Journal of Engineering Physics and Thermophysics, Vol. 77, No. 2, 2004

EROSION OF A COPPER CATHODE IN A NONSTATIONARY ARC SPOT. I. EXPERIMENTAL INVESTIGATION

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UDC 621.387.143.014.31

A study has been made of the dependence of the erosion of a copper cathode of an electric-arc heater on the basic operating parameters: the arc current, the velocity of movement of an arc spot, and the temperature of the electrode surface. The experiments were conducted in a coaxial electric-arc heater with a magnetic movement of the arc in an air medium for an arc current of 95–480 A and a magnetic field of 0.005–0.417 T. The duration of the experiment, the axial velocity of a plasma-forming gas, and the flow rate of a cooling water were held constant. It has been shown that there are two different erosion regimes: the microerosion regime characterized by a weak dependence on the current and the macroerosion regime with a strong dependence on the current; the transition from one regime to the other is realized upon the attainment of the critical value of the current, dependent on the magnetic field and the thermal regime of the electrode. The existence of a velocity interval in which the specific erosion is minimum has been shown, which confirms the predictions of the earlier thermal model of erosion of cold electrodes.

Introduction. Various plasma technological processes with the employment of electric-arc gas heaters (EAHs) are receiving an increasingly large development effort at present. However, the active commercialization of EAHs is hampered because of the insufficient time of their continuous operation, which is associated with the rapid destruction of the electrodes, particularly, the cathode, and the absence of reliable methods of prediction of the optimum operating regimes of the units with a minimum erosion of the electrodes and a maximum service life. Both theoretical and experimental investigations of "hot" cathodes manufactured from heat-resistant materials which are characterized by a high fusion temperature, for example, from tungsten (T_f = 3968 K) or hafnium oxides (T_f = 3047 K), or from zirconium (T_f = 2950–2983 K), have received the largest development effort at present. "Hot" cathodes operate in a stationary thermal regime with an immobile arc spot. Copper, which belongs to the type of "cold" electrodes with a low fusion temperature (T_f = 1356 K), is most widely employed in EAHs as the anode material.

At the same time, the employment of not only anodes manufactured from copper but of copper cathodes as well offers a number of advantages to EAHs. Such electrodes are, first of all, inexpensive and easy to manufacture. Furthermore, unlike thermoionic cathodes, they can operate in any medium, in practice, and at very high currents (tens of kiloamperes). The most substantial drawback of them is intense erosion, which leads to a higher-than-average contamination of the plasma and a reduction in the service life and reliability of EAHs.

Because of the low fusion temperature and high heat flux in the arc spot ($q_0 = 10^9$–10^{10} W·m^{-2} in the case of a copper cathode), "cold" electrodes are unable to operate with an immobile attachment of the arc. To distribute the thermal load on a large surface one usually forces the spot to move over the electrode with a high velocity with the use of a magnetic field or a vortex gas flow. The employment of a magnetic field makes it possible to attain the largest velocities of the arc. On the other hand, a magnetic field exerts an ambiguous influence on the erosion because of the dependence of the energy characteristics of the arc spot, such as the volt-equivalent of the heat flux U and the current density in the spot j, on the magnetic field (see [1–4]).

Theoretical investigation of the interaction between a moving arc and "cold" electrodes is made difficult by the complexity, diversity, and nonstationary character of the occurring processes, which become more intense in the presence

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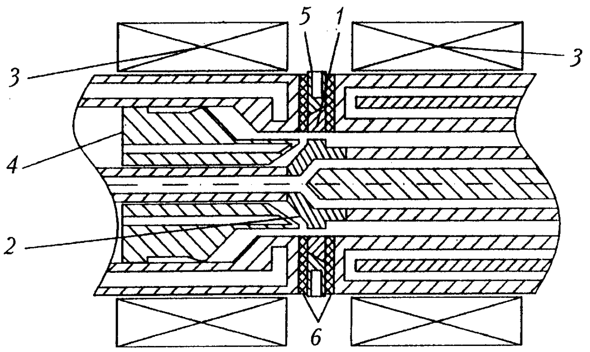


Fig. 1. Diagram of the experimental setup for investigation of erosion.

of the magnetic field. Therefore, a fairly comprehensive idea of the influence of the main operating parameters of an EAH on the erosion of the electrodes can be gained only experimentally at present. In this work, we present results of experimental investigation of the erosion of a copper cathode as a function of the main operating parameters, such as the current of the arc and its movement velocity caused by the external magnetic field, the electrode temperature, and the time of continuous operation.

Experimental Setup and Measuring Method. The experiments on investigation of the erosion of "cold" cathodes which is caused by the action of an electric arc moving in an air medium upon application of a magnetic field have been carried out on an experimental setup (shown diagrammatically in Fig. 1) of the Gleb Watagnin Institute of Physics at Campinas University (Brazil) (GWIP in what follows). The setup had cooled coaxial electrodes 1 and 2 which were placed in the axial magnetic field produced by two solenoids 3. The external electrode 1 acted as the cathode, whereas the internal electrode 2 acted as the anode. The arc moved in the interelectrode gap in the azimuthal direction under the action of the Lorentz force. The plasma-forming gas (air without preliminary purification) was fed in the axial direction without a twist. The arrangement of the structure was vertical.

To strike an electric arc we employed a mechanical igniter which initiated a pilot arc of interruption of the electric circuit formed by the relieving cathode 4 and the anode 2. Then this arc was blown into the gap between the basic electrodes 1 and 2 with the use of a small additional consumption of air (~4% of the total value). The pilot arc connected in parallel to the basic arc via an additional resistor went out spontaneously after the striking of the basic arc owing to its drooping volt-ampere characteristic and to a current decreased as compared to that of the basic arc. Ignition without high voltage made it possible to continuously record the operating parameters of the setup, beginning from the instant of initiation of the arc.

The cathode was manufactured in the shape of a ring of width 5 mm. The interior (working) surface (40 mm in diameter) was cylindrical, whereas the exterior surface (50 mm in diameter) had a small conicity (~3^{o}), necessary for a reliable thermal contact with the cooling jacket 5, ensured by pressurizing. The presence of heat insulation 6 on the lateral surfaces made it possible to employ the analytical solution of the problem of heating of an infinite cylinder with boundary conditions of the second kind (prescribed constant density of the heat flux on the interior surface) [5, 6] for calculation of its thermal regime. The small width of the cathode guaranteed its uniform thermal regime and made it possible to determine the surface temperature and the value of the heat flux by measuring the temperature in any axial cross section of the electrode. For this purpose we employed two Chromel-Alumel thermocouples arranged radially on one lateral cathode surface. Furthermore, the heat flux into the electrode was measured by a traditional method — from the heating and the flow rate of the cooling water in the cooling jacket.

According to the thermal model [7–9], the basic parameters determining the value of the erosion of an electrode are the surface temperature of the electrode T_0, the arc current I, and the velocity of movement of the arc spot v. It is not practical to obtain experimental dependences of the electrode erosion on each individual parameter mentioned above since variation of one parameter inevitably leads to a change in another. For example, the arc current influences both the velocity of movement of the arc in the magnetic field and the temperature of the cathode surface. On the other hand, even with a constant value of the current and variation of the arc velocity, for example, by controlling the axial gas velocity, the temperature of the cathode surface, nonetheless, does not remain constant because of the change in the intensity of convective heat exchange between the electrode and the plasma. Variation of the arc velocity by changing

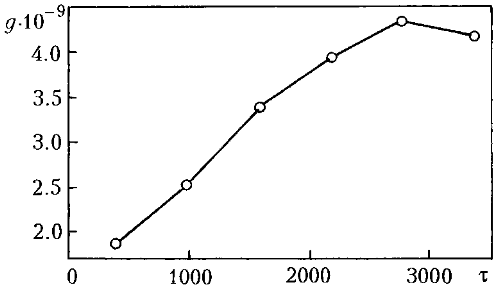


Fig. 2. Change in the specific erosion of the cathode g as a function of the operating time τ.

the magnetic field exerts a more complex influence on the electrode temperature and erosion, since not only does the convective heat exchange between the electrode and the plasma change, but the energy parameters of the spot itself — the current density $j(B)$ and the volt-equivalent of the heat flux in the spot $U(B)$ — also change [1–4].

Preliminary experiments have shown that the specific erosion $g = \Delta m/(I\tau)$ increases with the operating time of the electrode τ. Figure 2 gives the results of measurement of the specific erosion of the cathode as a function of time for a current $I = 230$ A and a magnetic field $B = 0.136$ T. The specific erosion was determined by weighing every 10 min of operation. It is clear from the figure that the g values measured after the operation of the electrode during the first 10 or 60 min differ more than twice.

Such behavior of $g(\tau)$ is quite simply explained in the context of the thermal erosion model [7–9] according to which the value of the erosion depends on the balance between the quantity of heat coming into the electrode from the arc spot and the quantity of heat removed from the surface by conduction. As the operating time of the cathode increases, its surface is contaminated by the products of chemical reactions occurring in the electrode zone. Furthermore, the cyclic thermal action of the spot on the surface because of the considerable thermoelastic stresses modifies the surface structure of the electrode up to the cracking of the polycrystalline structure of the material along the grain boundaries [10]. The presence of the oxide film on the surface and the microcracks in the surface electrode layer leads to a deterioration of the heat removal from the spot and accordingly a growth in the erosion.

As a consequence of what has been said above, the duration of each experiment was set constant and equal to 10 min. During this period, we held at a constant level the flow rate of the plasma-forming gas (120 liters/min) and the flow rate of water in the cathode's cooling jacket (4.4 liters/min). Taking account of the fact that the density of the current in the spot and the volt-equivalent of the heat flux are functions of the magnetic field, we carried out two different sets of experiments: in the first set, we changed the arc current for a fixed magnetic field and in the second set, we varied the magnetic field for a fixed arc current. Furthermore, when the value of the magnetic field was fixed, the temperature of the cathode surface changed due to the different thickness of the cooled electrode wall, which made it possible to keep all the remaining parameters constant.

Results of the Investigations. In investigating the dependence of the specific erosion on the current, we have carried out experiments for four fixed magnetic fields: $B = 0.01$, 0.137, 0.2, and 0.35 T. The arc current was varied within 95–480 A; the axial velocity of the plasma-forming gas was 7.6 m/sec for an interelectrode gap of 3 mm. A new cathode manufactured from commercial copper was employed for each experiment without any precleaning of the working surface. In this set, we obtained groups of experimental points for all of the fixed controlled parameters (magnetic field and flow rates of the gas and the cooling water), except for the arc current. It should be noted that with a change of 5 times in the current the rotational velocity of the arc also changed but to a lesser extent — just by a factor of 2.

Under such rigid operating conditions, the application of relatively low (0.01 T) or high (0.35 T) magnetic fields caused a limitation on the width of the range of variation of the arc current. The predominance of the action of one force (aerodynamic or magnetic) provoked an unstable arcing regime leading to a spontaneous quenching of the arc.

Figure 3A gives the results of measurement of the specific erosion g as a function of the arc current I, which have been obtained for different magnetic fields. It is clear that there exist two entirely different erosion regimes. In the first regime, identified as the microerosion regime, the specific erosion slightly increases with current. In this case, the electrode surface remains intact without traces of destruction visible to an unaided eye. The microerosion regime occu-

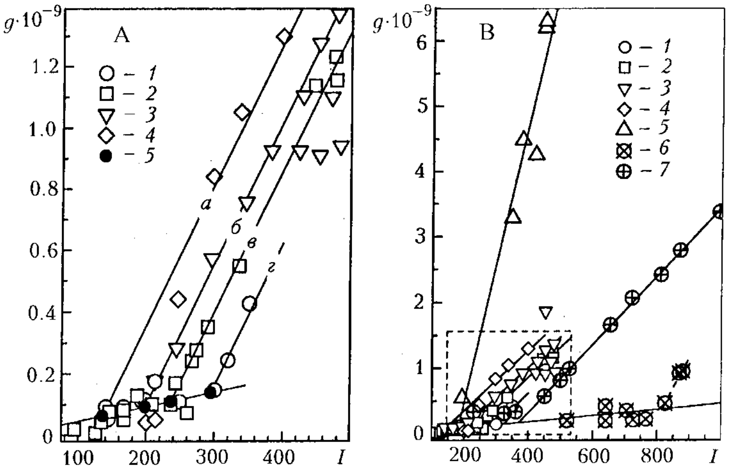


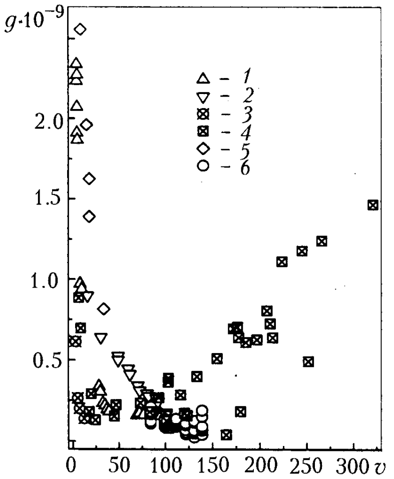
Fig. 3. Specific erosion of the cathode g as a function of the current I: A) results of the GWIP for d_1 = 40 mm and different magnetic fields B [1) 0.01; 2) 0.137; 3) 0.20; 4) 0.35 T; lines a–d, linear approximations of $g(I)$ for points 1–4; 5) points of intersection of the linear approximations a–d and the microerosion]; B) comparison of different results [1–4) results taken from Fig. 3A; 5) results of the GWIP for d_1 = 40 mm and B = 0.2 T with a cooled-wall thickness increased from 10 to 40 mm; 6) results of the HMTI for d_1 = 90 mm and B = 0.033 T; 7) results of the HMTI for d_1 = 50 mm and B = 0.133 T].

pies the range of low currents and propagates to a certain critical value I_{cr} dependent on both the structure of the setup and the operating parameters. The value of the critical current decreases with increase in the magnetic field, which is attributable to the increase in the density of the heat flux in the arc spot $q_0 = j(B)U(B)$; this increase leads to an earlier onset of the fusion of the electrode surface as the current rises.

The second erosion regime, identified as macroerosion, begins for $I > I_{cr}$ and is characterized by the presence of explicit macroscopic fused portions whose area rapidly increases with current. In approximation of the macroerosion regimes by a power function of the form $g = k(I - I_{cr})^{\alpha}$, we obtained values of the exponent α close to 1, which demonstrates the possibility of linear approximation of $g(I)$ with the identical angular coefficient k taken as an average for four magnetic fields and for the same setup, all other things being equal. The critical flux I_{cr} for which the microerosion becomes macroerosion is marked in Fig. 3A by points 5.

For the sake of comparison, Fig. 3B gives the so-called "highlighted" points 6, 7 from [2, 8], which have been obtained on an analogous setup at the Heat and Mass Transfer Institute (HMTI) for inside diameters of the cathode of 50 and 90 mm and a magnetic field of 0.13 and 0.03 T and when the flow rates of the plasma-forming gas and the cooling water were held constant. Furthermore, Fig. 3B gives the results of approximation of $g(I)$ which correspond to the higher-than-average cathode temperature obtained due to the increase in the thickness of the cooled wall (points 5). It is clear that the angular coefficients of linear approximation k are dissimilar for points 1–4 and 5–7. This demonstrates that such a dependence is not universal or suitable for any regime and any setup.

Figure 4 shows the results of measurement of the erosion of the copper cathode as a function of the velocity of motion of the arc; they have been obtained in another set of experiments in which the current was held constant (I = 293 A), whereas the velocity of motion of the arc was changed by variation of the magnetic field from 0.005 to 0.417 T and the rotational velocity of the arc was changed in accordance with the results of [11]. For the sake of comparison, Fig. 4 gives the data of other authors, which have been obtained under conditions different from ours and with the employment of different gases. Points 1 have been obtained in investigating the erosion of the copper cathode on a coaxial setup in a nitrogen–argon mixture [12] for an arc current of 100 A and magnetic fields of 0.005 and 0.1 T. Points 2 have been obtained on the same setup but in a nitrogen atmosphere [13] in the range of magnetic fields 0.0051–0.171 T. Points 3 have been found on a vortex plasmatron in purely gasdynamic movement of the arc without a magnetic field [15]. Points 5 have been obtained in a mixture of argon with titanium tetrachloride (0–30%) as a plasma-forming gas and on a cathode from metal-ceramic composite consisting of a copper- or aluminum-impregnated



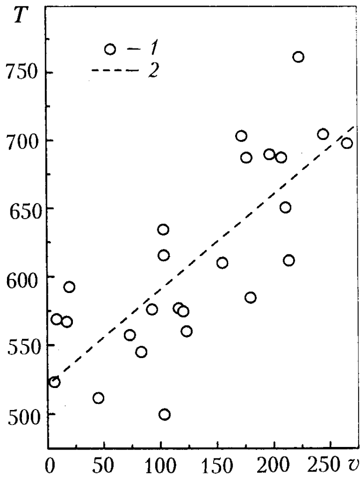


Fig. 4. Specific erosion of the cathode as a function of the arc velocity: 1) argon–nitrogen mixture [12]; 2) nitrogen [13]; 3) air, purely gasdynamic movement of the arc [15]; 4) data of the present work; 5) mixture of argon with titanium tetrachloride and metal-ceramic cathode [16]; 6) air [14].

Fig. 5. Cathode-surface temperature *T* as a function of the arc velocity *v*: 1) experiment; 2) linear approximation of *T*(*v*).

matrix of tantalum carbide [16]. Points 6 have been found [14] on a coaxial setup operating with air for magnetic fields of 0.1 to 0.35 T.

Common to the data employed for the sake of comparison is that all of them have been found for an arc velocity no larger than 150 m/sec and demonstrate a decrease in the erosion with increase in the arc velocity. At the same time, the thermal erosion model predicts an increase in the erosion with excessive increase in the magnetic field [7]. Shaboltas and Yas'ko [17] have shown a U-shaped character of the dependence of the erosion on the magnetic field, but the ascending branch of the erosion curve has been confirmed by a single experimental point. According to the thermal model [7, 8], the ascending branch of a U-shaped erosion curve can be obtained only in the case of a rise in the electrode temperature with increase in the arc velocity, whereas the descending branch is less sensitive to the temperature regime and can be obtained even at a constant electrode temperature.

Unlike the works mentioned above, we monitored the cathode temperature and carried out investigations in a wider range of arc velocities (to 300 m/sec) and magnetic fields (to 0.4 T). Points 4 in Fig. 4 show an explicit increase in the erosion with increase in the arc velocity above 150 m/sec. Figure 5 shows the behavior of the electrode-surface temperature as a function of the arc velocity. Despite the wide spread in the data obtained, it is clear that the temperature does increase with velocity. Szente et al. [12–16] did not monitor the temperature regime of the cathode and did not attain the range of such regimes; therefore, they could not detect the extremum in the behavior of the erosion.

Our experiments have shown that the minimum value of the specific erosion was attained only in a range of rotational velocities of the arc of $50 < v < 150$ m/sec, which was the optimum operating regime of this setup, and the erosion began to increase with further increase in the arc velocity.

Let us dwell in somewhat greater detail on the physical explanation of this phenomenon from the viewpoint of the thermal-spot model. As the velocity of movement of the arc spot increases, the time of thermal exposure of a given point of the electrode in the spot drops and the increase in the temperature of the surface in the spot decreases; the erosion should have decreased. Such is indeed the case for a purely gasdynamic movement of the arc spot where the arc column is transferred by the gas and its relative velocity is small in relation to that of the gas. Moreover, the gas velocity is usually increased due to the increase in its flow rate, which additionally cools the electrode.

The arc velocity in magnetic movement is limited mainly by the aerodynamic resistance of the arc column; therefore, its value in relation to the gas velocity is much higher than that in gasdynamic movement. The difference between the velocities of the arc and the gas increases with the arc velocity, which causes an intense turbulization of the plasma flow and an enhancement of convective heat exchange between the plasma and the electrode as the magnetic

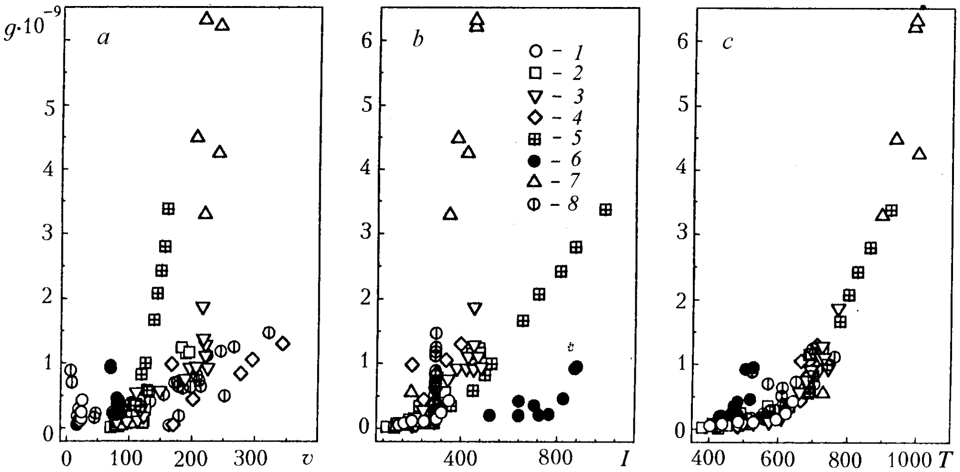


Fig. 6. Influence of the basic parameters [arc velocity v (a), current I (b), and cathode temperature T (c)] on the specific erosion of the cathode for d_1 = 40 mm [1) 0.01; 2) 0.137; 3) 0.20; 4) 0.35 T]; 5) d_1 = 50 mm and B = 0.133 T; 6) d_1 = 90 mm and B = 0.033 T; 7) d_1 = 40 mm and B = 0.2 T with a cooled-wall thickness increased from 10 to 40 mm; 8) d_1 = 40 mm and I = 293 A; B changes from 0.005 to 0.4 T.

field increases. The energy parameters of the arc spot – the current density and the thermal volt-equivalent — also increase [1–4]. All these factors lead to a growth in the electrode temperature with increase in the velocity of the arc in magnetic rotation.

In the presence of two oppositely acting factors — the increase in exposure time reduces the erosion, whereas the increase in the surface temperature and the density of the heat flux in the spot increase it — there appears a region of optimum regimes with a minimum erosion.

Figure 6 compares the same experiments on investigation of erosion but as a function of different parameters: the arc velocity, the current, and the electrode-surface temperature. It is clearly seen that the electrode temperature is the most substantial parameter of those given in the figure. Stratification of experimental results obtained under different conditions in the g–T plane is minimum as compared to the stratification observed in the g–v and g–I planes. In Fig. 6c, all the points lie as a close group, except for the points 6 obtained on the cathode of larger diameter (90 mm instead of 40–50 mm for the remaining points). When the currents are identical, the cathode of larger diameter is less thermally stressed and, consequently, has a lower temperature. Therefore, macroerosion began at a current of ~400 A and an average electrode temperature of ~600 K on all the small cathodes and at a current of ~800 A and a temperature of ~500 K on the large cathode. Thus, a change of only 20% in the critical temperature at the instant of the beginning of macroerosion led to a twofold change in the critical current, which speaks of the greater conservatism of the temperature in relation to the erosion than that of the current.

CONCLUSIONS

Of the three main parameters determining the erosion of the cathode in a nonstationary arc spot (current I, velocity of movement of the spot v, and average temperature of the surface T), the most important is the temperature. It is precisely this parameter that primarily determines the transition from the microerosion regime to a much more severe macroerosion regime. With such a tradition, the current and the velocity of movement of the spot play a subordinate role, probably, primarily due to the influence on the surface temperature inside the spot.

In magnetic movement of the arc, the electrode temperature increases with velocity; therefore, limitations related to the growth in the temperature and erosion of the electrode are imposed on the velocity. Experiment confirms the existence of a related velocity interval in which the specific erosion is minimum, which is consistent with the thermal model proposed earlier.

We express our thanks to A. A. do Prado for technical assistance in the work and to scientific funds of Brazil (CNPq, FAPESP, and FINEP) for financial support of this work.

NOTATION

B, magnetic induction, T; d_1, inside diameter of the electrode, mm; g, specific erosion, kg·C^{-1}; I and I_{cr}, current and critical current, A; j, current density, A·m^{-2}; k, proportionality factor; m, mass, kg; q_0, density of the heat flux in the arc spot, W·m^{-2}; T, T_0, and T_f, temperature, cathode-surface temperature, and fusion temperature, K; U, volt-equivalent of the heat flux in the arc spot, V; v, velocity of movement of the arc spot, m·sec^{-1}; α, exponent; τ, time, sec. Subscripts: cr, critical value; f, fusion; 0, value on the surface.

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