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TRANSFER PROCESSES IN LOW-TEMPERATURE PLASMA

ON THE INTERNAL GAS DYNAMICS AND EFFICIENCY OF A VORTEX WATER-VAPOR PLASMA GENERATOR

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Results of experimental investigations of a new-type generator of an arc water plasma, having a high thermal efficiency close to 100%, are presented. This generator represents a system comprising a vortex arc plasma generator, in which an electric arc is stabilized by water vapor and a straight-through-flow tubular electric steam generator. Such a high efficiency of the plasma generator system was achieved due to the refinement of the internal gas dynamics of the plasma generator and the heat and mass transfer in its discharge channel as a result of the improvement of the vortex stabilization and thermal insulation of an arc discharge in it by the specially organized "instantly permeable" channel wall cooled by only the working water used for generation of the plasma.

Keywords: *vortex water-vapor plasma generator, arc plasma, vortex stabilization.*

Introduction. A water plasma representing a mixture of hydrogen and oxygen atoms and molecules and their derivatives is a very promising substance for many technological applications. There exist two main concepts on the design of water plasma generators: an arc discharge in them can be stabilized by liquid water or by water vapor. The first concept was developed to advantage in the Czech Republic, and it has found a notable market application [1]. The second concept was developed in many organizations and countries. The most comprehensive and successful studies on this subject were conducted by B. I. Mikhailov at the Institute of Thermophysics of the Siberian Branch of the Academy of Sciences of the USSR [2, 3]. However, the results of these investigations have not gained sufficient market recognition because of the specific features of the plasma-forming substance (water vapor), due first of all to its high condensation temperature.

The chief drawback of the stabilization of an arc discharge in a plasma generator by water is the noncontrolled evaporation of water and the inevitable losses of a large amount of heat that is removed with the water used for stabilization of the discharge, because these losses reduce the efficiency of the generator to the typical level of about 60% [1]. At the same time, the use of the vapor obtained as a result of the controlled evaporation of water instead of water for stabilization of an arc discharge in a plasma generator theoretically makes it possible to increase the efficiency of the generator to 100% if one and the same amount of water is used initially for cooling of the generator and then for generation of a plasma in it. According to B. I. Mikhailov [2, 3], the main impediment here is the high condensation temperature of water, due to which water condenses inside the plasma generator, in particular on its water-cooled parts, with explosive transformation of the superheated water drops into vapor, which rapidly destroys the electrodes and the plasma generator as a whole. Moreover, in attempting to generate vapor in the water flow in the cooling jacket of a plasma generator or in the straight-through-flow tubular steam generator forming its part, it was impossible to prevent the separation of this flow into individual drops, and these drops also overheated, exploded, and, in so doing, disturbed the vortex stabilization of an arc discharge in the plasma generator and destroyed it. For suppression of the pulsations in a plasma generator, caused by the indicated effect, B. I. Mikhailov used capillary filling of its cooling jacket; however, this technique made the fabrication of the generator more difficult and increased its cost. He has designed an "auto-plasmatron" with generation of vapor directly in its cooling jacket.

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However, even with this improvement, the range of working regimes of the plasma generator was very narrow and was limited, on the one hand, by the condensation of vapor on the electrodes, if they experienced a low current, with their destruction and, on the other, by the destruction of the electrodes, if they experienced a high current, because of their overheating. For this reason, water-vapor plasma generators are practically not in demand in the market, and the problem on the development of an economically efficient water plasma generator remains to be solved. Even, if the operation conditions predetermined for such a generator are fulfilled, the service life of its copper anode is approximately equal to that of an air plasma generator (as large as 300 h) [3], and the efficiency of the generator is 82–87% [2, 3].

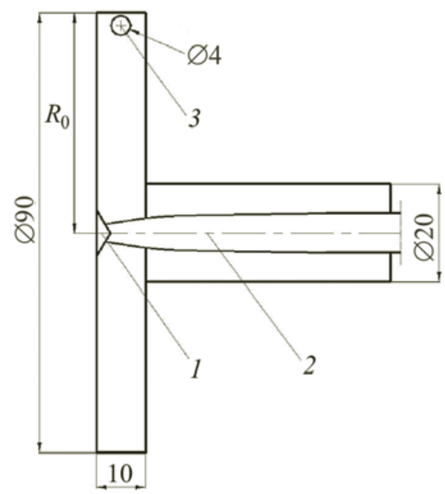
Many researchers proposed to increase the efficiency of a plasma generator with the use of a distributed discrete blow of a gas into the discharge channel of the generator through a large number of swirlers positioned along its axis or with the use of a continuous blow of a gas through the porous wall of the discharge channel of the generator [4]. The first method makes it possible to achieve an efficiency of 85–90% [5] even at a high pressure (as high as 3.5 MPa), and it has found application mainly in cosmic research for the production of modern powerful heaters for hypersonic wind tunnels [6]. However, this method is very expensive for wide use in industry. A theoretical analysis has shown that, in the case of blow of a gas into the discharge channel of a plasma generator through its porous wall, the efficiency of the generator can reach 100% [7]. However, it was established in the process of comprehensive investigations of the indicated effect that the porous wall of the discharge channel of a plasma generator is an active turbolator of the gas blown into it, which substantially increases the voltage–current ratio of the discharge channel and, consequently, the power of the arc discharge in it but decreases the reliability of the discharge channel and increases the requirements for its electric insulation. In the case of intensive blow of a gas into the discharge channel of a plasma generator, an arc discharge in it is divided into a large number of nonstationary conductive channels, with the results that a molecularly nonequilibrium plasma is generated in it even at a high pressure. This is why such discharges were investigated only for the formation of an inverse medium in experimental laser setups but not in plasma generators. In the generalizing work [4], the necessity of wider use of the indicated discharges was substantiated. In this connection, it would be especially valuable to combine the advantages of the transpiration cooling of the discharge channel of a plasma generator with the vortex stabilization of an arc discharge in it. In the work [8], it is proposed to swirl a gas flow in the discharge channel of a plasma generator by formation of an oriented porosity in it. In the work [9], a porous interelectrode insert with tangential guide vanes, capable of operating in a stable regime at a voltage across a discharge lower by 15–20% as compared to the usual one, was developed and tested. However, this insert is very difficult to fabricate and, therefore, was not brought to technological completion in the difficult restructuring years 1984–1988.

Formulation of the Problem and Substantiation of the Investigation Direction. The main objective of the present work is to increase the effective efficiency and the thermal efficiency of a water-vapor plasma generator to maximum values by improvement of the vortex stabilization and thermal insulation of the arc discharge in it in the case where one and the same amount of water is used for generation of a plasma and for cooling of the generator as well as to decrease the cost of the plasma generator with the use of inexpensive members and materials in it. Theoretically, the efficiency of the discharge channel of a plasma generator can be maximized in the case where only the heat lost in the electrodes, which cannot be isolated from the conducting plasma, are not compensated. On the hot surface of the electrodes forming a part of a plasma generator, such as a plasmatron-reactor with renewable molten electrodes, there can take place plasma-chemical reactions increasing the efficiency of the plasma generator. Such a plasmatron-reactor is also considered in the present work.

A diagram of a conventional vortex arc plasma generator with an end electrode is shown in Fig. 1. This design of a vortex arc plasma generator is not perfect from the standpoint of optimization of its gas dynamics. Traditionally it is assumed that the gas flow in the vortex chamber of a plasma generator is quasi-potential and rotates with a velocity whose tangential component increases progressively with decrease in the radius of rotation [10]:

$$v_{\varphi}R^{n} = \text{const}, \quad n \le 1. \tag{1}$$

However, detailed investigations of "short" swirl chambers (of small axial extent as compared to their diameter), typical for plasma generators, by nondisturbing laser-anemometry methods have shown that relation (1) is fulfilled unconditionally only for limited ranges of operating parameters and sizes of these chambers, namely, in the case where the dimensionless criterion of "potential" interaction of the gas in such a chamber with the boundary layer in it $A \le 3$. This criterion was proposed in the work [11] for definition of the operation of vortex switching devices and was used in the works [12–14] in a form modified for the swirl chambers of plasma generators:



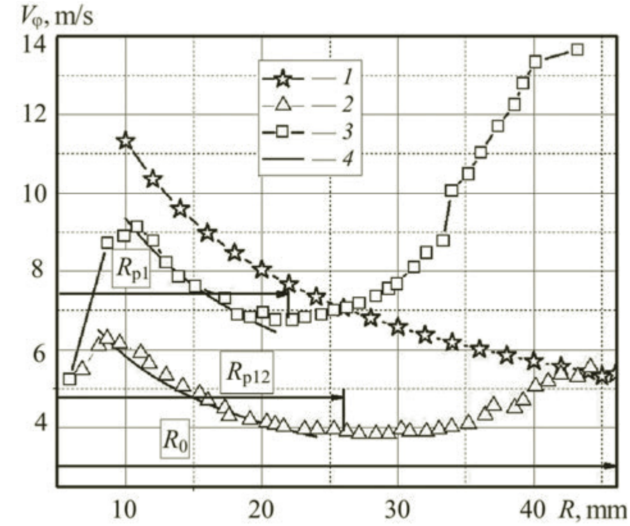


Fig. 1. Diagram of a plasma generator with a swirl chamber and an end cathode: 1) cathode; 2) electric arc; 3) opening of an inlet tangential conduit. The anode is not shown.

Fig. 2. Profile of the tangential velocity of the air flow in the swirl chamber of a plasma generator at a flow rate of 0.5 g/s: 1) calculation by the "ideal" formula (1) for 12 conduits; 2) measurement by a laser anemometer for 12 conduit; 3) measurement by the laser anemometer for one conduit; 4) approximation by (1)–(8) within the limits from R_p to r.

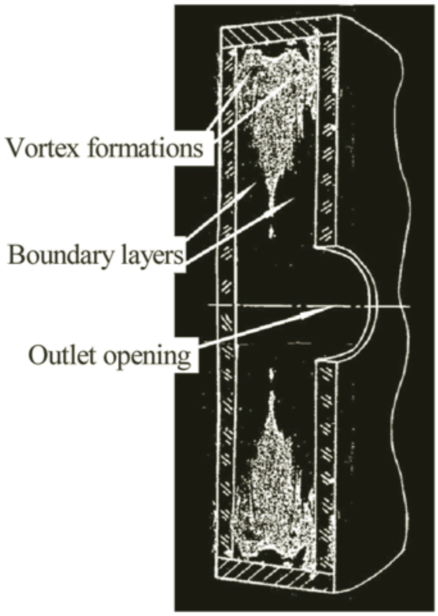
$$A = \frac{1.68 R_0^2}{\mathrm{Re}^{0.2}\ F}\ \varepsilon^{0.8}\ . \tag{2}$$

The main part of the criterion A is the geometric characteristic of the swirler in a plasma generator R_0^2/F, whose values for different plasma generators differ by more than an order of magnitude. The rate of the gas flow in a plasma generator also influences the criterion A: this criterion increases with increase in the gas-flow rate. If $A \le 3$, potential rotation of the gas in the swirl chamber of a plasma generator begins immediately from its peripheral radius R_0; otherwise this rotation begins from any radius of the potential zone $R_p < R_0$, and the whole periphery from R_0 to R_p is occupied by closed circulation flows similar to the Görtler pair of vortices [15]. In this zone, the tangential velocity of the gas flow remains unchanged in the case where $3 < A < 4$ or decreases with decrease in R_p when $A > 4$. Only beginning from $R_p < R_0$ does the potential rotation of the gas proceed in accordance with law (1), which is demonstrated in Fig. 2 where the profiles of the tangential velocity of the gas flow in the swirl chamber of a plasma generator (Fig. 1), determined for the cases of one and 12 inlet tangential conduits of cross-sectional area 6 mm^2 each in it, are presented. The "potential" profile calculated for the case of one inlet conduit is not shown in Fig. 2 because it is far beyond the limits of this figure.

Figure 3 shows a visualization of the gas flow in the swirl chamber of a plasma generator, obtained with the use of a laser cutter [12, 13]. The chamber was previously filled with smoke, and then a pure air was supplied into it. Initially the peripheral and both boundary layers near the ends of the side walls of the chamber were clarified, and the smoke in the central plane of the chamber remained during 10–15 s, which provided possibilities for photographing. In the photograph in Fig. 3 we can see closed vortex formations with a limited mass exchange, similar to the Görtler vortices [15]. The radius of the potential vortex core was determined at the site of disappearance of smoke, where the boundary layers near the wall ends close. The results of measurements of the radius R_p depending on the criterion A were generalized in the form of the empirical relation [12–14]

$$R_p/R_0 = (1.16/(A - 1.2) + 0.36) \le 1\ . \tag{3}$$

The velocity of rotation of the gas at the radius R_p was defined taking into account the coefficient of losses in the velocity of the gas flow at the input of the chamber and the losses in the velocity of the gas flow in the peripheral vortices:



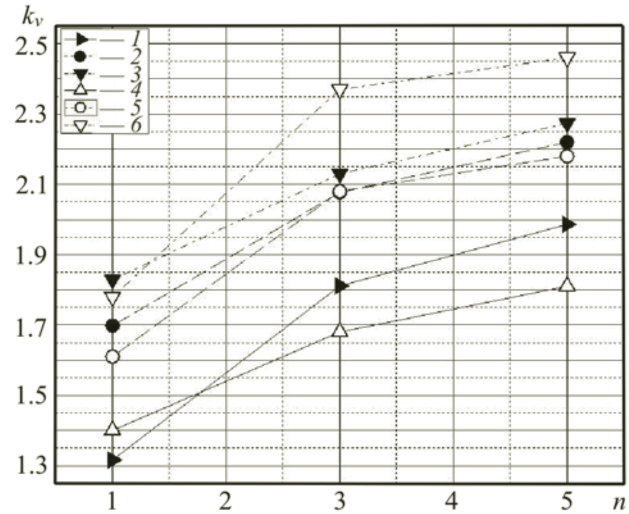


Fig. 3. Visualization of the circulation flows in the central plane of the swirl chamber of a plasma generator with the use of a laser cutter.

Fig. 4. Dependence of the swirl gain of the gas flow in the swirl chamber of a plasma generator on the number of inlet openings in it at a gas flow rate of 1(1, 4), 3 (2, 5), and 5 g/s (3, 6): 1–3) calculation by (1)–(8); 4–6) numerical simulation in [17].

$$v_p = \varepsilon v\left[0.08 + 4.69/(A + 1.08)\right] \text{ for } A \geq 4\,, \quad v_p = \varepsilon v \text{ for } A < 4\,. \tag{4}$$

The coefficient of the losses in the input flow velocity was determined by the empirical Rudnitskii relation [16]:

$$\varepsilon = 20\left[F/(2\pi R_0 H)\right]^{0.68}\,, \quad \varepsilon \leq 1\,. \tag{5}$$

The rotation of the gas in the space between the radius of the potential vortex core R_p and the electrode radius r, i.e., before it enters the plasma generator, was defined in accordance with (1), and the tangential velocity of the gas flow at the input of the plasma generator was determined from the relation

$$v_r = v_p(R_p/r)^n\,, \quad n < 1\,. \tag{6}$$

In this case, the exponent n was represented in the general form as a function of the local value of the potential criterion A_p at the radius R_p [14]:

$$A_p = 1.68 v_p R_p^2 \rho P/(\mathrm{Re}_p^{0.2} G)\,, \tag{7}$$

$$n = k_n\left\{\log\left[G/(2\pi\mu H A_p)\right]\right\}^{0.38} - 1\,, \quad n \leq 0.8\,, \tag{8}$$

where k_n is an empirical coefficient.

At present there are no analytical methods that would make it possible to calculate the detected deviation of the tangential velocity of the gas flow at the periphery of the swirl chamber of a plasma generator from the ideal profile. This deviation substantially influences the internal gas dynamics of the plasma generator and its energy characteristics formed in the process of heat and mass transfer between the vortex flow and the electric arc in it. In addition to experiments, the most accessible tool for investigating the behavior of the gas flow in the swirl chamber of a plasma generator is numerical

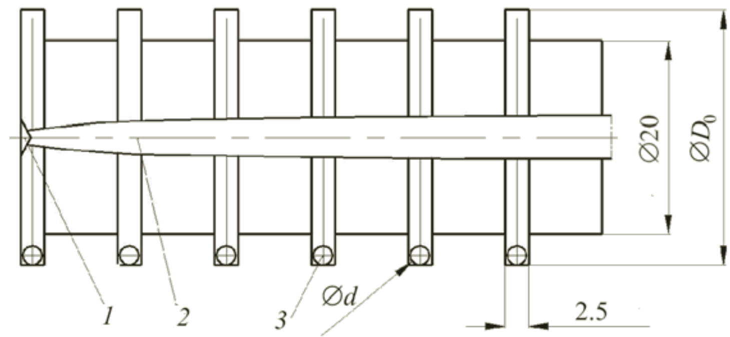


Fig. 5. Diagram of a plasma generator with a distributed gas blow at d = 1.5 mm: 1) cathode; 2) electric arc; 3) inlets.

simulation of this flow with the use of known program packages, e.g., the ANSYS package. The patterns of such gas flows and the profiles of their tangential velocities, constructed in the work [17] with the use of the indicated method, are very similar to those measured in experiments conducted in the works [12, 13]. Because of this, we compared the empirical approximations obtained in the works [12–14] with the results of the numerical simulation performed in the work [17]. Such a comparison is shown in Fig. 4 where calculated and experimental dependences of the twist gain of the gas flow at the input of the electrode in a plasma generator on the rate of the gas flows in the inlet tangential conduits of its swirl chamber are presented. It is seen from this figure that the results of calculations by formulas (1)–(8) agree satisfactorily with the corresponding experimental data if the coefficient k_n in relation (8) is somewhat corrected with respect to the exponent n in formula (1), i.e., in the case where $k_n = 1.05$ is used instead of $k_n = 1.14$ [14]. Therefore, the above formulas with this correction can be recommended at least for the primary optimization of the internal gas dynamics of a vortex plasma generator.

The indicated optimization is especially important for plasma generators with a vortex gas blow distributed along the length of their discharge channel. A diagram of such a generator is shown in Fig. 5. In this generator, it is necessary to provide an intensive swirl of the gas flow along the whole length of the discharge channel even in the case where the gas flow rate in it is small, the size of the discharge channel is small, and the swirlers are positioned at a small distances from each other. Of prime importance here is decreasing the diameter of the inlet conduits to the extent providing a direct blow of a gas into the discharge channel with no diaphragm or to a minimum value in the case of inflow of a gas into the discharge channel through diaphragms (introduction of a vortex flow with a radius larger than the radius of the discharge channel). We will call the ratio between the radius of the inlet for introduction of a gas flow into a plasma generator and the radius of its discharge channel the degree of diaphragming of the generator δ.

Figure 6 shows a vortex water-vapor plasma generator with a distributed direct blow of a gas into its discharge channel with no diaphragms in the case where diaphragms are set only in the main swirler positioned between the electrodes [18, 19]. At $A \leq 3$, the potential vortex core is "adhered" to the outer radius of the swirl chamber and changes with increase in this radius. In this case, an increase in the degree of diaphragming of the swirl chamber leads to an increase in the swirl gain of the gas flow. At $A > 3$, on the contrary, an increase in this degree can cause a decrease in k_v because of the decrease in R_p. The degree of diaphragming is maximum at $A = 3$. Therefore, the use of very large swirl chambers is unreasonable. Multiple tangential openings in the wall of the discharge channel of a plasma generator are also not necessary for vortex stabilization of an arc discharge in it by distributed gas blow, because, instead of using these holes, a gas flow can be swirled easier in a multi-pass spiral conduit built in the outer wall of the discharge channel, and this conduit can be connected with the discharge channel through annular slots cut in the channel walls [20, 21]. In this case, windows are formed at the sites of intersection of the spiral conduits with the annular slots in the discharge-channel walls, and these windows fulfill the role of inlet tangential nozzles that transfer the tangential moment of a momentum from the spiral conduits to the annular slots acting as swirlers. A large number of such openings can be made in the wall of a discharge channel along its length for provision of distributed vortex blow of a gas into it. The degree of diaphragming of a vortex flow introduced into such a channel is determined by the thickness of its walls. In this case, the channel wall becomes instantly permeable and, therefore, allows the tangential moment of a momentum to be transferred together with the gas mass to the discharge channel. A diagram of such a discharge channel is shown in Fig. 7 [10, 21]. The wall of this channel is similar in its heat and mass transfer properties to a porous wall but the difference is that, together with the gas mass, the moment of a momentum can be transferred through it.

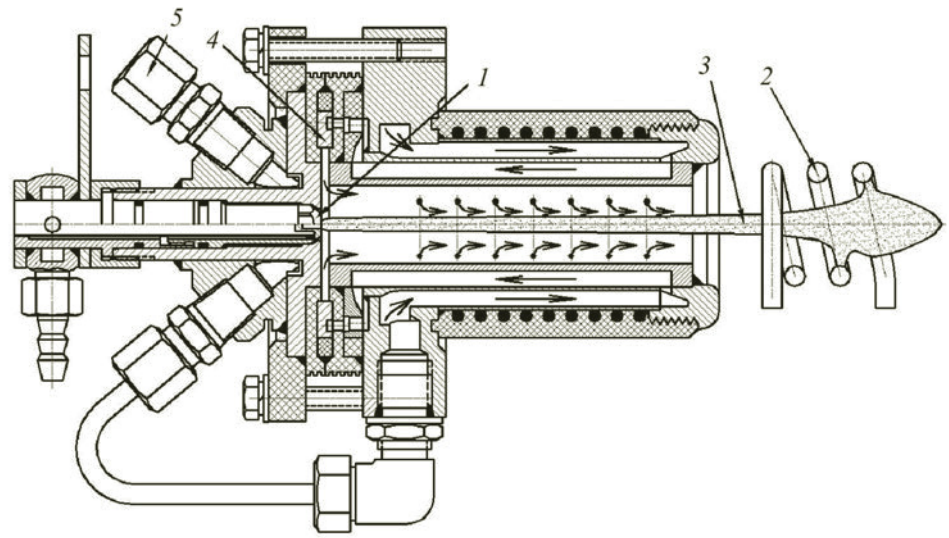


Fig. 6. Water-vapor W1 plasma generator with a distributed blow of a gas into its discharge channel with no diaphragms and with diaphragms only in the main swirler: 1) thermionic cathode; 2) external anode; 3) electric arc; 4) main swirler; 5) pipe connection for supply of vapor.

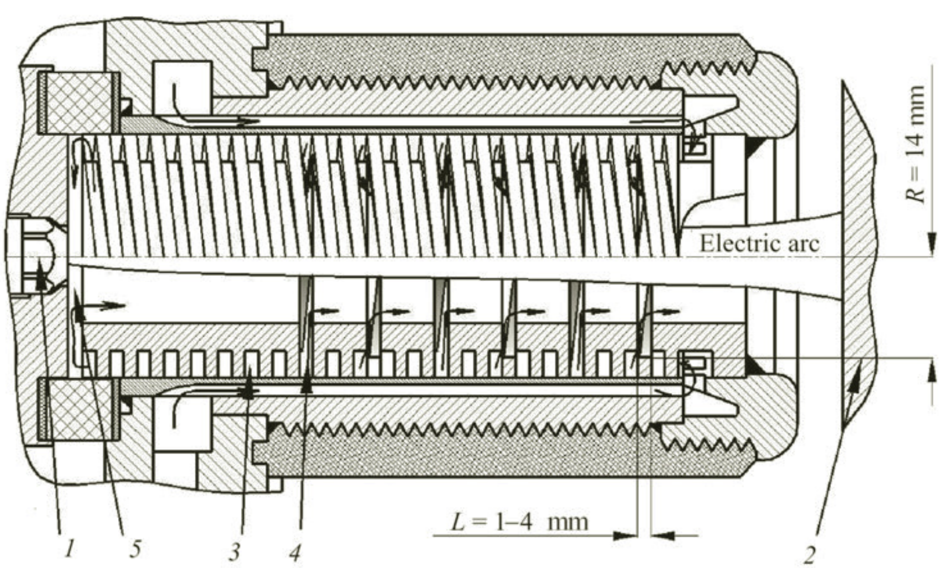


Fig. 7. Diagram of a vortex plasma generator in which the gas flow is swirled in an external spiral conduit and the arc is stabilized by the instantly permeable wall of the generator [20] at δ = 1.4 (14/10): 1) cathode; 2) anode; 3) spiral conduit; 4) vortex blow slots; 5) interelectrode space.

In a cylindrical discharge channel with an instantly permeable wall, this wall provides regeneration of the arc heat lost due to the radiation directed from the arc to the channel walls stabilizing the arc discharge due to the return convective transfer of this heat to the cooling air flow in the spiral conduits. In a discharge channel with a porous wall, this wall destabilizes an arc discharge in the case of strong blow of a gas into it. Quite the reverse, in a discharge channel with an instantly permeable wall, this wall enhances the vortex stabilization of an arc discharge, improves its thermal insulation, and, in so doing, increases the volume energy density of the discharge with retention of a high thermal efficiency of the discharge channel without recourse to the electrical insulation of the numerous swirlers as was done in the work [10].

Results of Experiments and Prospects for the Development of the Investigation Direction. Plasma generators with discharge channels, into which a gas is blown by the schemes corresponding to those of the plasma generators whose diagrams are shown in Figs. 6 and 7, were tested. Figure 5 shows a plasma generator of total efficiency about 80% [18] in which the discharge channel works with air without cooling by water. Such a channel was used to advantage in a steam plasma generator with a "penetrating arc," i.e., with an external anode [19], and it showed an efficiency higher than 97% with account of the heat lost in the thermionic cathode and without account of the heat lost in the external anode. The plasma generator shown in Fig. 7 [20, 21] has a more efficient system of gas blow compared to that of the plasma generator shown in Fig. 6, and, therefore it is more suitable for work as a part of a reactor due to the absence of large main swirler with a not heat-resistant cumbersome electrical insulation increasing the outer diameter of the plasma generator and, as a consequence, the heat losses associated with the introduction of it into the reactor and making this introduction difficult.

The plasma generators being investigated were tested in open air with the use of a water-cooled external anode representing a copper tube in the form of a solenoid (Fig. 6). The magnetic field generated by this solenoid increased the service life of the anode due to the displacement of the arc closures by the electromagnetic forces. In the case where these plasma generators were tested in combination with a reactor, an arc in them was initiated with the use of a base anode with an electrically conducting melt, as shown in Fig. 7.

As noted above, in the case of distributed blow of a gas into the discharge channel of a plasma generator, the rate of the gas flow in its swirl chamber and the degree of its diaphragming are substantially limited. It follows from formulas (1)–(8) that there exists an optimum solution for the provision of an efficient swirl of the gas flow in such a discharge channel. However, relations (1)–(8) can be used only for plasma generators with a short swirl chamber in which diaphragms are set, characterized by the ratio $H/R_0 < 1$, and they cannot be used for the case of distributed gas blow without diaphragms [18, 19]. Figure 8 shows the dependences of the swirl gain k_v of the gas flow in a plasma generator [19] on the parameters A and δ for the cases where the number of swirl-chamber openings is equal to 4–12. It is seen that the diaphragming is efficient only in the case where the area of the inlet for introduction of a vortex flow is fairly large, i.e., in the case where the number of swirl-chamber openings is larger than four. This means that, at a small rate of the gas flow in each swirler, a large number of disphragms and a small area of the vortex inlet become inefficient; however, this problem can be solved to a large measure with the use of a spiral slot blow of a gas into the discharge chamber of a plasma generator.

For rough estimates, the electrical analogy of hydrodynamics was used, and it was assumed that the gas flow upstream of each slot window is divided into two parts, one of which enters a window and the other enters a spiral conduit, and these parts are proportional to the flow areas of the window and the conduit to which the vector of the flow velocity is perpendicular. Since the directions of the velocity vectors of the flows in the windows are unknown, assuming that the radius of a spiral conduit is perpendicular to the area of a slot window, we prescribe a total pressure at the inlet of the spiral conduit and a static pressure at the side wall of the slot window. In this case, the rate of the gas flow in the spiral conduit after it passes through n swirl zones can be estimated by the formula

$$G = G_0 \left(1 - \frac{f_w}{F_{sp}} \frac{P_{st}}{P_0}\right)^n , \tag{9}$$

where f_w is the flow section of a window in the side wall of a discharge channel to which the channel radius is perpendicular, and F_{sp} is the flow section of a spiral conduit positioned at a right angle to its walls. According to Fig. 9, the swirl gain k_v of the gas flow in the discharge channel being considered increases with increase in the width of the slot windows and in the number of spiral conduits and reaches a maximum at $H \geq 2$ mm. This is explained by the fact that an increase in the width of the slot windows or in the number of spiral conduits leads to a decrease in the "potential" criterion A because of the increase in the area of the inlet F for introduction of a gas flow and causes it to approach an optimum value (Fig. 8a).

Many plasma-chemical technologies, including the processing of domestic and other organic wastes, are realized with the use of a water plasma having a temperature of about 300 K, which corresponds to a water enthalpy of about 18 MJ/ kg at atmospheric pressure. The energy necessary for efficient processing of solid domestic wastes was estimated on average at 1 kW·h/kg. This means that a plant with an output of 1 t/h requires a heat power of 1 MW, which corresponds to a vapor-flow rate in a plasma generator of about 55 g/s. A water flow with this rate is capable of providing a heat power of 130 kW in the case of its heating with evaporation from 100 to 200^{o}C. The efficiency of such a megawatt plasma generator should not be lower than 87%, which is provided with a reserve by our plasma generator system.

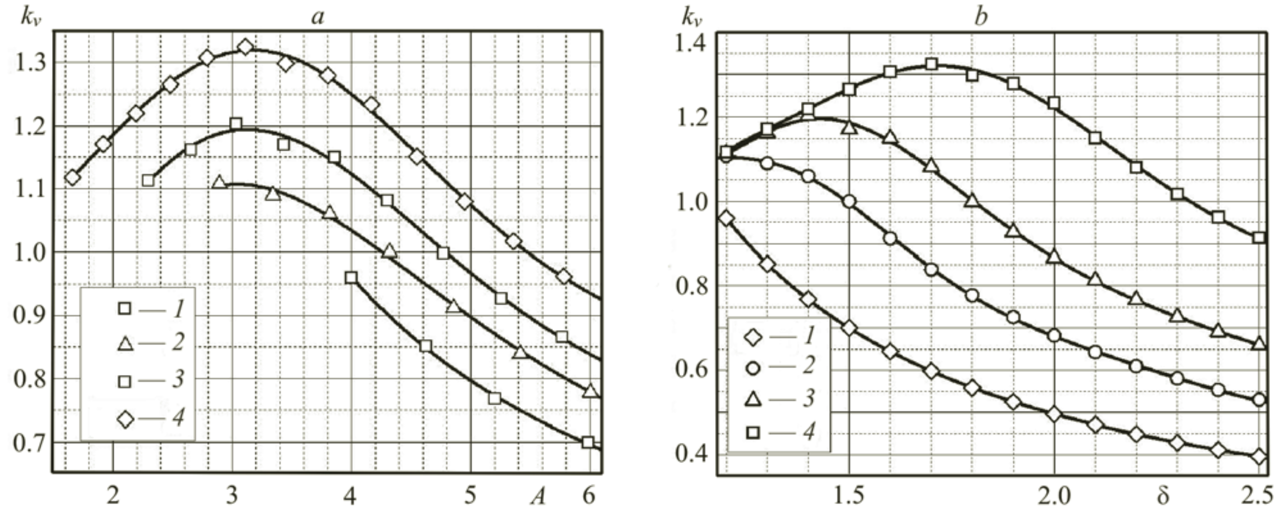


Fig. 8. Dependences of the swirl gain k_v of the gas flow in the plasma generator [19] on the boundary-layer interaction parameter A (a) and the degree of diaphragming of the swirl chamber δ (b) at $H = 2$ mm, flow rate 5 g/s, and $r = 10$ mm for the number of the swirl-chamber openings 4 (1), 6 (2), 8 (3), and 12 (4).

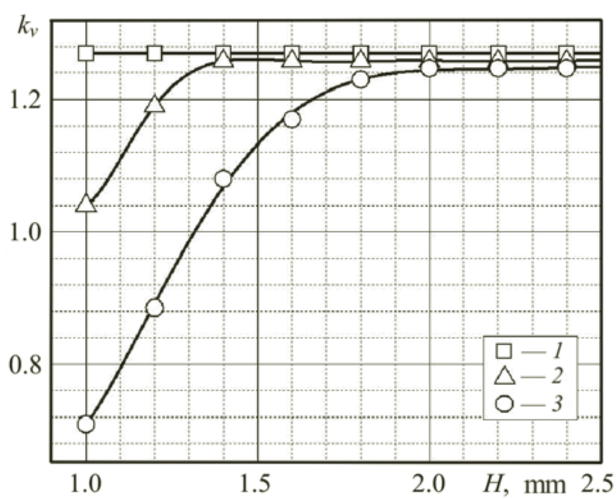


Fig. 9. Dependences of the swirl gain k_v of the gas flow in a plasma generator with a discharge channel with an external spiral swirler on the extent of the swirl chamber at $r = 10$ mm, $R_0 = 14$ mm, and a helix angle of 15^o for the cases where the number of spiral conduits is equal to 6 (1), 4 (2), and 3 (3).

Figure 10 shows the efficiency of a plasma generator with a slot discharge channel, determined by the results of measurements without account of the heat lost in the external anode and with account of the heat lost in the cathode. It is seen that the efficiency of this plasma generator exceeds 97%. This value can be used for calculating the mean-mass parameters of the plasma at the nozzle exit section of the generator, i.e., at the input of a reactor. If the water cooling the cathode is fed to the first stage of a steam generator, the efficiency of the whole plasma generator system will increase to 100%; however, the reasonability of this 2–3% of gain vs. complication of the design of the plasma generator should be estimated in each individual case. In Fig. 11, the generalized voltage–current characteristic of such a plasma generator at a vapor-flow rate of 2–4 g/s is shown, and, in Fig. 12, the mean-mass parameters at its nozzle exit section, determined by this characteristic, are presented.

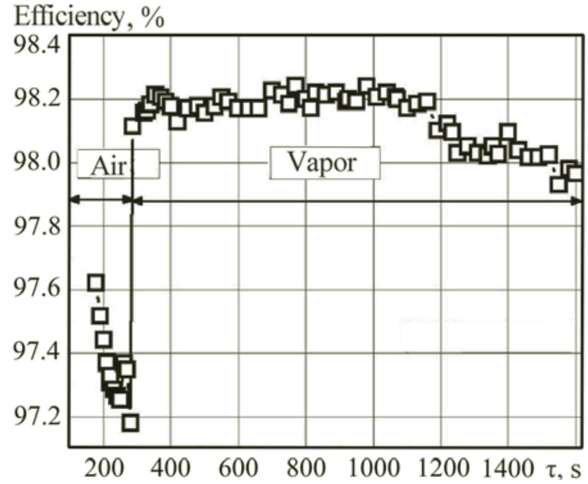
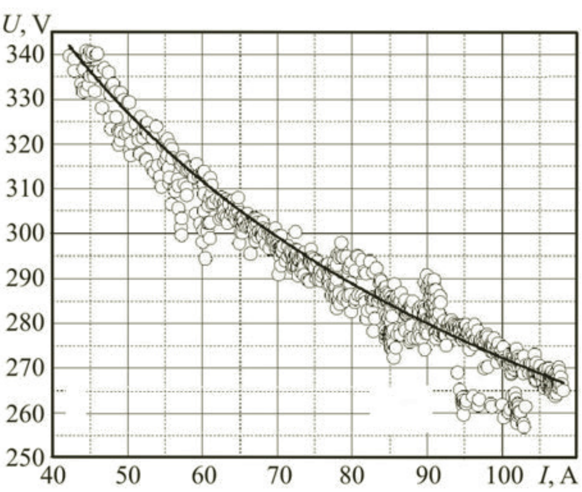


Fig. 10. Efficiency of a TS1 plasma generator in the cases of its operation with air and vapor at a gas-flow rate of 2.5 g/s.



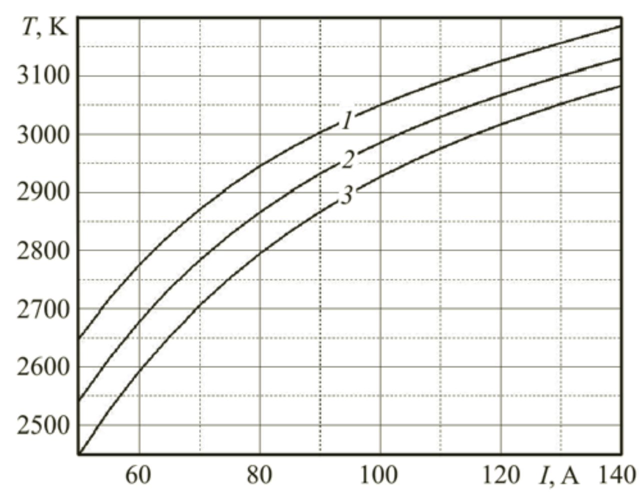


Fig. 11. Generalized voltage–current characteristic 1089(I2/Gd)–0.132(G/d)0.4L/d of the TS1 water-vapor plasma generator with a slot blow of a gas at a gas-flow rate of 2–4 g/s.

Fig. 12. Mean-mass temperature of the gas at the nozzle exit section of the TS1 plasma generator depending on the strength of the current carried by it at a vapor-flow rate of 2 (1), 2.5 (2), and 3 g/s (3).

Figure 13 shows time dependences of a plasma generator of power as high as 300 kW with a tungsten cathode having a conventional argon protection, measured in the process of its testing in combination with a reactor. It is seen that the temperature of the vapor at the output of the steam generator is equal to approximately 150^{o}C, and the temperature of the vapor at the input of the plasma generator is equal to approximately 120^{o}C. This is explained by the heat losses due to the heating of the feed pipeline, which should be taken into account in the regulation of the nonstationary regimes of operation of the plasma generator because of the appearance of hysteresis between the control signal and the temperature response to it at the input of the generator. For decreasing the time of control of the indicated regimes and improvement of the quality of this control in the process of testing the plasma generator in combination with the reactor positioned at a distance of 5 m or at a larger distance from the generator, an electrically conducting pipe in the form of a bellows with a wire braiding of a stainless steel was connected in series to the electrical circuit of the second stage of the steam generator. This made it possible to prevent the condensation of vapor and to drastically reduce the hysteresis between the signal for control of the temperature and the response to it. Such a plasma generator can work to advantage in both the cases of supply of an overheated dry vapor or a wet vapor into it.

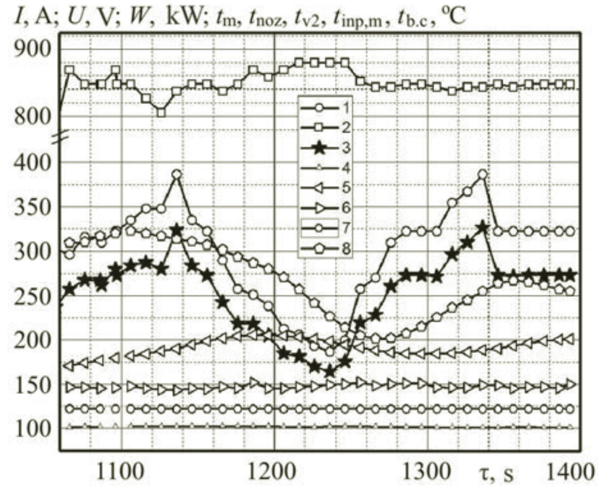


Fig. 13. Time dependences of the parameters of a TS2 plasma generator measured in the process of its testing in combination with a reactor: 1) current; 2) voltage; 3) power; 4) temperature in the intake manifold; 5) temperature in the nozzle; 6) temperature of the vapor in the second stage; 7) temperature of the vapor at the input of the manifold; 8) temperature of the body of the plasma-generator cathode.

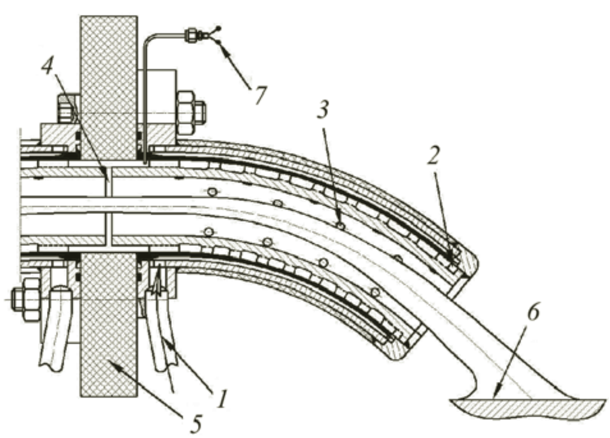


Fig. 14. Two-sided outflow plasma generator with molten electrodes (right half): 1) steam inlet; 2) nozzle; 3) tangential openings; 4) interelectrode space; 5) insulator; 6) molten electrode; 7) thermocouple.

In [22], a two-sided outflow vortex plasma generator with molten electrodes is described. In the case where a discharge channel working with steam and cooled by water is used in this plasma generator, its thermal efficiency, estimated without account of the heat lost in the electrodes, reaches 89%. Figure 14 shows a diagram of such a plasma generator working without water cooling and so having an efficiency, estimated without account of the heat lost in the electrodes and the heat transferred to the ambient air due to the free convection, close to 100%. It should be noted that a water-cooled plasma generator working in a reactor with an incandescent lining is potentially explosive in the case of water leakage. This effect is excluded for the plasma generator shown in Fig. 14 because water is absent in it, which is an additional merit of this plasma generator. Such a plasma generator is cooled only by a wet vapor whose temperature is measured by a temperature detector controlling the work of the steam generator [23]. The division of the discharge channel of the indicated plasma generator into two electrically insulated sections decreases the potential difference across the discharge channel and the arc by two times as compared to the plasma generator described in [22], which increases the resistance of this channel to an accident-related electrical breakdown from the arc to the channel wall. Moreover, this division of a plasma generator working in a hot reactor with molten electrodes ensures its easy restart, in the case of an accidental extinction of the arc in it, by conventional high-voltage initiation of an arc discharge without the depressurization of the reactor, which is dangerous if it works with harmful substances.

Conclusions. Experimental investigations of a vortex arc plasma generator with a discharge channel, analogous to a porous one, having the property of quasi-transpiration cooling, i.e., cooling by only the working gas or vapor blown through it and over the inside and outside surfaces of its walls without recourse to other external coolers, have shown that the merits of this plasma generator are its high thermal efficiency, reaching 100%, and high serviceability at a low cost of the generator provided by the use of inexpensive materials (a low-carbon steel), which are not in short supply, in it without recourse to nonferrous and less-common metals. The intensive vortex motion of the gas inside the discharge channel of the generator provides an effective reduction of the convective heat transfer from the arc to the channel walls, and the blow in the external spiral conduits provides the convective regeneration of the heat transferred to the channel walls due to the radiation and the residual convection and the return of this heat to the plasma, as in the case of blow through a porous wall. This channel substantially surpasses an analogous porous discharge channel in the cost and the energy consumed due to the vortex stabilization of an arc discharge in it and the enhanced thermal insulation of the discharge column, which increases the electric, thermal, and gasdynamic stability of the plasma generator at high flow rates of the working gas (this is especially important for powerful technological plasma generators) and, in combination with the molten electrodes, changed as they burn out, provides an unlimited service life of the plasma generator and its explosion-proof operation in a hot atmosphere due to the absence of liquid water in it. A water plasma is a promising substance for many technological applications because of the unlimited reserves of water in the Earth, the absence of harmful nitric oxides in it, and the large energy density that is second only to the energy density of hydrogen.

Water-vapor plasma generators with a penetrating arc and an external anode of power 50–300 kW were developed and tested. Exact calculation of the discharge channels of these generators is a fairly complex problem even in the case where they operate in the regimes with no electric arc. Therefore, the indicated plasma generators were designed with the use of the empirical and semiempirical relations derived for cold regimes. However, these relations showed their applicability also for the optimization of hot regimes. Using them, we demonstrated the high reliability of the discharge channels of the plasma generators considered as to the thermal and electrical insulation of the electric arc in them.

It is profitable to further improve arc water-vapor plasma generators on the basis of numerical simulation of hot regimes of their operation with an electric arc in their discharge channel with the use of program packages such as the ANSYS package. On the basis of the principles proposed, an indirect-operation plasma generator, having no external electrode, with a fully regenerative cooling can be developed.

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NOTATION

A and A_p, boundary-layer interaction parameter and its value at the boundary of the potential vortex core; d, diameter of the inlet tangential conduits of the swirl chamber; F, total area of the inlets of the swirl chamber; F_{sp}, area of the section of a spiral swirler square with the swirler wall; f_w, area of a window in the wall of the discharge channel; G, rate of a gas flow; H, axial extension (height) of the swirl chamber; I, strength of current; k_v, swirl gain of a gas flow; L, length of the arc downstream of the nozzle; N, power of an arc discharge; P, pressure, P_0, total pressure; P_{st}, static pressure; R, current radius of the potential vortex core; r, radius of the outlet of the swirl chamber; R_0, radius of the inlet of the swirl chamber; R_p, radius of the potential vortex core; R_{p1} and R_{p12}, radii of the potential vortex cores for the cases of swirl chambers with a single conduit and 12 conduits; Re, Reynolds number; Re_p, Reynolds number for the potential vortex core; t_{noz}, temperature of the gas flow in the nozzle; t_m, temperature of the gas flow in the intake manifold; $t_{inp.m}$, temperature of the vapor at the input of the manifold; $t_{b.c}$, temperature of the plasma-generator cathode body; t_{v2}, temperature of the vapor in the second stage; U, voltage; v, gas velocity; v_0, mean-mass velocity of the gas in the conduits of the swirl chamber; v_φ, swirl velocity; v_p, swirl velocity of the gas flow at the potential vortex core radius; v_r, swirl velocity of the gas flow at the output of the swirl chamber; δ, degree of diaphragming; ε, coefficient of local decrease in the flow velocity; μ, dynamic viscosity; ρ, density of the gas; τ, time. Subscripts: b.c, body of cathode; m, manifold; inp.m, input of the manifold; noz, nozzle; p, potential; sp, spiral; st, static; v, vapor; w, window.

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