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Experimental Study of Hydrogen Heating in Powerful Electric Discharge Launcher

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The results of a heat transfer study on the discharge chamber of an electric discharge launcher under test conditions is presented. The test conditions are an initial H_2 pressure of 5–40 MPa, a discharge chamber volume of 1400 cm^3, a current of $\leq$1.5 MA, energy stored at 1.3 MJ, and a circuit ringing frequency of 1 kHz. A diagnostic discharge chamber was constructed to simulate gas heating in the electric discharge launcher (EDL) discharge chamber and to facilitate the use of a high-speed camera. Based on the arc dynamics study in the diagnostic discharge chamber, estimates of the temperature and conductivity of the arc channel were carried out for the EDL chamber. The measured pressure of 200 MPa and conductivity of 230 $(\Omega \times cm)^{-1}$ correspond to temperatures of (3.3–3.5) $\times$ 10^4 K and of (2.3–2.4) $\times$ 10^4 K for the arcs, burning in copper vapor and hydrogen, respectively. The real temperature seems to lie between these two values. Since pressure equilibrium in the volume was reached, acoustic oscillations may be used to evaluate the gas temperature. The moving arc causes shock waves that are measured by pressure transducers, placed along the discharge length, and by high-speed camera photographs. The arc-to-gas energy transfer efficiency rises along with initial H_2 pressure increase and reaches 90% for 40 MPa. Both the propagation of the shock wave and the arc radiation absorption contribute to this rise.

Introduction

TODAY the use of a powerful electric discharge is considered to be one of the methods for accelerating masses of 20–200 *g* up to the velocities of 3–5 km/s. For this range of masses and velocities, electric discharge launchers (EDL) have some advantages when compared with normal one- or two-stage light gas guns and railguns. The EDL discharge chamber design was originally taken from the designs of the combustion chamber of conventional powder guns. Hence, most of the units are close to optimum and it is easy to calculate the desired pressures and energy load. The energy input to the chamber can be controlled by programming the discharge rate from the primary energy store. Thus, it is possible to get an optimum pressure–time profile at the projectile. Under optimum conditions, the efficiency of the transfer of stored energy into kinetic energy may be as great as 20–30%. EDLs are much smaller in size than two-stage gas guns and use no explosives. However, an appropriate energy store (usually a battery of capacitors) is needed. The electric discharge may be performed both in condensed media with low molecular weight[1–3] and in hydrogen or helium under high pressure.[4–6] Among the disadvantages of this system are the erosion of the electrodes, leading to working gas contamination and higher molecular weight, and the severe demands placed on the electrical insulation under the combined conditions of $\leq$2 MA, $\leq$20 kV, and $\leq$500 MPa. During the pulse, the pressure rises at a rate of 10^6 MPa/s.

In an earlier paper, the arc temperature in the chamber of a high-density plasma pulse generator was estimated for nitrogen,[7] where the arc was assumed to consist of metal vapor resulting from the sublimation of the igniting wire and electrodes. In this paper similar estimations were made for an arc in hydrogen with initial pressures of 5 and 20 MPa. This paper presents test results from the discharge chamber of an EDL, operating with hydrogen at initial gas pressures in the range of 5–40 MPa, maximum currents up to 1.5 MA, and a maximum rate of current buildup in the short-circuit test of 1.8 $\times$ 10^{10} A/s. High initial hydrogen pressure reduces both the energy losses and the thermal load on electrodes and discharge chamber walls as energy is transferred from the arc to the gas. The capacitance of the energy store varied from 0.02 to 0.11 F. The charge voltage was 5 kV, corresponding to a maximum stored energy of 1.3 MJ. For comparison with other results and to develop an operational model of electric thermal launchers, nitrogen was used that is similar to the results obtained by evaporation of liquids with low weight.[1–3] In this paper, we will make estimates of the temperature of the discharge channel, average gas temperature in the discharge chamber, and the efficiency of the process of energy transfer from arc to surrounding gas.

Experimental Setup

The EDL discharge chamber shown in Fig. 1 has a volume of 1.4 dm^3, and an acceleration channel 2 m in length and 30 mm in diameter. The discharge was initiated in a 2-mm gap between a conic cathode and separable anode by a 2-mm-diam copper wire. After initiation in the gap, the arc travels out along the electrodes' surface, heating the gas inside the launcher chamber. At sufficiently high pressure, the diaphragm ruptures and the projectile is accelerated down the launcher. Figure 2 presents typical oscillograms of discharge current, voltage on the discharge gap, and pressure in the discharge chamber of the EDL for hydrogen and nitrogen at the initial pressure of 20 MPa. For these conditions the velocity of the 20-g accelerating body is 3400 m/s for hydrogen and 1200 m/s for nitrogen. Because of difficulties in chamber–launcher diagnostics, caused by the 500-MPa pressure pulse in the EDL chamber, a special diagnostic discharge chamber was built to simulate the gas-heating processes (Fig. 3). This chamber has the same geometry and electrode design as that for the EDL

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chamber. For ease of diagnostics, two parallel windows and four pulse pressure transducers were located along the length of the discharge volume. Both chambers had the same rate of current rise during discharge. In these experiments, hydrogen initial pressures were similar to those used in the launcher discharge chamber. Therefore, one may consider arc-to-surrounding gas heat transfer to be similar in both chambers. Experiments with the diagnostic chamber were carried out with an energy input of about 250 kJ producing a discharge current of about 400 kA. Special experiments with the EDL were conducted using a manometric bomb for more precise estimation of the energy transferred from the arc to the gas.

Results and Discussion

Diagnostic Chamber Research

Current and voltage oscillograms obtained in the diagnostic chamber at an initial hydrogen pressure of 5 MPa are presented in Fig. 4. Pressure oscillograms at two different points within the discharge volume, separated by 19 cm, are presented in Fig. 5. Strobe camera photographs of the arc channel are presented in Fig. 6.

The arc was initiated in the narrow gap between the electrodes by the explosion of a copper wire. Arc movement after the ignition is determined both by the heated gas pressure and the arc interaction with magnetic field. The observed voltage rise in the discharge gap is not connected with a change of the circuit inductance. The induced electric field, caused by the arc movement, opposes the outer driving field, and its value is small as determined by an arc channel velocity of 1.6×10^3 m/s. The voltage rise is not connected with the growing voltage–current characteristic, since the voltage rise was observed even after maximum current had occurred. Because the diaphragm remains closed, there is no supersonic flow that would rapidly cool the plasma and give rise to a subsequent voltage increase. A similar voltage rise was observed in the EDL chamber at the moment of the first current maximum that corresponds with the diaphragm opening (Fig. 2 for hydrogen). Hence, we can suppose the arc voltage rise to be connected with the change in its length. This explanation is confirmed by comparing the strobe camera photographs with current and voltage records. These curves show steps corresponding to the current breaks at the maximum arc length with secondary breakdown at the initial position of the igniting wire. These secondary breakdowns correspond to abrupt arc voltage drops and to the formation of a pressure pulse.

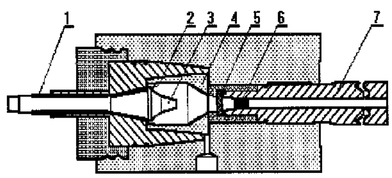

Fig. 1 Sketch of the discharge chamber. 1, insulation; 2, igniting wire; 3, cathode; 4, anode; 5, diaphragm; 6, accelerated body; and 7, barrel.

High-speed photography of the arc channel in the diagnostic chamber and the current and voltage data were used to estimate the conductivity (Fig. 6). An increase in the channel diameter could be observed simultaneously with its movement along the central electrode after the wire explosion. Approximately 40 μs after the beginning of the process the velocity of the front boundary was about 1.6×10^3 m/s. Nonhomogeneities in the form of current channels can be observed after 12 μs. After 40 μs the discharge channel loses its compact form and continues to move along the electrode, separating into zones with different optical intensity. After 28 μs, corresponding to a current of 210 kA, voltage drop on the discharge gap of 1430 V, average arc length of 1.5 cm, and total discharge diameter of 6.7 cm, the arc has separated into five channels. In this case the average current density in each channel would be 3.0×10^4 A/cm^2. This magnitude corresponds quite well to a current density of 3.5×10^4 A/cm^2 in arc discharges with thermal cathode spots.[8]

The voltage drop as a function of arc length is linear as determined previously in experimental studies for arcs in hydrogen with current of several hundred kiloamperes and initial pressures of several megapascals.[9] Because of these results, we assumed that the electrodes' voltage drop and the arc cross section in the zone of the positive column where there is no space charge remain the same for this series, allowing us to subtract the positive column contribution. The electrode fall was estimated to be as high as 1 kV. The current density was about 3×10^4 A/cm^2; however, it may be even higher next to electrodes. Our value for the electrode fall is in agreement with the data for a 10^6 A/cm^2 arc current density in hydrogen discharge with tungsten electrodes.[10] The same magnitude was

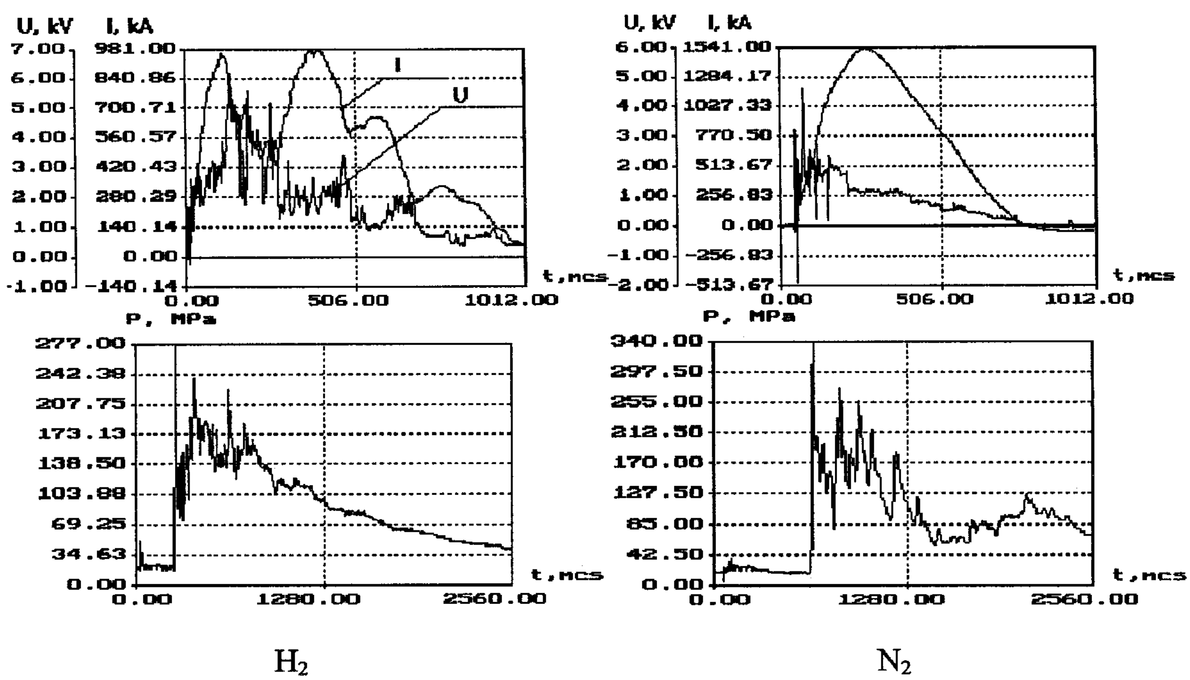

Fig. 2 Current, voltage, and pressure for the electric discharge launcher, operating with hydrogen and nitrogen.

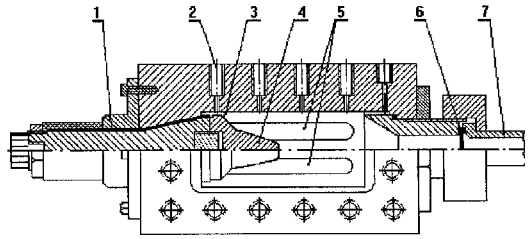

Fig. 3 Diagnostic chamber. 1, insulation; 2, pressure transducer hole; 3, igniting wire; 4, cathode; 5, windows; 6, diaphragm; and 7, gas outlet.

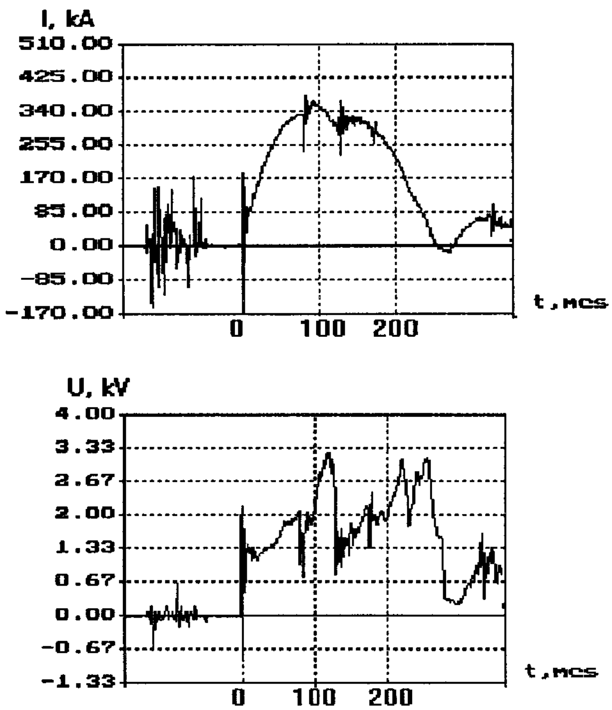

Fig. 4 Current and voltage for the diagnostic chamber.

obtained by measurement of the voltage drop between the electrodes of the EDL just after the secondary breakdown, when the arc burns in the narrow gap of 1–3 mm. We consider the contribution of the positive column to be negligible. It was established that the arc voltage rise and the decrease of discharge current were connected with the arc motion out of the interelectrode gap. The abrupt decrease of the arc voltage and the formation of pressure pulses, spreading along the discharge chamber, correspond to repeated breakdowns at the position of the initiating wire.

The propagation rate of the pressure pulses, the natural oscillation frequency of the pressure waves in the EDL chamber, and the amplitude of the final pressure were used to determine the temperature of the gas in the discharge chamber. Arc temperature was also estimated from arc conductivity. The temperature of the transfer zone between the arc and surrounding gas was defined in a similar experiment using spectral measurement techniques.[11] Thus, 28 μs into the discharge, the electric field in the discharge is 290 V/cm with a conductivity of 110 $(\Omega \times \text{cm})^{-1}$. Within the volume, the average concentration of metal vapor is about 10^{18} cm^{-3}. The metal vapor comes primarily from the initiating wire and the evaporation from the electrodes. The average value of the erosion of the cathode and anode is 60 mg/C. A previous series of experiments with electric discharge launchers[12] has determined essential electrode erosion data (Table 1).

High erosion is connected with the possible formation of a group of discharge spots and a zone of melting. Erosion by drops is possible as well. For a complete discharge of 400–600 C passed through electrodes, the resultant erosion may lead to an average metal vapor concentration of 10^{20} cm^{-3} in the EDL chamber. For these experiments, the exact plasma composition is unknown. Therefore, we consider two limiting cases to estimate plasma temperature from conductivity: 1) an arc burning in metal vapor and 2) an arc burning in pure hydrogen. Assuming that the arc burns in metal vapor,[8] a pressure of less then 1 MPa corresponds to a concentration of 10^{18} cm^{-3} and to an arc temperature of 10^4 K. The magnitude of the arc pressure, mentioned earlier, is obviously underrated. Thus, either the concentration of metal vapor in the volume is higher than average or the arc burns in a mixture of hydrogen and metal vapor. In the first case, the metal vapor's concentration

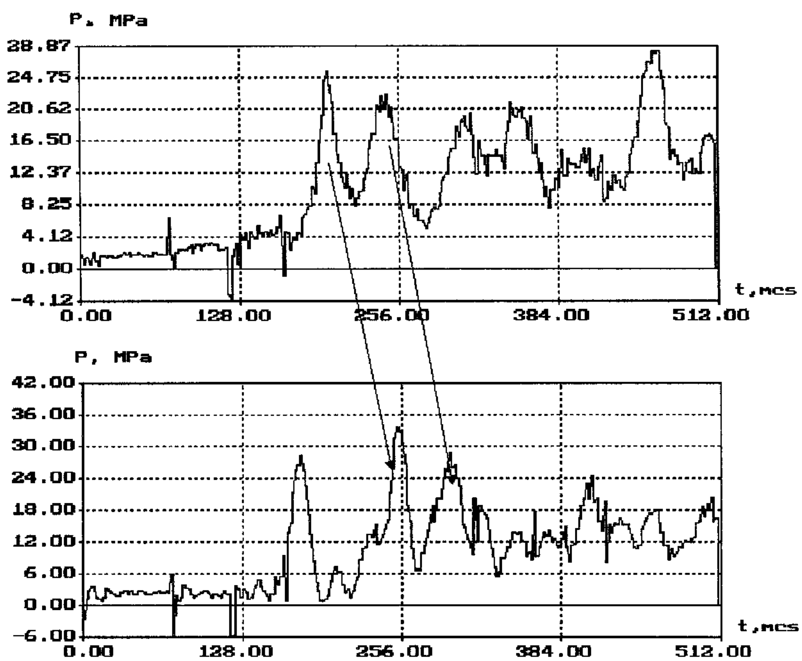

Fig. 5 Diagnostic chamber pressure data from two different pressure transducers.

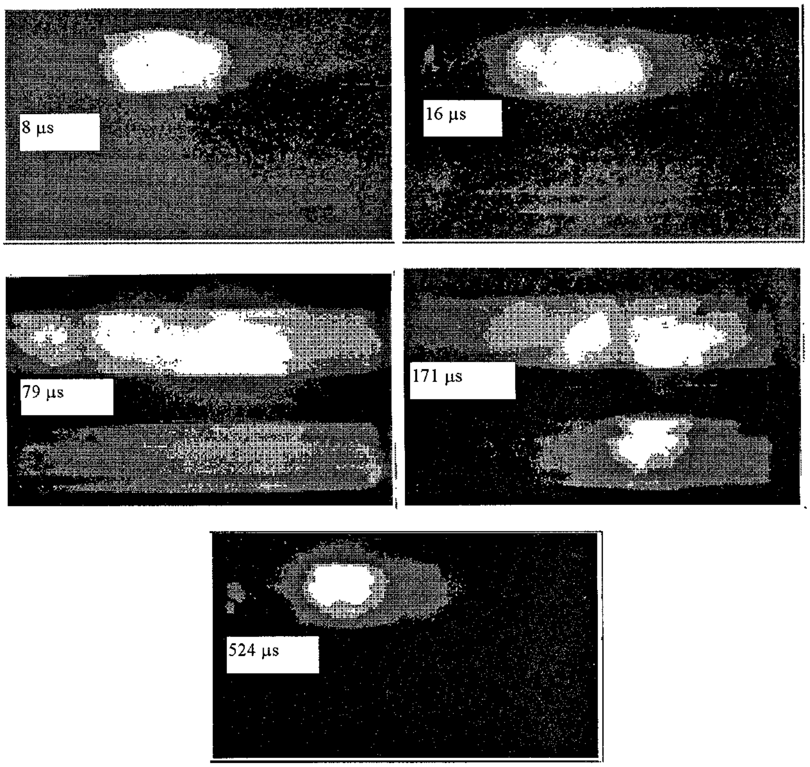

Fig. 6 Strobe camera photographs taken from the diagnostic chamber test under initial hydrogen pressure of 5 MPa. Time from the moment of ignition is indicated.

Table 1 Electrodes' erosion in EDL experiments

Material	Erosion, mg/C
Anode	
Tungsten	40
Copper	51
Steel	72
Cathode	
Aluminum	40
Steel	8

in the arc for a measured pressure of several tens of megapascals and conductivity of 110 $(\Omega \times \mathrm{cm})^{-1}$, from estimations for a copper plasma,[8] corresponds to a temperature of (1.6–1.7) $\times$ 10^4 K. For a pure hydrogen plasma with conductivity of 110 $(\Omega \times \mathrm{cm})^{-1}$ at an electron concentration[13] of 10^{19}–10^{20} cm^{-3}, totally corresponding to our conditions, we have a plasma temperature[13] of (1.9–2.0) $\times$ 10^4 K. The second approach better matches the real situation when the arc burns in a mixture of hydrogen and metal vapor with an intermediate temperature of 18 $\times$ 10^3 K. This value correlates with estimates acquired from spectral measurements. A dense plasma in the discharge channel radiates a blackbody continuum. On this background we observed (time-integrated) absorption lines of the elements contained in the electrodes. This absorption takes place in the transition zone between arc and surrounding gas. Having measured the effective half-width of NaI D-lines, 5890 and 5896 Å, in absorption, it is possible to estimate the temperature somewhere in this thin intermediate zone. This approach gives a value of (1.1–1.4) $\times$ 10^4 K and is at the same time a lower estimate for the current channel temperature.

Electric Discharge Launcher Chamber Research

The conductivity of the arc channel in the EDL was estimated at the first maximum of the discharge current (Fig. 2). The time of this maximum coincides with the beginning of the diaphragm opening, which causes a sharp increase of the voltage across the arc and a drop in the discharge current. The opening time was determined independently using a photoelectric technique. The time at opening corresponds to the time when the first shock wave reaches the diaphragm (t = 120 μs). The shock was caused by the moving arc channel and was measured by a pressure transducer. A time delay in the pressure records, caused by a 210-mm transducer-to-chamber channel, was also taken into account. Measurements performed in the diagnostic discharge chamber showed that the velocity of the moving current channel, as defined by high-speed photography (except for the early period), coincides with the velocity of spreading pressure front, which is determined by data from the pressure transducers. As the shock front is located close to the current zone, we assume that at the moment of the first maximum of the discharge current the arc's length is equal to the distance from diaphragm to cathode. For an EDL arc with a current of several mega-amperes, the electrode voltage drop is unknown. According to Ref. 8, the voltage drop increases with the rise in current density after the value of 10^5 A/cm^2 is reached. The current density in the EDL chamber may be higher than in the diagnostic chamber as indicated by the arc crater size. Therefore, we can expect the electrode voltage drop for an EDL operating with hydrogen to exceed 1 kV. In this case the arc conductivity and, hence, its temperature, will be higher than those for 1 kV value. Therefore, later in time, we get a lower estimation of the current channel temperature.

In the discharge we have an electric field of 150 V/cm for an arc length of 13 cm. Assuming the current density to correspond to that in arcs with a thermal cathode spot of 3.5 $\times$ 10^4 A/cm^2, the conductivity is 230 $(\Omega \times \mathrm{cm})^{-1}$. By this time, the concentration of metal vapor, averaged throughout the volume and defined by the erosion of anode and cathode, is about 10^{19} cm^{-3}. This corresponds to a pressure of 10 MPa when the arc burns in metal vapor. However, the pressure in the discharge, measured by the transducer, reaches several hundred megapascals. Thus, from the diagnostic chamber arc temper-

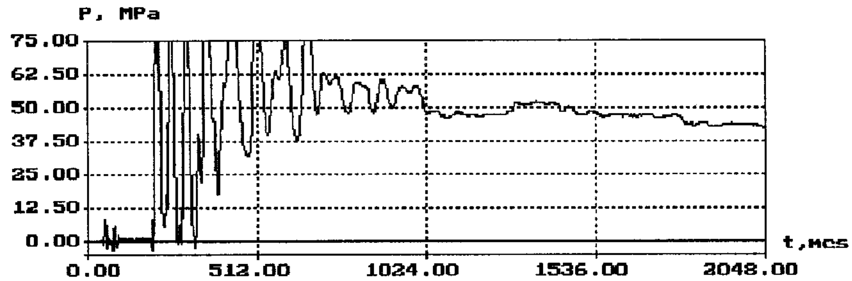

Fig. 7 Pulse pressure for the EDL discharge chamber. Initial pressure is 40 MPa.

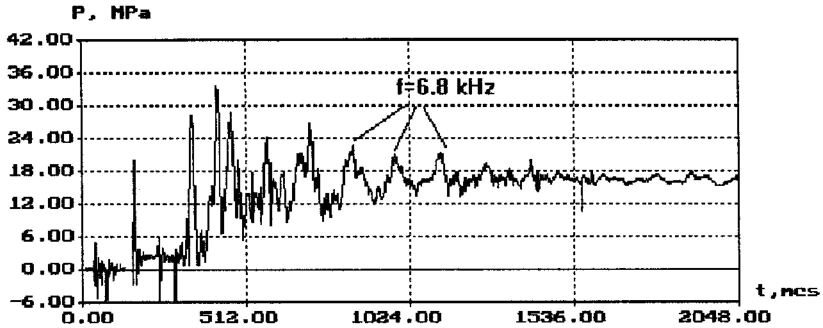

Fig. 8 Pulse pressure for the diagnostic discharge chamber. Initial pressure is 5 MPa.

ature definition, and using the results of previous estimations[8,13] for an arc in copper vapor at a pressure of 200 MPa and a conductivity of 230 $(\Omega \times \text{cm})^{-1}$, we obtain a temperature of 3.3–3.5 $\times$ 10^4 K, and 2.3–2.4 $\times$ 10^4 K for an arc in hydrogen. The estimates presented for the hydrogen arc temperature in the EDL chamber, corresponding to the oscillograms in Fig. 2, probably are the lower limit values. At current levels of 1 MA, the self-magnetic field of the arc can play a significant role, causing an increase of the arc current density due to magnetic compression. In this case the arc channel conductivity, and consequently, the temperature, will be higher. For example, estimates for nitrogen,[7] using the same scheme for estimation (Fig. 2), yield the arc channel temperature to be about 5 $\times$ 10^4 K. The energy input into the EDL chamber was estimated from the final pressure and initial hydrogen density. Measurements were conducted at an initial pressure of 40 MPa in a manometric bomb. The pressure transducer was placed next to the sealing diaphragm. In this case there are pressure pulses caused by shock waves (Fig. 7).

The first pulse is associated with the shock front initiated by the arc movement as a whole after the ignition and by the broadening of the current channel. The Mach coefficient is 1.4 in this case. The second and third pulses are shock waves caused by secondary breakdowns at the initial position of the igniting wire. The Mach coefficient for the second shock wave is 2.7. Later in time a complicated set of waves appear, connected both with reflection of the earlier waves from the chamber walls and from new ones generated as a result of repeated breakdowns. We observe a similar phenomena in the diagnostic chamber using a strobe camera. However, Mach coefficients are lower as a result of lower energy input. For example, in Fig. 8 there is an increase in both the slope of the pressure pulse front and in the amplitude, corresponding to the first breakdown as measured by the pressure transducers placed along the chamber.

In the case of a closed volume there are no deep valleys in the current traces, corresponding to diaphragm opening. Sometimes acoustic oscillations with frequencies, corresponding to resonance modes of the diagnostic discharge chamber (Fig. 8) are registered after pressure equalization. The propagation speed of these oscillations corresponds to the sound velocity determined from the final pressure value. For example, the measured frequency of the acoustic oscillations is 6.8 kHz for

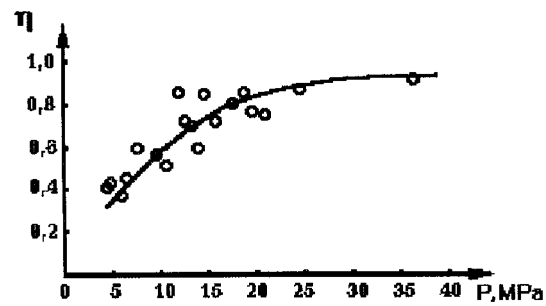

Fig. 9 Arc-to-gas energy transfer efficiency ratio vs initial hydrogen pressure.

a final pressure in the diagnostic chamber of 22 MPa with an initial hydrogen density of 4.4 $\times$ 10^{-3} g/cm^3. For hydrogen an average mass temperature of 1200 K matches these conditions.[14] It corresponds to a sound velocity of 2.5 $\times$ 10^3 m/s. Under these conditions, the frequency of natural longitudinal acoustic oscillations f, determined from the equation $f = c/2l$, will be 6.2 kHz for a chamber length of 20 cm. This value is close to the observed frequency of 6.8 kHz. The frequency corresponding to the natural lateral oscillations is also observed. Arc-to-gas energy transfer efficiency was determined as a ratio of the energy stored in gas to that in the discharge. The dependence of this efficiency on initial hydrogen pressure[15] is presented in Fig. 9. The high efficiency for pressures above 20 MPa is associated with almost complete absorption of the arc radiation in the border zone of the discharge. It is valid generally for high and ultrahigh pressure arcs. For example, in Ref. 10, for an arc in helium under a pressure of 40 MPa, the hot central zone was detected only by probe and x-ray means. Optical radiation from this region is completely screened by the discharge periphery. The conditions for which the results are presented in Fig. 2 show a total energy transfer efficiency from the store to the 20 g mass body is 8%. Gas-to-body energy transfer efficiency rises with body mass. Therefore, it follows from our results that a high total efficiency of 30% may be achieved for accelerating a body mass of 200–300 g. As previously mentioned, efficiency increases from 50 to 90% if there is a growth of hydrogen initial pressure from 5 to 40 MPa (Ref. 4). This fact seems to improve the heating efficiency with the growth of initial pressure caused by the propagation of the shock waves and the absorption of energy radiated by the arc. For the full-scale experiment (Fig. 2), 70% efficiency may be accepted as the lower limit. If the energy loaded into discharge is 1200 kJ as determined from current and voltage oscillograms, then the value of energy within the gas will be 840 kJ. The kinetic energy of the accelerated body is 100 kJ. The efficiency of energy transfer from the gas to the body in this case is about 12%, and the efficiency of energy transfer from the power supply to the accelerated body is about 8%. The acceleration time for the body while in the channel from the experiment presented in Fig. 2 is very close to the time of gas heating in the chamber and is about 1.32 ms. Thus, gas thermal energy is not used effectively. It is possible to increase the efficiency of gas-to-body energy transfer by increasing the length of the accelerating channel.

Summary

Estimates are made for the arc channel temperature of an electric discharge launcher chamber and for a similar diagnostic chamber. The temperature is 3.4×10^4 K and 2.4×10^4 K for the EDL chamber, assuming the arc to burn in metal vapor and in pure hydrogen, respectively. The temperature is about 1.8×10^4 K in both cases for an arc in the diagnostic chamber. The temperature was also determined from the resonance frequencies of the diagnostic chamber. Using a manometric bomb, we observed shock waves with Mach coefficients of about 2.7 and determined arc-to-gas energy transfer efficiency. The high value of this efficiency, 90% for an initial hydrogen pressure of 40 MPa, enables us to achieve total energy transfer efficiency from energy store to projectile kinetic energy of 30%. This value is much better than the value for railguns.

Acknowledgment

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