Gas heating by controlled impulse arc

K. Korytchenko[1], V. Zakutin[2], N. Reshetnyak[2], I. Chertischev[2], A. Smorodskiy[3]

[1] *Kharkiv Institute of Armored Forces by NTU "KhPI",192 Poltavsky Shlyakh St., Kharkiv, 61034, Ukraine*
[2] *National Science Center KIPT, 1 Akademicheskaya St., Kharkiv, 61108, Ukraine*
[3] *Military Prosecuting Magistracy of Kharkiv Garrison, 36 Rydnev Sq., Kharkiv, 61050, Ukraine*

It has been proposed to change the voltage supplied to a discharge gap to increase the efficiency of gas heating by high-current pulse arc during arcing. The influence on discharge processes has been achieved due to growth of frequency of elastic collisions and due to the rising of resistance of arc cannel by arc driving. An equation for maximum of electric-field strength which is needed to be achieved by arc driving has been found. The influence of a driving voltage supplied to a gas-discharge gap on discharge dynamics has been investigated by monitoring of current and voltage on the gap. The influence of the arc driving voltage on efficiency of gas heating has been investigated by comparison of velocities of plasma-jet spreading.

1. Introduction

A very small part of electrical energy stored into a capacitor is deposited into gas heat during high-voltage pulse arcing [1, 2]. In initial stage of pulse arc the temperature of electrons is differed considerably from the temperature of heavy gas components such as ions, atoms and molecules. It is well known that the kinetic gas temperature determines an ignition process. Thus, it has to make arrangements for acceleration of energy transition from electrons to ions, atoms and molecules.

The order of gas ionization grows with average electron temperature increasing. As a result, an order of the gas ionization taking place in pulse arcs usually exceeds the order which is typical of equilibrium arcs by equal discharge currents. It must be kept in mind that a required equilibrium thermodynamic temperature, which is necessary to be achieved by the pulse arc heating, is no more than 1 eV. Energy equaled to 10 eV is spent on ionization of a molecule. So, if there is total single ionization at the discharge channel and the channel volume equals to the volume of the discharge cavity it means the energy input is ten times higher than the energy one required by equilibrium thermodynamic conditions. Therefore, there is arisen the necessity to increase the efficiency of the energy transforming to achieve a restriction on the ionization order in pulse arcs.

Fast decreasing of the cannel resistance causes the change in the balance of electric energy deposition into a discharge channel. The part of the discharge energy losing in a discharge gap is reduced sharply comparing with energy input at connecting wires and internal ohmic resistance of an energy source.

The purpose of this work is to find out new ways allowing to rise of efficiency of the heating.

2. The ways affecting gas-discharge processes under driving by pulse arc

The efficiency of pulse transformation from electric energy to thermal gas one is increased due to driving of the arc. The discharge process is influenced by changing of a voltage supplied to the discharge gap:

<u>The way affecting balance of energy deposition</u>:

$E \downarrow$, $T_e \downarrow$, $R_к \uparrow (R_к \sim 1/\sigma_к,\ \sigma_к \sim T_e^{3/2})$: $R_к >> R_a$.

The conductivity $\sigma_к$ of highly ionized plasma is in direct proportion to the electron temperature T_e: $\sigma_к \sim T_e^{3/2}$. The resistance $R_к$ of a discharge cannel increases by decreasing T_e because $R_к \sim 1/\sigma_к$. Hence, there is aroused the ability to vary the channel resistance "by force" affecting T_e by changing of electric-field strength E in discharge gap using external voltage. Thus, the primary energy input is attained in the discharge gap if the condition $R_к >> R_a$ is fulfilled, where R_a is the resistance of external electric circuit (fig. 1).

<u>The way of rising of heating efficiency</u>:

$E \downarrow$, $T_e \downarrow$, $\delta_{ei} \uparrow$ ($\delta_{ei} \sim 1/T_e^2$), $\nu_m \uparrow (\nu_m = NU\delta_{tr} + n_eU\delta_{ei})$.

Relaxation time between the electron temperature and the temperature of ions, atoms and molecules is basically affected by frequency ν_m of elastic collisions at pulse arcs: $\nu_m = NU\delta_{tr} + n_eU\delta_{ei}$, where N is the density of atoms and molecules, U is a velocity of elastic particles, n_e is an electron density, δ_{tr} and δ_{ei} are cross-sections of elastic collisions of electrons with atoms (molecules) and ions accordingly.

There is possibility to increase significantly the frequency by changing the cross-section of electron-ion elastic collisions because $\delta_{ei} \sim 1/T_e^2$ by changing of the voltage supplied to the gap.

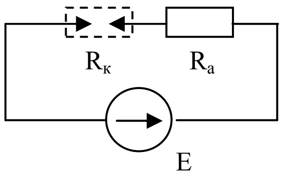

Fig. 1 Electric discharge circuit: $R_к$ is the ohmic resistance of the discharge gap, R_a is the external ohmic resistance, E is the source of electromotive force

3. Calculation of electric-field strength created by driven pulse arc

The energy of electric field can be effectively transformed into gas kinetic one if there is the balance between electron energy obtained by the field and its losses due to elastic collisions of the electrons with heavy gas particles. Plasma is highly-ionized in the cannel of a high-current gas discharge during the arcing. It is a main period of the gas heating. The deposition of Joule heat is determined in this case by process of energy exchange between the electrons and ions basically. Thus, a calculation of the electric-field strength has to make by an equation of electron energy balance into condition of presence of balance between electron energy obtained by the field during the moving without collision and full loss of the obtained energy via electron-ion collision [3]:

$$\frac{d\varepsilon}{dt} = (\Delta\varepsilon_E - \beta\varepsilon)\nu_m = (\frac{e^2 \cdot E^2}{m \cdot \nu_m^2} - \beta\varepsilon)\nu_m = 0\,, \qquad (1)$$

where $\Delta\varepsilon_E$ is the electron energy got by the field between collisions, $\beta\varepsilon$ is the electron energy loss via collisions, e is the electron charge, m is the electron mass.

Substituting the frequency into the balance equation (1) with the equation of frequency of elastic collisions related to highly-ionized plasma

$$\upsilon_m = \mathrm{n_e} \cdot \mathrm{U} \cdot \delta_{\mathrm{ei}} = n_e \left[6,71 \cdot 10^7 \cdot \sqrt{T_e\left[eV\right]}\right] \cdot \left[\frac{2,87 \cdot 10^{-14}\ \ln\wedge}{(T_e\left[eV\right])^2}\right]$$

one may obtain:

$$E = \nu_m \cdot \sqrt{\frac{\beta \cdot T_e\left[eV\right] \cdot m}{e^2}} = \frac{1,79 \cdot 10^{-15} \cdot n_e \cdot \ln\wedge}{T_e\left[eV\right]} \cdot \sqrt{\frac{1}{A}}\,, \quad (2)$$

where A is the atom mass of an ion (for example, A=28 into N_2 discharge medium). It has been suggested that the electron temperature is significantly higher than the ion one.

Calculated results of the dependence of average electron energy on the electric-field strength are presented in Table 1 in a case of air discharge plasma with $n_e = 10^{17}$ cm^3 and the presence of the balance.

According to equation (2) the energy has the inversely proportional dependence on the strength. This is caused by a reason that the fixed coefficient β (β = const) of the electron energy loss correlated with electron-ion collisions has been used. In real discharges this coefficient is determined by taking into account all processes of elastic and inelastic collisions of electrons with other gas-discharge particles. So, the coefficient is unfixed and non-linear. It is known that in the real discharge the average electron energy increases when the electric-field strength rises. Thus, the strength and the related energy calculated by equation (2) show a maximal energy value providing the energy balance due to electron-ion collisions only if this process is dominant in the calculated energy range. For example, the balance is supported by low-energetic part of electron energy function only (where the energy is less than 0.3 eV) if the strength exceeds 475 V/cm in calculated conditions. The decreasing of the electric-field strength supplied to the discharge gap causes the increasing a fraction of electrons supported the balance. It means that equation (2) allows finding out a maximal value of the strength providing effective gas heating in real discharge conditions.

Table 1

Electric-field strength, V/cm	Electron density n_e, cm^{-3}	average electron energy, eV	Cross-section of elastic collisions of electrons with ions δ_{ei}, cm^2
475	10^{17}	0.3	$1.4 \cdot 10^{-12}$
306		0.5	$5.3 \cdot 10^{-13}$
168		1	$1.45 \cdot 10^{-13}$
92		2	$3.96 \cdot 10^{-14}$

There is a minimal value of the field strength caused by ability to use the equation (2). The balance of electron energy has been considered to highly-ionized plasma. The rise of electron energy causes the decreasing of the transport cross-section of elastic collisions of electrons with ions. As a result, the influence of other collisions on the electron balance increases significantly. It is the reason of the gas heating efficiency decreasing too. For example, if the electron temperature T_e is equaled to 0.3 eV in air plasma ($\delta_{ei} = 1.4 \cdot 10^{-12}$ cm^2) by density of neutral gas particles equaled 10^{19} cm^{-3} and electron density of 10^{17} cm^{-3} then elastic collisions of electrons with ions are dominant due to the next collision correlation: $10^{19} \cdot (7 \div 9) \cdot 10^{-16} < 10^{17} \cdot 1.4 \cdot 10^{-12}$. If T_e = 2 eV then $\delta_{ei} = 3.96 \cdot 10^{-14}$ cm^2, and $\delta_{tr} = (1 \div 3) \cdot 10^{-15}$ cm^2. So, the collision balance is $10^{19} \cdot (1 \div 3) \cdot 10^{-15} > 10^{17} \cdot 3.96 \cdot 10^{-14}$ and the plasma is weakly-ionized in this case.

It should be noted, it is the necessity to take into account an electron energy field where there is insignificant influence of inelastic collisions in comparison with elastic ones. As for air discharge it is suitable if the electron temperature is less 1 eV.

Hence, the application field of the equation (2) is limited by next conditions: the discharge plasma should be highly-ionized, the number of elastic collisions is much more than inelastic ones, the electron temperature is significantly higher than the ion one.

If there is the necessity to calculate the strength value supplying to discharge gap after the low-energy break-down in case of practical application of the driven arc for gas heating into technical devices, the electron temperature which is used in equation (2) has to make equal to a temperature T_n required to be achieved in a discharge cavity by Joule heating. The electron density can be taken from the condition of the non-total single ionization within the suggestion that a preliminary discharge is low energetic. The further increasing of an ionization order or supporting of the order level can be realized via thermal ionization only due to “forced” decreasing of the electric-field strength to a level which is lower than one corresponded to collision ionization. The maximum strength value which is needed to be achieved by arc driving to increase the efficiency and velocity of the gas heating has been found out within the suggestion that n_e is $0.01 \cdot N$:

$$E = \frac{1{,}79 \cdot 10^{-17}}{T_n} \cdot \sqrt{\frac{1}{A}} \cdot N \cdot \ln\wedge \,. \qquad (3)$$

As one can see from the equation (3), there is the possibility to increase the the strength required for arc driving via increasing of the gas density. Thus, it is expedient to arrange gas heat into dense discharge medium that can be achieved by increasing of initial gas pressure in the discharge cavity.

The increasing of the gas temperature causes the increasing of the electron temperature that is in the same conditions when the electric field is absent. It means that the average electron energy can not be decreased by elastic collisions to the level that is lower than gas energy one. Therefore the equations (2) and (3) should be corrected if the electron temperature approaches the gas one. In this case, the energy which determines the fraction of an electron energy loss in the collisions should be presented as the difference between electron energy and ion one: $\varepsilon = T_e[\text{eV}] - T_i[\text{eV}]$. Based on above it has been obtained the corrected equation of the driving intensity calculation:

$$E = 1{,}79 \cdot 10^{-15} \cdot n_e \cdot \ln\wedge \cdot \sqrt{\frac{1}{A}} \cdot \frac{\sqrt{(T_e - T_i)T_e}}{T_e^2} \,. \qquad (4)$$

The equation (4) shows that the strength of the driving electric-field has to be decreased if the gas temperature rises.

4. Experimental researches

4.1. Investigation of driven arc dynamics

The influence of a driving voltage supplied to a gas-discharge gap on discharge dynamics has been investigated by monitoring of current and voltage on the gap. The arc has been driven by the next way. A low-power spark discharge formed preliminary-ionized plasma channel into gas by energy deposition up to 1 J/cm. Then an electric capacitor with a high capacitance that was charged up to relatively low voltage U_0 discharged on the gap. The total stored energy was equaled to 100 J by changing of the capacitance. The arc was created in air with initial temperature of 293 K. The initial gas pressure P_0 was regulated in the discharge cavity. The length of the discharge gap was 10 mm.

It has been obtained that there is a condition of arc driving when the capacitor does not discharge completely. The dynamics of the current was similar to forms which are typical for aperiodic discharges. The residual voltage U_{res} was kept growing by rising of the initial pressure after the not-completed capacitor discharge. Moreover, the increasing of the pressure caused the decreasing of the current amplitude and the reducing of the discharge period τ (Table 2). Due to comparison of the arc dynamics obtained on gas-filled gap with the ones formed by the shot circuit, it has been found that the aperiodic type was caused by the gas-discharge cannel properties (fig. 2, 3).

Table 2

Influence of initial gas pressure on dynamics parameters of the driven arcs

U_0, V	P_0, 10^5 Pa	U_{res}, V	τ, μs
300	1	160±10	220±10
	1,5	170±5	200±10
	2	180±5	150±5
250	1	140±10	150±5

Thus, the resistance of the discharge channel of the pulse arc is increased both with decreasing of the voltage supplied to the gap and with the increasing gas density in the gap.

4.2. Investigation of energy input efficiency by arc driving

Influence of the arc driving on the efficiency of gas heating has been investigated by comparison of velocities of plasma-jet spreading.

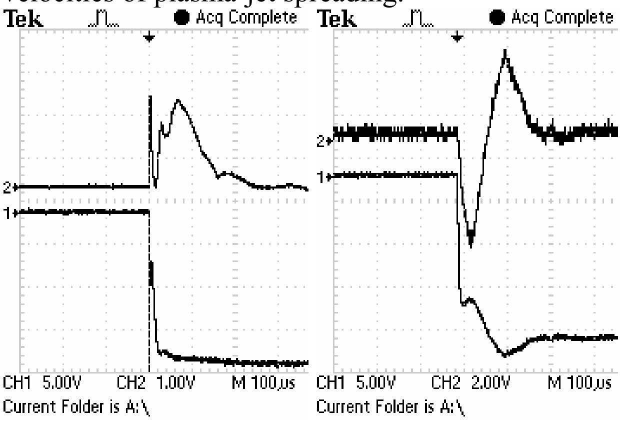

Fig. 2 Typical voltage (1) and current (2) oscillograms of driven arc (on the left) and the oscillograms in the case of the shot circuit (on the right)

The plasma-wave system [4] was used to form the pulse plasma jet (fig. 3). The plasma jet was created by pulse gas heating in the semi restricted discharge cavity. The air or hydrogen-enriched mixtures were taken as a discharge medium. "SFR" was used as a high-speed photo camera to register dynamics of plasma-jet spreading. Average electric-field strength of arcing and the initial pressure in the discharge cavity were changed during experimental researches.

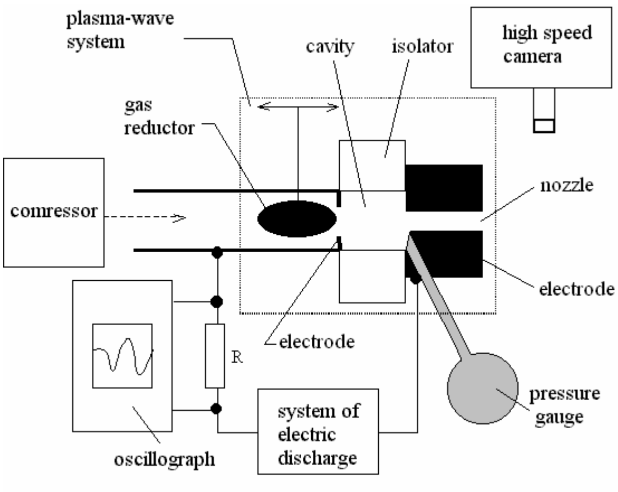

Fig. 3 Schematic of the experimental set-up

The increasing of the external voltage supplied to the gap caused the decreasing of the jet velocity in a condition of equaled energy Q stored into the electric capacitor initially. When the intensity exceeded 150 % of the calculated one in the driving discharge, the average velocity of a forward front of the hydrogen-enriched plasma jet calculated per injection time of 100 µs decreased down to 60 m/s. The decreasing of the voltage permitted to increase the jet spreading in the cross direction too (fig. 4, 5). The investigation has confirmed the necessity to increase the efficiency of the gas heating to change the electric field strength of arcing by force.

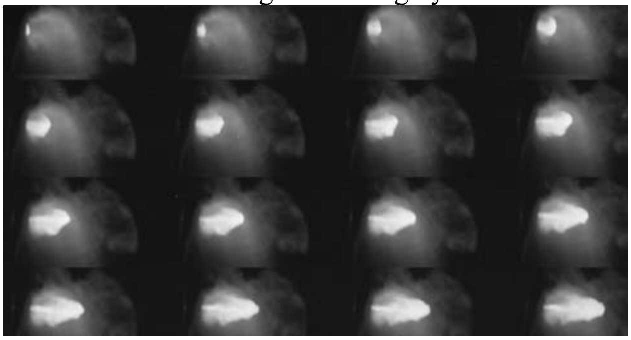

Fig. 4. Development of hydrogen-enriched plasma jet: U_0 = 16 kV, Q = 100 J. Shooting time is 8 µs

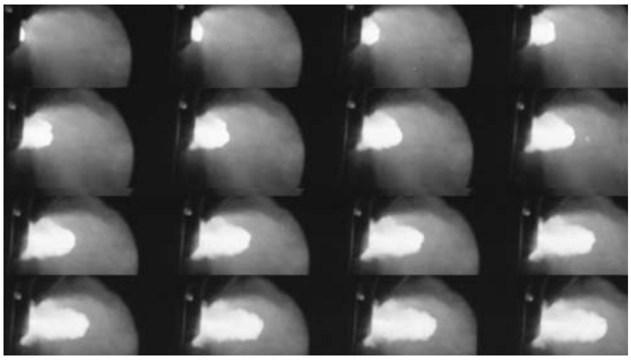

Fig. 5. Development of hydrogen-enriched plasma jet: U_0 = 900 V, Q = 100 J. Shooting time is 8 µs

5. Conclusion

The "forced" decreasing of the voltage by an external circuit allows:

- to limit a gas ionisation order. It is the way to save energy;
- to transform a plasma from weakly-ionised state to highly-ionised one by keeping the low ionisation degree. It is the way of increasing of elastic electron-ions collisions that cuases the quick heating;
- to rise the resistance of the discharge channel. It allows depositing the most part of the discharge energy into the gap via changing of the energy balance.

6. References

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