

# Heating of High-Density Hydrogen by High-Current Arc Radiation

A. V. Budin, Ph. G. Rutberg, M. E. Pinchuk, A. A. Bogomaz, and V. Yu. Svetova

**Abstract**—The investigation results of high-density hydrogen heating by high-current electric arc are presented at initial pressure from 5 MPa to 160 MPa with current amplitude up to 1.6 MA and current rate of rise  $10^9$ - $10^{11}$  A/s. When changing the initial pressure and current rate of rise, channel temperature varies from several electronvolts to hundreds electronvolts. Arc channel radius is several millimeters. But the radius of the discharge chamber greater than the radius of the arc channel on approximately order of magnitude. High efficiency of gas heating is caused by radiation absorption of hydrogen surrounding the arc. Current channel consist from vapor of the initiating wire. At current rate of rise of  $10^9$  A/s and relatively small current amplitude gas heating occurs due to radiation absorption in the band transparency of hydrogen by the wire vapours with photon energies less than 13.6 eV. At current rate of rise of  $10^{11}$  A/s gas heating is due to hydrogen absorption of soft X-rays from discharge channel.

**Keywords**—High-density hydrogen heating by high-current electric arc.

## I. INTRODUCTION

RESULTS, presented in this paper, are farther continuation of experimental studies of self-constricted discharge in dense hydrogen with current amplitude up to 1.5 MA and current raise rate  $dJ/dt=10^9$ - $5 \times 10^{11}$  A/s [1]-[4]. The discharge with first current half-cycle duration of 70–200  $\mu$ s is initiated by electric wire explosion. Here we present some research results of mechanisms of heat exchange between powerful pulse arc and gas at initial pressure up to 160 MPa, that corresponds to particles concentration before the discharge over  $10^{22}$  cm<sup>-3</sup>.

## II. EXPERIMENTAL INSTALLATION DESIGN

Experiments were performed on two electrodischarge installations [5], [6]. The electrode system have axisymmetric

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geometry, the distance between electrodes could vary from 0.5 cm up to 5.0 cm. The central electrode insulated from the chamber's housing serves as the cathode, and the chamber casing plays the role of the anode. Steel, copper and tungsten have been used as the electrode material. Arc ignition is performed by wire explosion. At the initial instant the wire joins the cathode with the anode. The energy input in arc achieved 0.5 MJ. The energy source is the capacitive battery [7].

For research of energy transfer from an arc into gas the experiments were carried out in a mode of a manometrical bomb (i.e. at constant volume when the chamber was muffled with thick unbreakable diaphragm and gas did not expire after the discharge). The energy enclosed into gas was defined from the steady-state pressure in the discharge chamber up to a stage of gas cooling. At high energy input and ultrahigh initial pressure the experiments were carried out with breaking diaphragm as required by safety. The estimation of the energy enclosed in gas in this case was defined on the base of pulse pressure maximum.

More detailed description of installations and diagnostic methods can be found in [3]-[6].

## III. RESULTS OF EXPERIMENTS AND DISCUSSION

On Fig. 1 and Fig. 2 oscillograms for typical experiments performed at an initial hydrogen pressure  $P_0$  of 32 MPa and 84 MPa, correspondingly are presented. In the first case (Fig. 1) the steel electrodes were used, and current amplitude  $J_A$  was 1250 kA. In the second case (Fig. 2), the tungsten electrodes were used, and  $J_A$  was 400 kA.

At initial gas pressure of 5-35 MPa electric field strength in the arc is about  $\sim 1$  kV/cm, which considerably exceeding ones in more slowly or stationary burning arcs, indicating the presence of the powerful channel of energy losses from the discharge. Under these conditions the discharge channel has temperature up to several hundreds electronvolts and it is a source of soft x-ray radiation (SXR) [3], [4]. And the discharge radiation apparently plays the role of such losses.

Current channel consist from vapor of the initiating wire. Main part of the energy in metallic plasma for our conditions is emitted from the discharge channel by quanta with the energy of  $h\nu = 2kT$  [8]. It was assumed that the gas heating is performed by the SXR. In this case, energy of the passed radiation is estimated as follows:

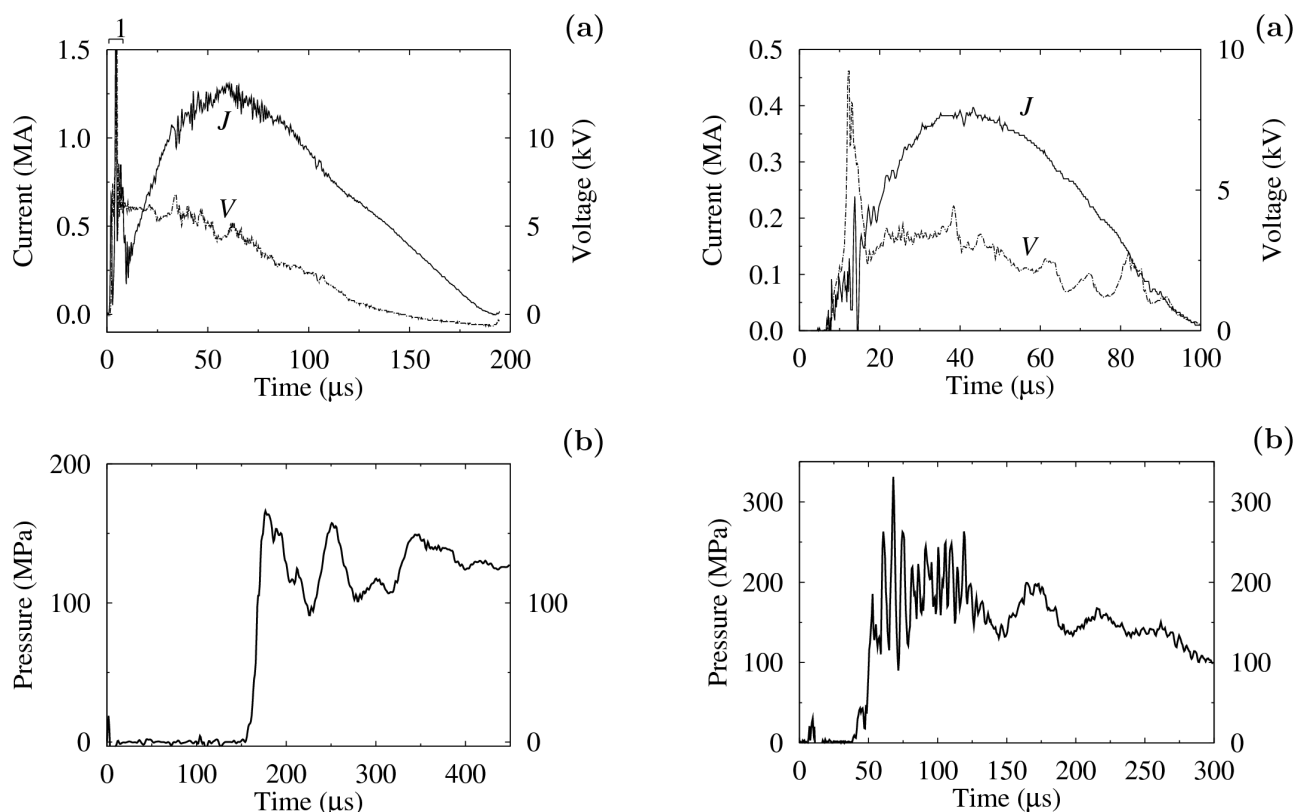


Fig. 1 Discharges in hydrogen at  $P_0$  of 32 MPa for steel electrodes and copper igniting wire: (a) – current and voltage curves, (b) – pulse pressure due to current pulse; 1 - wire explosion and current pause stage; Input energy into arc is ~500 kJ. Steel electrodes with  $\varnothing 20$  mm. Interelectrode gap is 20 mm

$I = I_0 \exp(-n\sigma\ell)$ , where  $n$  is the gas concentration in the chamber;  $\ell$  is the distance from the arc to the chamber wall;  $\sigma$  is the cross-section of the quantum absorption and  $\sigma = 5.4 \times 10^{-17} (h\nu_0/h\nu)^{3.5}$  for the quanta energy above gas ionization energy [9].

So the energy, that heats the gas, was defined from the relation:  $1 - \eta = \exp(-n\sigma\ell)$ .

Dependence of efficiency  $\eta$  of transmitting the energy from an arc into gas versus the initial pressure  $P_0$  is shown in Fig. 3. The dependence has the growing character. The curve 1 illustrates the  $\eta$  behavior under energy input larger than 300 kJ; the curve 2 corresponds to energy lower than 300 kJ. Value of  $\eta$  is defined as a ratio of the energy transmitted into gas to one embedded into the arc. The first energy is found by value of the final pressure and the gas initial density. The second one is determined as the integral  $\int J(t)U(t)dt$ .

Dependence of  $\eta$  versus the energy embedded into the arc (Fig. 4) illustrates the fact that the efficiency  $\eta$  grows as the energy embedding into the arc decreases. This is determined by the decrease of the plasma temperature in the arc channel and, as a result, by increase of the cross-section of the radiation absorption.

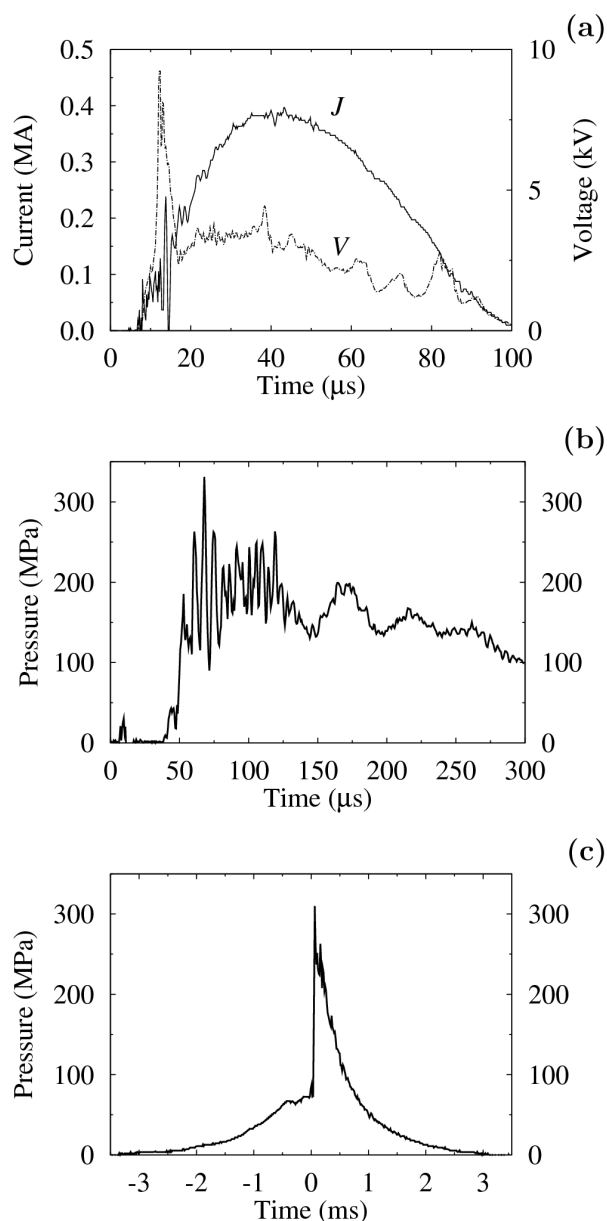


Fig. 2 Discharges in hydrogen at  $P_0$  of 84 MPa (just before discharge ignition,  $\rho = 3.5 \times 10^{-2} \text{ g/cm}^3$ ) for tungsten electrodes and copper igniting wire: (a) – current and voltage curves, (b) – pulse pressure due to current pulse, (c) – pulse pressure for full experiment time (see [5] for better understanding). Input energy into arc is ~60 kJ. Tungsten electrodes with  $\varnothing 6$  mm. Interelectrode gap is 12 mm

At transition to essentially greater initial density of working gas with initial pressure up to 160 MPa it was observed other discharge parameters. In the experiments thick wire 0.5 mm in diameter was used. The radius  $r_1$  of scatter of the wire vapor may be estimated from the equality between the internal energy of the wire material vapor and the energy spent to expand the gas surrounding the wire after adiabatic compression of the gas:  $nkT / (\gamma - 1) = \pi r_1 P$ .

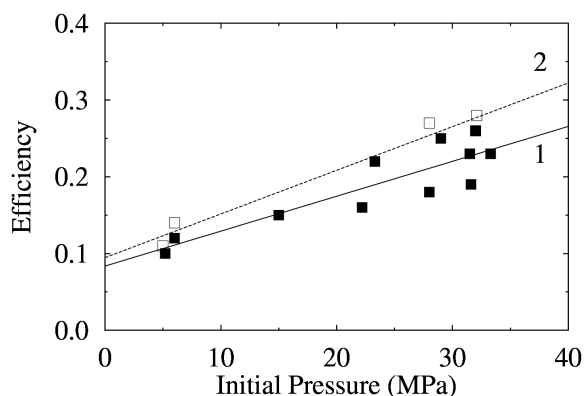


Fig. 3 Dependence of the efficiency  $\eta$  of transmitting the energy from the arc into the gas versus the initial pressure  $P_0$  for discharges with steel electrodes: 1 – the solid curve and black squares correspond to the energy (embedded into the arc) larger than 300 kJ; 2 – the curve in dots and white squares corresponds to the case with embedded energy lower than 300 kJ

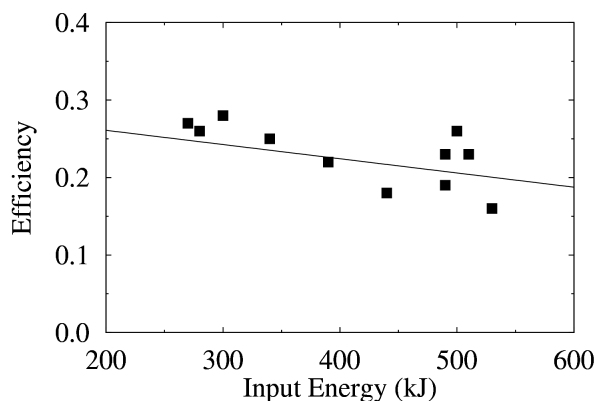


Fig. 4 Dependence of the efficiency  $\eta$  of transmitting the energy from the arc into the gas versus the energy embedded into the arc for discharges with steel electrodes under the initial pressure  $P_0$  of 15-35 MPa

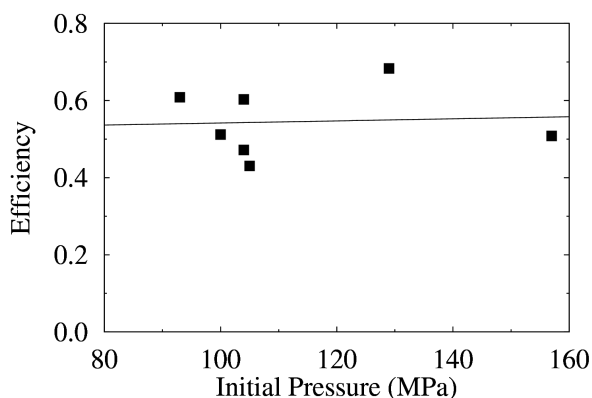


Fig. 5 Dependence of the efficiency  $\eta$  of transmitting the energy from the arc into the gas versus the initial pressure  $P_0$  for discharges with tungsten electrodes. Input energy into arc is  $\sim 50-100$  kJ

Here,  $n = 6 \times 10^{22} \text{ cm}^{-3}$  is the concentration of the wire material before expansion,  $T \sim 1 \text{ eV}$  [10],  $P = 160 \text{ MPa}$  is the pressure in the chamber at the end of adiabatic compression at the moment of the discharge initiation,  $\gamma = 1.66$ .

In this case,  $r_l \sim 0.2 \text{ cm}$  and the vapor concentration is roughly  $\sim 10^{21} \text{ cm}^{-3}$ . The wire plasma conductivity was determined by data of [11]. The channel temperature of about  $10^5 \text{ K}$  corresponds to this value of pressure and to a metal vapor concentration of approximately  $10^{21} \text{ cm}^{-3}$ . The mean radiation path according to Rosseland is  $10^{-2} \text{ cm}$ ; that is, the discharge is nontransparent.

Thus, a situation is possible when the entire current flows through vapor of a wire with a radius of  $r \sim 0.2 \text{ cm}$  and the concentration is approximately  $n \sim 10^{21} \text{ cm}^{-3}$ . The discharge channel is screened by a colder thin transitional zone between arc channel and gas. Energy of most quanta is in the band transparency of hydrogen (quanta with energy  $h\nu < 13.6 \text{ eV}$ ). The high efficiency of energy transfer from the arc to surrounding gas (Fig. 5) is apparently due to the absorption of radiation by metal vapors with subsequent transfer of energy to hydrogen, as well as by the absorption of radiation by hydrogen molecules. And also gas is heated by shock waves from discharge channel. Both mechanisms of energy transfer play a significant role in power balance at ultrahigh value of gas pressure.

#### IV. CONCLUSION

For pulsed powerful high-current electric arc at initial working gas (hydrogen) pressure from 5 MPa to 160 MPa with current amplitude up to 1.6 MA and current rate of rise  $10^9-10^{11} \text{ A/s}$  the channel temperature varies from several electronvolts to hundreds electronvolts. Arc channel radius is several millimeters. But the radius of the discharge chamber greater than the radius of the arc channel on approximately order of magnitude. High efficiency of gas heating is caused by radiation absorption of hydrogen surrounding the arc. Current channel consist from vapor of the initiating wire. At current rate of rise of  $10^9 \text{ A/s}$  and relatively small current amplitude gas heating occurs due to radiation absorption in the band transparency of hydrogen by the wire vapours with photon energies less than 13.6 eV. At current rate of rise of  $10^{11} \text{ A/s}$  gas heating is due to hydrogen absorption of soft X-rays from discharge channel.

#### ACKNOWLEDGMENT

This work was supported in part by the Russian Foundation for Basic Research under Grant № 10-08-00739a.

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