NUMERICAL SIMULATION OF INITIAL PRESSURE EFFECT ON ENERGY INPUT IN SPARK DISCHARGE IN NITROGEN

K.V. Korytchenko[1], R.S. Tomashevskyi[1], I.S. Varshamova[1], D.P. Dubinin[2], A.A. Lisnyak[2], V.O. Lipovyi[2]

[1]National Technical University "KhPI", Kharkiv, Ukraine

E-mail: omsroot@kpi.kharkov.ua;

[2]National University of Civil Defence of Ukraine, Kharkiv, Ukraine

E-mail: korytchenko_kv@ukr.net

An influence of initial gas pressure on energy deposited by spark discharge in nitrogen during the spark channel expansion is evaluated. Influence of the pressure on efficiency of energy deposition and emitted energy in a discharge channel is simulated. Dependencies of dynamic of energy input and an energy correlation coefficient on the pressure are found out. It was suggested to use an average value of the correlation coefficient to model a load of spark channel by the any initial pressure when a spark load is formed by atmospheric conditions.

PACS: 52.80.Mg

INTRODUCTION

Spark discharge is widely used at different technologies where initial discharge conditions are various. An influence of initial pressure on breakdown voltage at spark discharge is well known. For example, Paschen`s law gives dependence of a breakdown voltage on initial pressure and gap length at short-gap spark discharges.

Initial pressure influences on a spark channel expansion happens after the breakdown, too. It was found out that growth in the initial pressure causes an increase in deposited energy [1 - 3]. But there is a problem to find out dependence function of spark energy inputted in a gas-discharge channel and initial gas pressure due to low measurement accuracy.

Accuracy of measurement of energy deposited in spark channel is important factor to evaluate minimum ignition energy [4]. It was found out that a gas pressure rise leads to a decline of the minimum ignition energy due to growth in combustible gas density [5]. But the pressure rise produces an increase in spark efficiency too [2]. Thus during an investigation of the minimum ignition energy by spark discharge it needs to divide influences of this processes.

Additional difficult task is an evaluation of energy loses caused by anode and cathode voltage drops to extract energy inputted in spark gas channel from total energy dissipated by the spark. Researches do not exclude near electrode process often [6, 7] that leads to a rough evaluation of the minimum ignition energy.

A spark channel evolution, which happens after breakdown, depends on discharge current mainly. The discharge current determines by a discharge circuit in turn. Thus, simulation of spark channel evolution by influence of the discharge current allows avoiding influence of near electrode process on a spark energy calculation.

We simulated a spark channel evolution by various initial pressures to evaluate an influence of initial pressure on an energy deposition into gas during the spark expansion and to find out a correlation coefficient between the pressure and deposited energy growth.

THE NUMERICAL MODEL OF A SPARK CHANNEL EXPANSION

Energy deposited in a cylindrical spark channel can be calculated by equation

$$Q_d = \iint 2\pi r \sigma i^2 dr dt\,, \tag{1}$$

where σ is the gas conductivity; i is the current; r is the radial coordinate; t is time.

A radial distribution of conductivity and electrical current are changeable during the spark expansion. It is possible to use simulation tools to investigate spark parameters evolution.

We summarized and simplified results of previous researches to create a numerical model of a spark channel expansion to simulate discharge process in gas by various initial pressures when only electric circuit parameters (R, L, C) and the discharge gap length are given [8 - 12].

The setup was simplified to a one-dimensional problem in cylindrical symmetry where only radial dependencies were modelled. A system of gas dynamic equations (continuity, momentum and energy) was solved for the multicomponent chemically reactive gas mixture, written as

$$\frac{\partial\rho}{\partial t} + \frac{\partial(r\rho u)}{r\partial r} = 0\,; \quad \frac{\partial\rho u}{\partial t} + \frac{1}{r}\frac{\partial\left[r\left(p+\rho u^2\right)\right]}{\partial r} = \frac{p}{r}\,;$$

$$\frac{\partial\left[r\left(u\left(\rho\varepsilon + \frac{\rho u^2}{2} + p\right) + k_T\frac{dT}{dt}\right)\right]}{r\partial r} + \frac{\partial\left[\rho\varepsilon + \frac{\rho u^2}{2}\right]}{\partial t} = \tag{2}$$

$$= \sigma E^2 - W_{\mathrm{em}}\,; \qquad \frac{\partial y_i}{\partial t} + \frac{1}{r}\frac{\partial(r u y_i)}{\partial r} = \omega_i\,,$$

where ρ is the gas density; u is the velocity; p is the pressure; ε is the internal energy of gas per the mass unit of gas; k_T is the heat conduction coefficient; E is the electric field strength in the discharge channel column, W_{em} is the discharge energy radiation loss; T is the gas temperature; y_i is the molar concentration of the i-th component (N, N_2), and ω_i is the rate of change of concentration of the i-th component of the mixture due to chemical reactions.

Equations of non-equilibrium chemical reactions and gas state equations were used, too.

Application of the previous model [8 - 12] is limited by a plasma state of gas in the discharge channel, when the gas is highly ionized. The transition of air plasma from a highly ionized to a weakly ionized state occurs at a temperature in the range of 9000…10000 K at atmospheric pressure. It is known that the gas temperature in stationary arc plasma can be 5000…6000 K. Therefore, the previous model does not allow investigating the transition from spark to stationary arc discharge. To expand the field of the model application when the gas temperature decreases up to 5000 K, we used in this work the equation of plasma conductivity, written as

$$\sigma = 2.82 \cdot 10^{-4} \frac{n_e}{N\upsilon\sigma_{tr} + n_e \upsilon \sigma_{cul}}, \qquad (3)$$

where n_e is electron number density; σ_{tr} is the transport cross-section of the elastic collisions of the electrons with the neutral plasma components; σ_{cul} is the Coulomb collision cross-section; N is the number density of neutral components; υ is a thermal velocity of electrons.

So, the verification of the condition when there is a prevalence of Coulomb collisions over electron collisions with the neutral components, previously used in the model [4 - 7] for calculating the conductivity region, is excluded at the modified model.

The numerical model was previously validated in a few works [2 - 4], where various total energy, gas and circuit parameters were applied.

INVESTIGATION OF INITIAL PRESSURE INFLUENCE ON ENERGY DEPOSITION IN SPARK DISCHARGE

We applied a capacitor bank with a total capacitance of C = 0.1 μF and inductance of L = 2 μH in the calculation. The charge voltage was U_c = 30 kV. The circuit resistance was 1 Ω. For initial conditions the computation region was filled with molecular nitrogen. The initial gas temperature was T_0 = 300 K. The initial gas pressure was in the range of 0.1…1 MPa. A gap length was 1 mm.

Results of pressure, temperature and conductivity distributions at different time are presented (Figs. 1 - 3).

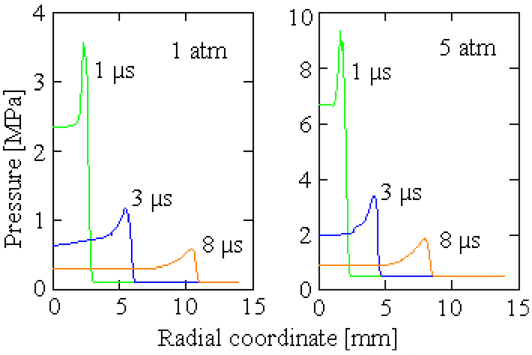

Fig. 1. Pressure distribution at time of 1, 3, and 8 μs by the initial pressure of 1 and 5 atm

It is observed that increased initial pressure causes the delayed spark expansion. Increased gas conductivity by the high initial gas pressure happens due to increased gas temperature in the discharge channel. A delayed expansion takes place both at a shock wave front and at a conductive channel.

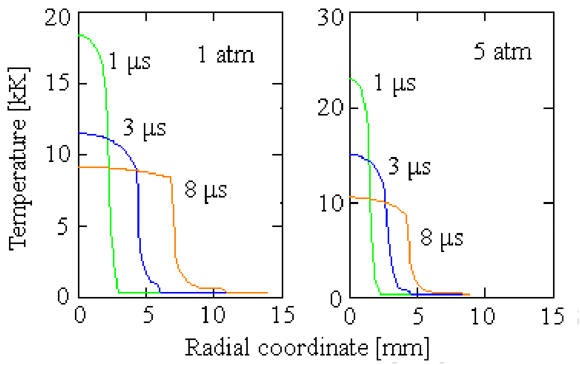

Fig. 2. Temperature distribution at time of 1, 3, and 8 μs by the initial pressure of 1 and 5 atm

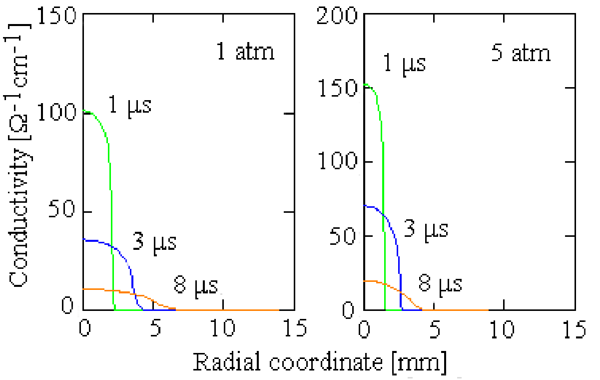

Fig. 3. Conductivity distribution at time of 1, 3, and 8 μs by the initial pressure of 1 and 5 atm

Time histories of deposited energy and efficiency are given on Fig. 4. It is observed that initial pressure growth leads to a rise in the deposited energy and the efficiency. But an energy growth coefficient does not equal a pressure growth coefficient.

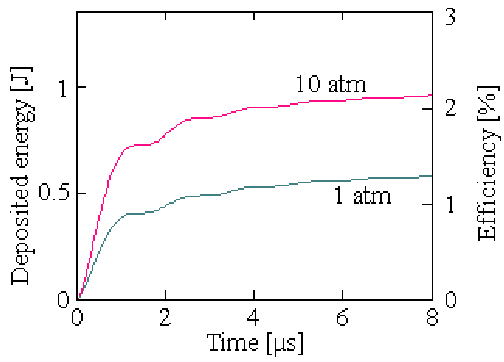

Fig. 4. Time histories of deposited energy and efficiency by the initial pressure of 1 and 10 atm

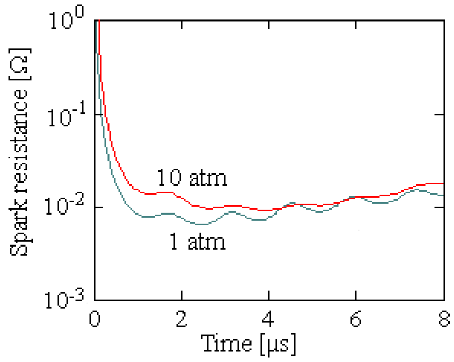

Fig. 5. Time histories of spark resistance by the initial pressure of 1 and 10 atm

It was found out that the initial pressure influences on a discharge current slightly. Thus, a fluctuation of deposited energy at the various initial pressures is caused by changing into the spark resistance. Result of spark resistance simulation is given on Fig. 5.

We evaluated a correlation between the pressure growth and the deposited energy rise. A dynamic correlation coefficient was used, written as

$$k = Q_{dp}(t) / Q_{d1}(t)\,, \qquad (4)$$

where Q_{dp} is the deposited energy by the initial pressure p at time t; Q_{d1} is a deposited energy at time t by the initial pressure of 1 atm.

Dependence of the correlation coefficient on the initial pressure is presented on Fig. 6. It is observed that the correlation coefficient is variable during the spark expansion. A maximum value of the correlation coefficient achieves initially. The coefficient is not linearly proportional to the pressure growth.

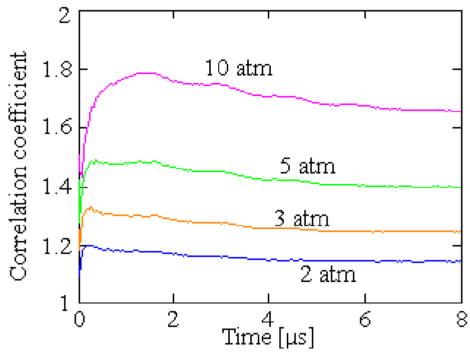

Fig. 6. Time histories of the correlation coefficient by the initial pressure of 2, 3, 5, and 10 atm

An average value of the correlation coefficient can be applied to model a load of spark channel by the any initial pressure when a spark load is formed by atmospheric conditions. For example, the correlation coefficient by the initial pressure of 10 atm is about k = 1.7. Thus, the length of the spark gap formed in the atmosphere can be increased in 1.7 times to simulate the similar load when the initial pressure grows in 10 times.

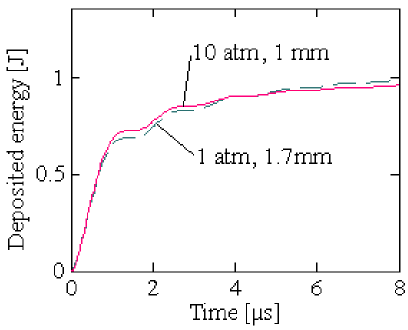

Fig. 7. Deposited energy comparison

Deposited energy comparison when the initial pressure is 10 atm by the gap length of 1 mm and when the initial pressure is 1 atm by the gap length of 1.7 mm is presented on Fig. 7.

Dynamic of energy input plays a significant role. We investigated an influence of the initial pressure on the dynamic of energy deposition. Relative deposition rate was used, written as

$$R_d = \frac{Q_{dp}(t)}{Q_{dp\,\max}} 100\%\,, \qquad (5)$$

where $Q_{dp\max}$ is the total deposited energy by the correspond initial pressure.

It is well known that a major energy deposition happens during the first semi period of the discharge. It is found out that the pressure rise causes a further increase in energy deposited during the first semi period (Fig. 8).

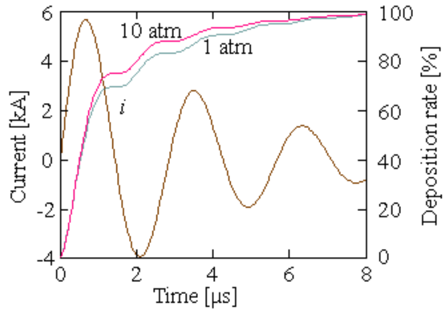

Fig. 8. Time histories of the discharge current and the deposition rate by the initial pressure of 1 and 10 atm

Spark discharge is used as lighting source often. We simulate an initial pressure effect on emitted energy (Fig. 9). It is observed that pressure growth leads to a rise in the emitted energy. Moreover, a growth coefficient of the emitted energy is higher than a growth coefficient of the deposited energy by the similar pressure growth coefficient.

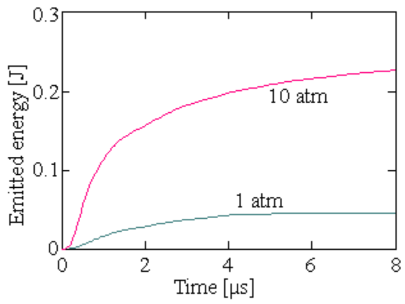

Fig. 9. Time histories of the energy emitted by spark channel by the initial pressure of 1 and 10 atm

Relative emission efficiency was introduced to evaluate a part of energy emitted from a spark channel, written as

$$R_{em} = \frac{Q_{em}(t)}{Q_{dp}(t)} 100\%\,, \qquad (6)$$

where $Q_{em}(t)$ is the emitted energy during the time interval t by the correspond initial pressure.

Simulation result of the relative emission efficiency is given on Fig. 10.

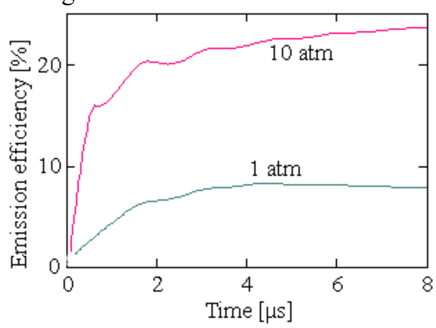

Fig. 10. Time histories of the relative emission efficiency by the initial pressure of 1 and 10 atm

We observe that maximum emission efficiency achieves after the first discharging period of the oscillation.

CONCLUSIONS

An influence of initial pressure on an energy deposition into gas during the spark expansion was evaluated by simulation of a spark channel evolution at various initial pressures. It was found out that a fluctuation of deposited energy at the various initial pressures is caused by changing into the spark resistance. The initial pressure growth leads to a rise in the deposited energy and the efficiency. But an energy growth coefficient is lower than a pressure growth coefficient.

REFERENCES

1. M. Lee, M. Hall, O. Ezekoye, R. Matthews. Voltage, and Energy Deposition Characteristics of Spark Ignition Systems // *SAE Technical Paper* 2005-01-0231.
2. C.J. Benito Parejo, Q. Michalski, C. Strozzi, J. Sotton, M. Bellenoue. Characterization of Spark Ignition energy transfer by optical and non-optical diagnostics // *Digital proceedings of the 8-th European Combustion Meeting*. 2017, hal-01537769.
3. Bronisáaw Sendyka, Wáadysáaw Mitianiec, Marcin Noga, Wáadysáaw Wachulec Determination of thermal efficiency of the spark ignition systems // *Journal of KONES Powertrain and Transport*. 2010, v. 17(1), p. 365.
4. J.J. Lee, J.E. Shepherd. Spark Ignition Measurements in Jet A: part II // *California Institute of Technology*. 2000, Explosion Dynamics Laboratory Report FM 99-7.
5. Gan Cui, Weiping Zeng, Zili Li, Yang Fu, Hongbo Li, Jie Chen. Experimental study of minimum ignition energy of methane/air mixtures at elevated temperatures and pressures // *Fuel*. 2016, v. 175, p. 257.
6. Zulin Peng, Yu Zhang, Dongjie Chen, Jinsong Miao, Jiting Ouyang. Experimental investigation of spark discharge energy // *J. Phys.: Conf. Ser.* 2013, v. 418, p. 012100.
7. A. Zhang, R. Scarcelli, S. Lee, T. Wallner. Numerical Investigation of Spark Ignition Events in Lean and Dilute Methane/Air Mixtures Using a Detailed Energy Deposition Model // *SAE Technical Paper*. 2016, 2016-01-0609.
8. K.V. Korytchenko, S. Essmann, D. Markus, U. Maas, E.V. Poklonskii. Numerical and Experimental Investigation of the Channel Expansion of a Low-Energy Spark in the Air // *Combustion Science and Technology*. 2018 (in print).
9. K.V. Korytchenko, V.I. Golota, D.V. Kudin, O.V. Sakun. Numerical simulation of the energy distribution into the spark at the direct detonation initiation // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2015, № 3, p. 154.
10. K.V. Korytchenko, V.S. Markov, I.V. Polyakov, E.D. Slepuzhnikov, R.G. Meleshchenko. Validation of the numerical model of a spark channel expansion in a low-energy atmospheric pressure discharge // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration"*. 2018, № 4, p. 144.
11. K.V. Korytchehko, A.N. Ozerov, D.V. Vinnikov, Yu.A. Skob, D.P. Dubinin, R.G. Meleshchenko. Numerical simulation of influence of the non-equilibrium excitation of molecules on direct detonation initiation by spark discharge // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration"*. 2018, № 4, p. 194.
12. K.V. Korytchenko, E.V. Poklonskii, P.N. Krivosheev. Model of the spark discharge initiation of detonation in a mixture of hydrogen with oxygen // *Russ. J. Phys. Chem. B*. 2014, v. 8, p. 692.

Article received 14.05.2019

ЧИСЛЕННОЕ ИССЛЕДОВАНИЕ ВЛИЯНИЯ НАЧАЛЬНОГО ДАВЛЕНИЯ НА ВВОД ЭНЕРГИИ В ИСКРОВОЙ РАЗРЯД В АЗОТЕ

К.В. Корытченко, Р.С. Томашевский, И.С. Варшамова, Д.П. Дубинин, А.А. Лисняк, В.А. Липовой

Исследовано влияние начального давления газа на энергию, выделяемую искровым разрядом в азоте при расширении искрового канала. Рассчитано влияние давления на эффективность введения и излучения энергии в канале разряда. Выявлены зависимости динамики энерговвода и коэффициента энергетической корреляции от давления. Предложено использовать среднее значение коэффициента корреляции для моделирования нагрузки искрового канала при любом начальном давлении на искровой нагрузке в атмосфере.

ЧИСЕЛЬНЕ ДОСЛІДЖЕННЯ ВПЛИВУ ПОЧАТКОВОГО ТИСКУ НА ВВЕДЕННЯ ЕНЕРГІЇ В ІСКРОВИЙ РОЗРЯД В АЗОТІ

К.В. Коритченко, Р.С. Томашевський, І.С. Варшамова, Д.П. Дубінін, А.А. Лісняк, В.О. Липовий

Досліджено вплив початкового тиску газу на енергію, що виділяється іскровим розрядом в азоті при розширенні іскрового каналу. Розраховано вплив тиску на ефективність введення і випромінювання енергії в каналі розряду. Виявлено залежності динаміки енергоуводу і коефіцієнта енергетичної кореляції від тиску. Запропоновано використовувати середнє значення коефіцієнта кореляції для моделювання навантаження іскрового каналу при будь-якому початковому тиску на іскровому навантаженні в атмосфері.