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POROUS ELEMENTS IN PLASMA GENERATORS WITH A LIQUID ELECTROLYTIC CATHODE

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Variants of basic diagrams and energy characteristics of generators of an atmospheric-pressure nonequilibrium gas-discharge plasma the working surfaces of whose cathode units are manufactured from a porous nonmetallic material have been given. Tap water and aqueous solutions of different salts and alkalis have been employed as the electrolytes. It has been shown that the use of porous elements in the cathode unit substantially extends the possibilities of structural design of plasma generators with liquid electrodes, contributes to a significant increase in the discharge gap (to 200 mm), and makes it possible to increase the fraction of heat going to heat up the plasma in the positive column in the heat balance of the discharge.

Introduction. Porous cooling is known to be an efficient means of protecting thermally stressed elements of different heat-engineering devices. In plasma technology, it is employed for thermal protection of the walls of the plasmatrons' arc chamber [1–4]. Supply of a plasma-forming gas via the porous elements of the arc chamber enables one not only to safeguard its walls against the thermal action of the discharge but also to substantially change the properties of the discharge itself. From this viewpoint, porous cooling of the electrodes is of special interest. It has been shown that the discharge voltage increases stepwise for a certain rate of flow of the gas through a porous anode [5, 6]. The reason is the sharp change in the spatial structure of the discharge in the anode part of the plasma column. The anode region is extended and the discharge changes from a contracted form to a diffuse form.

Porous metal electrodes find application in spectral analysis of liquid substances [7]. For this purpose a porous electrode is wetted with a probe liquid and this liquid, evaporating under the action of electric discharge, arrives at the plasma column. Variants of structural design of plasma generators with liquid electrodes are few in number, and no porous elements are employed in them.

One possible way of using porous materials in the structure of plasma generators with liquid electrodes is as follows. If a porous dielectric is impregnated with electrolyte, it becomes conducting and can be used as the electrode of a plasma generator. For the plasma generator with such an electrode to operate in the stationary regime it is necessary to observe some measures to prevent drying of the porous material under the action of gas discharge. Practical solution of this problem has been the objective of the present investigation.

Discharges with Liquid Electrodes and Basic Diagrams of Plasma Generators. For the sake of brevity, a porous dielectric impregnated with electrolyte in the case of application of negative potential to the electrolyte will be called in what follows a porous electrolytic cathode (PEC), and in the case of application of positive potential to the electrolyte it will be called a porous electrolytic anode (PEA). We selected refractory material — chamotte brick with a porosity of ~60% — as the porous dielectric. The electrolyte was continuously pumped through the interior cavity of the porous electrode. The experiments have shown that the optimum thickness of a porous wall on the source side of the discharge region is 5 to 10 mm. A thick wall was poorly wetted, while a thin wall had through holes because of the inhomogeneity of the porous material. The structure of the porous electrode has been proposed in [8].

The discharge initiated between the PEC and the solid-state or liquid anode has a multichannel structure, i.e., the same structure as in the case where the cathode coupling is to be found on the free surface of a liquid electrolyte. This type of discharge has different names at present: "space vapor-gas discharge," "glow discharge" [10], and others.

When a PEA is employed, the discharge is formed with a small number of channels and it has a small geometric volume which is in an unstable position in the discharge gap. Therefore, the PEA is not a candidate for plasma generators.

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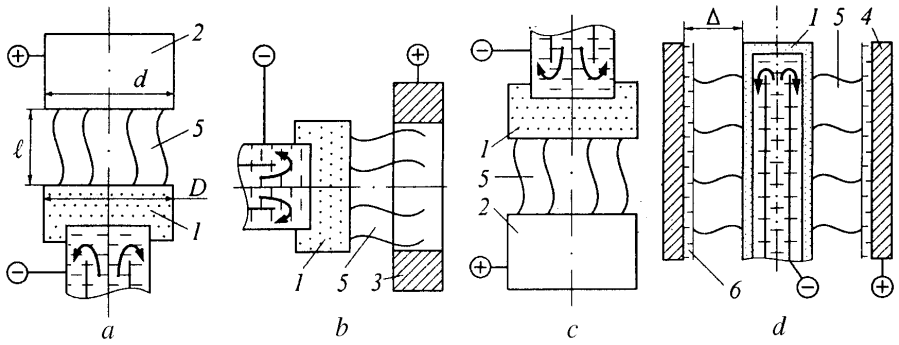


Fig. 1. Basic diagram of plasma generators: 1) PEC; 2) solid-state cylindrical anode; 3) orificed anode; 4) cylindrical current lead; 5) discharge region; 6) liquid anode.

A porous electrolytic cathode brings about a substantial novelty in the basic diagrams of plasma generators with liquid electrodes. With such a cathode one can produce a discharge and sustain it with all kinds of orientations of the plasma column in space (Fig. 1).

Devices containing a PEC and an orificed anode represent a linear-type plasma generator (Fig. 1b). Plasma jets tens of centimeters long in all spatial directions have been formed, with the use of these devices, from electrolytes containing easily ionized alkaline metals (sodium, potassium, etc.) [11].

For the upper arrangement of the PEC (Fig. 1c) the liquid in the electrolytic bath can be used as the lower electrode (anode). The method of initiation of a discharge between two liquids ("liquid-to-liquid" discharge) was implemented in such a variant [12]. To keep the electrolyte from dropping down one creates a small rarefaction inside the PEC cavity. Electrolytes employed as liquid electrodes can have different chemical compositions. This enables one to compare the influence of the composition of the cathode and the anode on the characteristics of the liquid-to-liquid discharge.

Another variant of "liquid-to-liquid" discharge was realized in a coaxial plasma generator [13] (Fig. 1d). In this case, the liquid film 6 on the surface of a graphite cylindrical current lead 4 acted as the anode. The film was produced by tangential supply of the electrolyte. The minimum size of the radial gap Δ between the central electrode (PEC) and the external current lead was 5 mm. Units for separate supply and discharge of electrolytes were provided in the casing manufactured from dielectric materials. The plasma generator operated in the vertical position.

The solid-state metal anodes of all plasma generators were massive and had fairly large dimensions. This made it possible to do without forced cooling. Copper, steel of various grades, and other metals were used as the anode material. Gray-cast-iron anodes turned out to be the least prone to oxidation.

Experimental Setup. We carried out investigations on a setup whose diagram is given in Fig. 2 (the plasma generator is shown as the dashed contour). The generator was energized from the constant-current source 1. To protect the plasma generator against accidental current jumps we employed the ballast resistor 2 with variable electrical resistance.

The gas discharge in the plasma generator presented belongs to the "liquid-to-liquid" type. Electrolyte *A* in the bath 3 with a current lead 4 is used as the anode. The other electrolyte *B* is supplied to the interior cavity of the PEC from the vessel 6 using the hydraulic pump 5. The interior cavity is formed by the metal current lead 7 and the porous cathode body 8. Part of the electrolyte *B* penetrates down via the porous wall, evaporates under the action of the gas discharge 9, and forms plasma.

Joule heat is released inside the porous body of the cathode 8. Thermal energy also comes from the gaseous discharge. The entire heat coming into the porous body is removed by pumping electrolyte *B* through the PEC. Electrolyte *B* can arrive at the working surface of the cathode in excess, i.e., far in excess of the amount that will manage to evaporate under the action of the gaseous discharge. Such an excessive arrival of the electrolyte is undesirable, since it results in the closure of the discharge gap by an electrolyte jet and the gaseous discharge decays. For other arrangements of the PEC in space, excessive penetration of the electrolyte through the porous body will require additional measures aimed at collecting the electrolyte flowing from its surface.

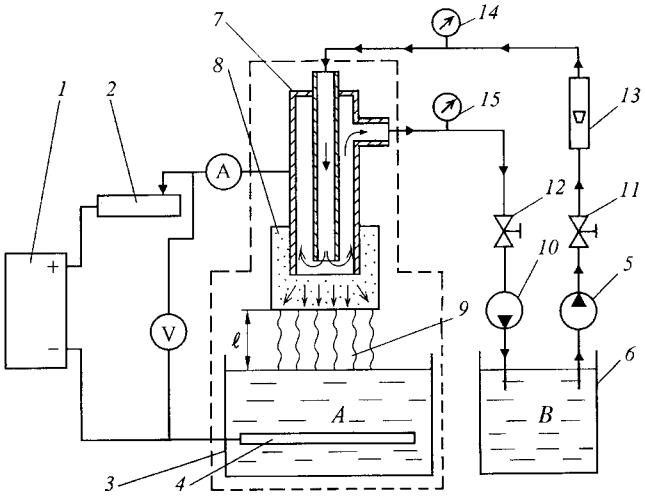


Fig. 2. Basic diagram of the experimental setup ("liquid-to-liquid" discharge).

To keep the electrolyte from flowing out in excess through the porous body we compulsorily remove it from the interior cavity of the PEC using the hydraulic pump 10. The flow rate of the electrolyte *B* is set using vents 11 and 12 in accordance with the operating regime of the plasma generator. We monitor the flow rate of the electrolyte with the use of rotameter 13, pressure gauge 14, and vacuum pressure gauge 15.

Measurement Procedure. The current I and the voltage U_g on the plasma generators were controlled by changing the output voltage of the power supply within 0–4500 V and stepwise variation of the electrical resistance of the ballast resistor from 0 to 2000 Ω. The voltage U_g was measured by an M2016 pointer-type instrument (accuracy class 0.2) with additional resistors, while the current I was measured by an M2015 pointer-type multirange instrument of the same accuracy class. The current and the voltage were recorded simultaneously by a PDP4-002 two-coordinate potentiometer.

The value of U_g is made up of the voltage in the discharge gap U and the voltage drops U_a and U_c on the liquid electrodes. We measured U_a and U_c inside the PEC in the electrolytic bath by the electrode-contact method in the absence of a gaseous discharge.

Because of the fact that it is impossible to change the mutual position of the electrodes of the coaxial plasma generator we manufactured for it a special auxiliary electrode in the form of a thin-walled metal cylinder with an inside diameter equal to the diameter of the porous element. We installed it at the site of the PEC surface where the cathode coupling of the discharge was observed and connected it to the positive pole of the power supply. In this case, the value of U_c is equal to the voltage between the auxiliary electrode and the PEC. In view of the small thickness of the liquid electrolyte film (Fig. 1d), U_a on the coaxial generator is much lower than U_c; therefore, in determining the discharge voltage I in such a generator, we disregarded U_a.

The heat loss Q_{loss} by the PEC was determined by the calorimetric method. The temperature and the head of the electrolytic flow at the inlet to the cathode cavity and the rarefaction at the outlet from the cathode cavity were maintained constant in the experiments. The outlet pressure was within $(1.1–1.5)\cdot10^5$ Pa in accordance with the operating regime of the plasma generator, while the rarefaction at the outlet from the PEC cavity was $(0.95–0.8)\cdot10^5$ Pa.

In the experiments on measuring the mass velocity $\dot{m}$ of evaporation of the electrolyte, the vessel 6 with liquid *B* (Fig. 2) was hermetically closed. The generator operated first at a current of the order of 2 A for 10 min. Over this period, the pH value of the electrolyte was stabilized and it changed insignificantly thereafter. In this manner we attained a constant electrolytic conduction in the experiments. The pH value and the initial temperature of the electrolyte were equal in all cases.

The heat flux from the discharge plasma to the cathode was calculated from the formula

$$Q_c = Q_{loss} - Q_J + Q_{ev}\,.$$

To study the temperature distribution in the plasma flow we used a PR-30/6 thermocouple with a diameter of the thermoelectrodes of 0.4 mm and a PDP4-002 potentiometer.

TABLE 1. Limiting Discharge Gaps

Electrolyte	l_{max}, mm	
	liquid cathode	PEC, D = 40 mm
	"Glow discharge"	
Tap water	12–13	27
$CuSO_4$ 0.5%	5	7
KOH 0.2%	5	13
NaCl 0.05%	8	15
NaCl 0.5%	5	30
NaCl 1.0%	Not realized	26
NaCl 2.5%	»	12
NaCl 3.0%	»	Not realized
	Mixed regime	
Tap water	16	46
$CuSO_4$ 0.5%	20	45
KOH 0.2%	18	70
$NaHCO_3$ 0.5%	20	150
NaCl 0.05%	20	45
NaCl 0.5%	20	200
NaCl 1.0%	20	160
NaCl 3.0%	20	170

Tap water and aqueous solutions of common salt, sodium bicarbonate, copper vitriol, and caustic potash were employed as the electrolytes. The characteristics of plasma generators with a PEC were obtained in the range of currents from 0.5 to 5.0 A. For the sake of comparison, we determined the characteristics of a discharge between a liquid cathode and a metal anode for the same current and with the same electrolytes. The liquid cathode represented an electrolyte in an open vessel with a current lead.

Basic Results of the Experiments. We are able to maintain a discharge between the metal anode and the liquid cathode at interelectrode distances no larger than 20 mm (see Table 1). The employment of a PEC makes it possible to substantially increase the discharge gap. Table 1 gives the values of the maximum length of the discharge gap l_{max} for the PEC, which were obtained in vertical burning of the discharge according to the scheme of Fig. 1a. As is seen, l_{max} depends on the chemical composition of the liquid electrolyte. For brevity of representation, the name of an electrolyte is given here by the formula of a chemical agent and the numerical value of the mass concentration of a solution. Such a notation of the electrolyte will also be employed thereafter.

A significant increase in l_{max} is observed for electrolytes prepared from the salts of alkaline metals and alkalis. This effect occurs only in the case of weakly concentrated solutions. The maximum value of the discharge-gap length, equal to 200 mm, was attained when we employed a solution of common salt in tap water, whose mass concentration amounted to 0.5%. The increase in the mass concentration of NaCl above 3% led to a sharp reduction in l_{max}. The spatial structure of the discharge simultaneously changed: the discharge was switching to an explicitly spark regime.

The regime "glow discharge" with a multichannel structure was observed for lower values of the discharge-gap length. In this regime, the discharge was burning uniformly and its volume increased with increase in the current; in the limit, the entire surface of either the cathode or the anode was covered with the discharge, depending on which of them had the smaller area of the end surface. For equal transverse dimensions of the electrodes their end surfaces were entirely covered with the discharge. The discharge volume increased due to the increase in the number of discharge microchannels. Further increase in the current led to a compaction of these microchannels; gradually, spark channels were formed in the discharge gap, i.e., the discharge switched to a mixed regime that is intermediate between the "glow" and spark regimes.

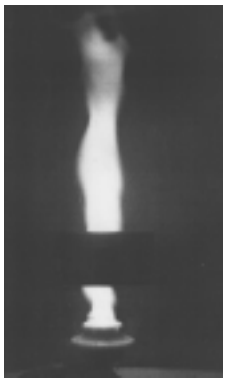


Fig. 3. Linear plasma generator in the operating condition. I = 3.5 A. The electrolyte is 0.5% NaCl. D = 40 mm.

In the case of the liquid cathode, evaporation occurs from the free surface of the electrolyte in an open vessel, whereas in employment of a PEC vapor is partially formed inside the channels of the porous body and the density of the vapor flow increases. Hydrogen released on the current-lead surface goes out through the porous body simultaneously with the vapor; therefore, the density of the flow increases still further. The vapor-gas mixture flows out of the channels of the porous body, picking up a rather high speed. Probably, it is precisely these factors that contribute to the realization of long discharge gaps.

The presence of the high-velocity vapor-gas flow is also confirmed by the fact that the discharge is burning at substantial interelectrode distances not only in the vertical direction but in the horizontal direction as well. The maximum horizontal discharge gap for the 0.5% NaCl electrolyte was 160 mm.

When the orificed anode in the plasma generator is located at a small distance to the PEC (Fig. 1b), coupling of the discharge channels to the electrode occurs on the interior surface of the orificed anode and the plasma flow passes through the anode's orifice almost completely. A long luminous flame is formed behind the anode in all spatial arrangements of the linear plasma generator. In Fig. 3, the plasma flow is directed upward. As is seen, the length of the flame is severalfold larger than the diameter of the working end of the PEC (it is at the bottom). The orificed anode (dark portion along the plasma jet) is made of gray cast iron and it is located at a distance D from the PEC. Its thickness is 45 mm, outside diameter is 100 mm, and inside diameter is 40 mm.

The discharge-gap voltage in all the investigated types of plasma generators is current-independent, in practice, in operation in the "glow discharge" regime. Certain features of the influence of the porous cathode body on U, when tap water is employed as the electrolyte, have been considered in [14]. We can generalize the results of measuring U for this case in the form

$$U = U_c + El\,, \tag{1}$$

where U_c = 650 V and $E = 8 \cdot 10^4$ V/m. It should be noted that water taken from a municipal water supply has been called service water in [14].

The independence of U from the current is also preserved for other electrolytes in operation of the generator in the "glow discharge" regime. Figure 4 gives results of measuring U in the case where the surface of the porous cathode body was entirely covered with discharge microchannels. Their number decreases with increase in l. Therefore, for the discharge to occupy the entire end surface of the cathode's porous body it is necessary to increase the current. As is seen in Fig. 4a (lines 1 and 5), for the 0.5% NaCl electrolyte, the corresponding value of the minimum current increases from 1.5 to 3 A with an increase from 5 to 40 mm in l. The number of discharge microchannels also decreases with increase in the concentration of the electrolyte. In this case, for the cathode surface to be entirely covered with discharge one also has to increase the current. Thus, for example, for l = 5 mm and with the solution of common salt employed, an increase from 0.5 to 1.0% in the mass concentration leads to an increase of 1.5 A in the corresponding value of the minimum current (line 1 in Fig. 4a). Such an influence of the electrolyte composition on the discharge confirms the fact that the higher the concentration of the electrolyte, the larger the number of easily ionizable alkaline-metal atoms arriving at the discharge region. The electrical conductivity of the medium in the discharge

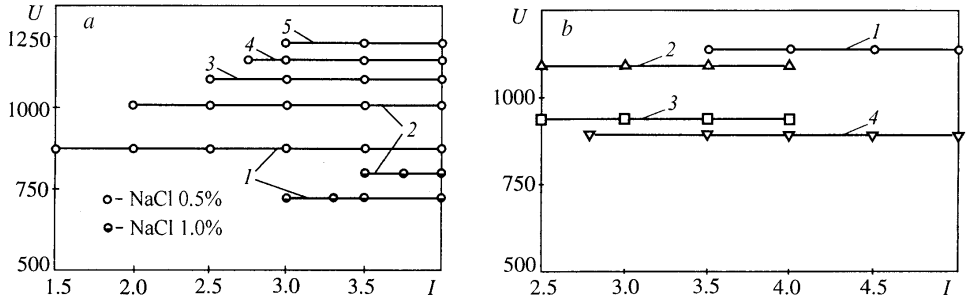


Fig. 4. Volt-ampere characteristics of the discharge with a PEC: a) vertical orientation: the cathode is at the bottom and the anode is at the top [1) l = 5, 2) 10, 3) 15, 4) 20, and 5) 40 mm]; b) vertical (1, 2, 3) and horizontal (4) orientations: the cathode is at the top and the anode is at the bottom (1); the cathode is at the bottom and the anode is at the top (2, 3) [1) l = 15 mm and 0.5% NaCl, 2) 10 mm and 2.0% KOH, 3) 7 mm and 0.5% $CuSO_4$, and 4) 5 mm and 0.5% $NaHCO_3$]. D = 40 mm, copper anode, and d = 30 mm. U, V; I, A.

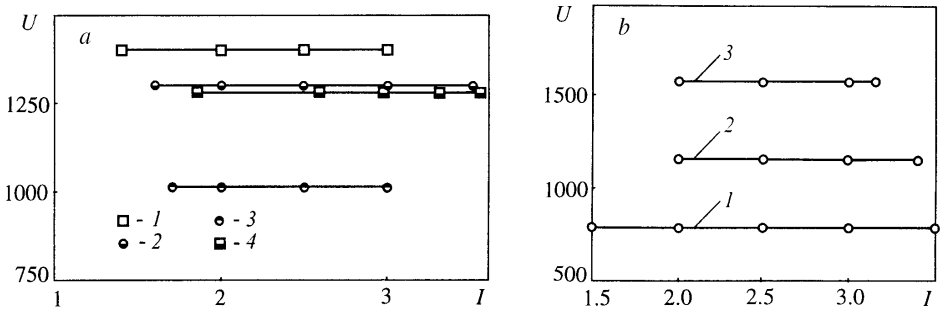


Fig. 5. Volt-ampere characteristics of the "liquid-to-liquid" discharge (the anode is at the bottom and the PEC is at the top): a) influence of the chemical composition of the electrodes: 1) D = 90 mm, l = 10 mm, cathode–anode: tap water–tap water; 2) D = 40 mm, l = 10 mm, tap water–0.5% NaCl; 3) D = 90 mm, l = 10 mm, 0.5% NaCl–tap water; 4) D = 90 mm, l = 10 mm, tap water–4.0% NaCl; b) influence of the interelectrode distance: 1) l = 5, 2) 10, and 3) 15 mm. D = 90 mm. Tap water – 0.2% KOH. U, V; I, A.

region increases and the current density in an individual discharge microchannel accordingly increases, which leads to a decrease in the total number of discharge microchannels.

As follows from Fig. 4 for l = 15 mm (0.5% NaCl), for the upper arrangement of the PEC the porous body is entirely covered with discharge microchannels at increased values of the current (line 1, Fig. 4b) as compared to the lower arrangement of the cathode (line 3, Fig. 4a). In this case, the reason is that, under the action of the upward convective heat flux, the porous cathode body is partially dried and the formation of discharge channels is hindered.

The above features of the PEC are observed in combined operation not only with a solid-state metal anode but with a liquid anode as well. Figure 5 gives results obtained in the "liquid-to-liquid" discharge with the use of an electrolytic bath as the liquid anode (precisely this variant is considered in Fig. 2). As is seen in Fig. 5a, the increase in the conduction of the liquid cathode and anode leads to a decrease in U. It may be inferred that the electrolyte vapor arrives at the discharge region on the source side of both electrodes. The vapor flow on the source side of the PEC is more intense than that on the source side of the electrolytic bath (anode). Therefore, U decreases much more rapidly with increase in the conduction of the cathode than in the case of an increase in the conduction of the anode. Line 1 has been obtained for the same compositions of the liquid electrodes: tap water. Line 3 corresponds to the cathode from a 0.5% NaCl solution, while plot 2 corresponds to the anode from the same solution. The decrease in U is ~400 V in passage from 1 to 3 and it is about 100 V in passage to 2. Thus, with increase in the anode conduction

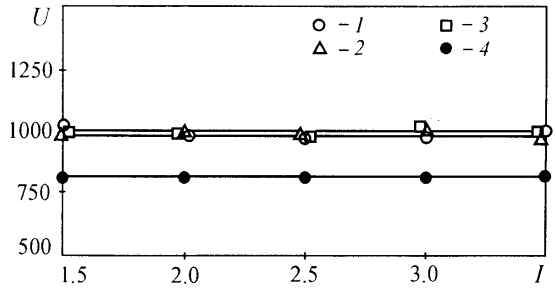


Fig. 6. Volt-ampere characteristics of the discharge in a coaxial plasma generator. The chemical composition of the anode is as follows: 1 and 2) tap water, 3) 0.5% NaCl, and 4) 1.0% $NaHCO_3$. The chemical composition of the cathode is as follows: 1 and 3) tap water, 2) 0.5% NaCl, and 4) 1.0% $NaHCO_3$. *U*, V; *I*, A.

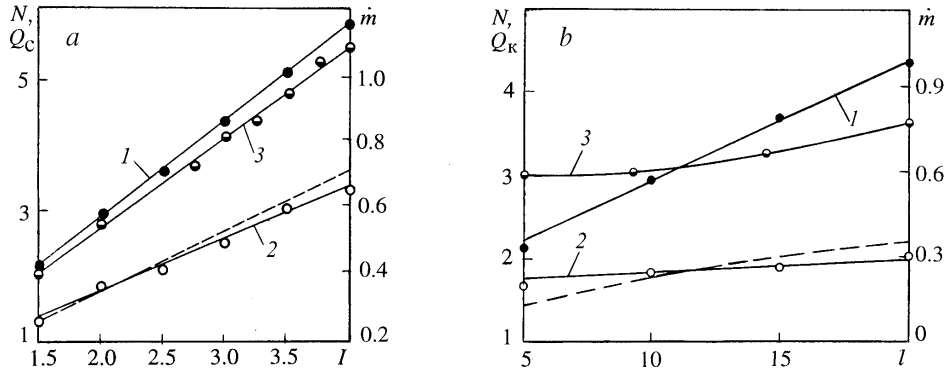


Fig. 7. Basic energy parameters of the discharge with a PEC vs. current for l = 10 mm (a) and length of the discharge gap at I = 2 A (b): 1) N; 2) Q_c; 3) $\dot{m}$, dashed line, calculation from the empirical formula (2). D = 90 mm. N and Q_c, kW; $\dot{m}$, g·sec^{-1}; I, A.

the effect of the produced influence on U is four times smaller than the effect produced for the same increase in cathode conduction.

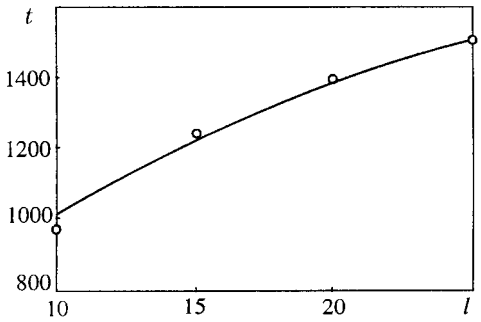
In the radial gap of the coaxial plasma generator, U weakly depends on the compositions of the liquid electrodes (Fig. 6). In this case, the liquid anode is flow-type, because of which the discharge microchannels continuously move and we have a partial splashing of the electrolyte employed as the anode. This is, apparently, the reason for the less substantial influence of the composition of the liquid cathode on U. An appreciable decrease in U is observed with simultaneous increase in the electrical conductivity of the two liquid electrodes, which is clear from a comparison of lines 1 and 4 in Fig. 6.

Investigations of the heat balance on the cathode have shown that the heat flux arriving at the cathode from the discharge in the case of employment of tap water as the electrolyte can be calculated from the formula

$$Q_c = 3.55 \cdot 10^3 \, Il^{0.3} . \qquad (2)$$

The disagreement between calculation and experiment is no higher than ±15%. It is remarkable that an analogous formula has been obtained in [15] for a liquid cathode at low currents and powers which are one order of magnitude lower than in the case in question.

The heat flux Q_c makes up a considerable portion of the discharge power. As is seen in Fig. 7a, when l = 10 mm, about 2/3 of the energy released in the discharge region goes into the liquid cathode. As the discharge gap increases, the fraction of Q_c in the heat balance of the discharge decreases (Fig. 7b). Consequently, as l increases, the discharge power is expended to a greater extent in heating the plasma in the positive column of the discharge. Since



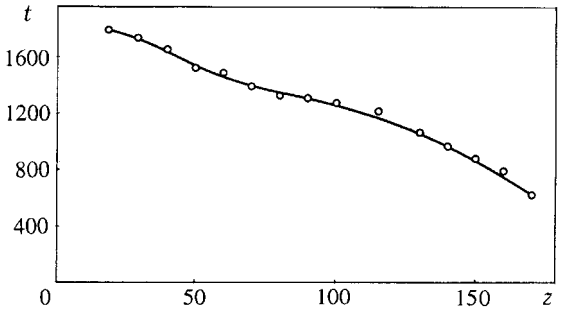


Fig. 8. Plasma temperature vs. discharge-gap length. I = 1.5 A, D = 90 mm, d = 65 mm, the anode is cast iron. The cathode is at the bottom and the anode is at the top. The thermocouple is at the center between the cathode and the anode. The electrolyte is tap water. t, ^{o}C; l, mm.

Fig. 9. Temperature distribution along the axis of the plasma jet flowing out of the linear generator in the vertical direction upward. I = 3.5 A. t, ^{o}C; z, mm.

the discharge is maintained from the PEC at significantly large interelectrode distances, one can attain higher temperatures of the plasma flow in generators with such a cathode than in those with a liquid cathode.

A portion of Q_c is removed from the cathode surface into the cathode by heat conduction, while the remaining heat is expended in evaporating the electrolyte and returns back to the discharge region with the electrolyte vapor. Thus, we have partial regeneration of heat removed from the discharge plasma to the cathode.

The mass velocity $\dot{m}$ of evaporation of the electrolyte increases in direct proportion to the current, as it increases (Fig. 7a), and changes insignificantly with increase in l (Fig. 7b). The heat flux Q_c also weakly depends on l (Fig. 7b). This results in the plasma temperature increasing in the discharge region with l (Fig. 8).

The results of measurements of the temperature of a jet flowing out of the linear generator confirm the heating of the plasma to comparatively high temperatures. As is seen in Fig. 9, the jet temperature remains higher than 1000^{o}C at a distance of 100 mm or more. These data hold true for the generator shown in Fig. 3.

CONCLUSIONS

The use of porous elements in the form of PECs in plasma generators with liquid electrodes substantially extends the possibilities of practical application of a nonequilibrium electrolytic plasma. The flows of the liquid-electrolyte plasma can be formed in all kinds of directions in space. The maximum length of a discharge gap significantly increases and attains 200 mm in the case of employment of the aqueous solution of NaCl with a mass concentration of 0.5%, which is one order of magnitude higher than in the gas-discharge devices "liquid cathode–solid-state anode." The power of the generators increases linearly with the discharge-gap length, while the heat flux to the cathode changes in proportion to $l^{0.3}$. Therefore, the increase in the discharge gap leads to the fact that the fraction of energy released in the positive discharge column increases in the total heat balance, and the plasma is heated more strongly. Thus, generators with PECs enable one to increase the mean-mass temperature of the plasma and the thermal efficiency by increasing the discharge gap above the limits realizable in gas-discharge devices with a liquid cathode.

NOTATION

I, current, A; U, discharge voltage, V; U_g, plasma-generator voltage, V; U_c, cathode-voltage drop, V; U_a, anode-voltage drop, V; E, electric field strength, V/m; N, discharge power, W; Q_c, heat flux to the cathode, W; Q_{loss}, heat loss on the cathode, W; Q_{ev}, power expended in evaporating the electrolyte, W; Q_J, power of Joule heat release, W; $\dot{m}$, mass velocity of evaporation of the electrolyte, g·sec^{-1}; l, length of the discharge gap, mm; D, diameter of the porous cathode body, mm; d, diameter of the solid cylindrical anode, mm; Δ, radial gap, mm; t, plasma temperature, ^{o}C; z, coordinate along the plasma jet at the generator outlet, mm. Subscripts: c, cathode; a, anode; loss, loss; J, Joule heat release; ev, evaporation; g, generator; max, maximum.

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