wall of the waveguide, b = 45 mm.

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