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THERMAL RADIATION IN SPARK DISCHARGE

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The work is devoted to numerical study on thermal radiation in spark discharge. The influence of radiative thermal conductivity on the expansion of the spark channel has been established. The study of the effect of value of the capacitance of the discharge capacitor on the energy emitted by the discharge has been carried out. The change in the thermodynamic state of the gas in the spark channel is considered taking into account following factors: change in the capacitance of the discharge capacitor, the length of the discharge gap and the initial gas pressure. The influence of the initial gas pressure and the gap length on the parameters of thermal radiation of a gas under conditions of a constant breakdown voltage supplied to the spark gap is investigated.

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INTRODUCTION

As a source of thermal radiation, a high-current spark discharge is used in various processes. For example, a spark discharge is used for pulsed photolysis and ultrafast photography. Also, a spark discharge is applied to simulate high-temperature radiation-gasdynamic phenomena and in brightness standards.

It is known that during the discharge of a capacitor through the spark gap, only a part of the discharge energy is released in the gas-discharge channel [1]. The energy released at the spark gap is distributed into thermal energy, kinetic energy of the gas flow, absorbed by dissociation and ionization processes, and part of the energy is emitted by electromagnetic radiation. As a result, only part of the discharge energy is radiated. It is of interest to establish the influence of the initial conditions of the discharge and the parameters of the discharge circuit on the efficiency of thermal radiation of the spark channel.

The study of the thermal radiation of the spark channel is presented in [2], where the dependence of the effective radiation temperature on the discharge time is established. Experimental confirmation of the influence of the initial gas pressure on the brightness of the spark discharge radiation was made in [3]. In [4], the influence of the gas type (Xe, Kr, Ar, air, N2, Ne, and He) on the limiting gas temperature which leads to saturation of the radiation brightness was investigated. In a number of works, the influence of the length of the spark gap on the energy input into the spark channel was also established. And in the works [5, 6] the influence of the parameters of the electric discharge circuit on the efficiency of energy input into the spark channel was shown.

Numerical models have been developed to study the development of a spark channel during its expansion [7 -13]. The known models take into account the processes of gas-dynamic expansion of the spark channel, non-equilibrium chemical reactions, ionization, thermal conductivity, and radiation. Among mentioned models, there are models [2 - 4], which take into account radiative heat conductivity. But the contribution of radiative thermal conductivity to the expansion of the spark channel was not considered in these works.

The current study is carried out using the developed numerical model of the spark channel expansion [14 - 16]. In earlier works, the model was validated in the range of spark discharge energies from tens of microjoules to hundreds of joules. Additionally, among other influences, the influence of discharge conditions on the process of thermal radiation by a spark channel was studied in these works. Due to the fact that such studies have been published in different works, a comprehensive understanding of the process of thermal radiation in a spark channel is shown in this work.

NUMERICAL MODEL OF SPARK CHANNEL EXPANSION

The Euler's equations of gas-dynamics for one-dimensional problems endowed with cylindrical symmetry was solved for the multicomponent chemically reactive gas mixture (molecular and atomic nitrogen). Taking into account that the model was described previously in works [14 - 16], we give equations in this work that connected with radiative process only. So, this process is considered by equation

$$\frac{1}{r}\frac{\partial\left[r\left(u\left(\rho\varepsilon+\frac{\rho u^2}{2}+p\right)+k_T\frac{dT}{dt}\right)\right]}{\partial r}+\frac{\partial\left[\rho\varepsilon+\frac{\rho u^2}{2}\right]}{\partial t}= \quad (1)$$
$$=\sigma E^2-W_{\mathrm{em}},$$

where ρ is the gas density; u is the velocity, p is the pressure, ε is the specific internal energy of the gas, k_T is the thermal conductivity, E is the electric field strength, σ is the electrical conductivity of the gas, W_{em} is the radiative loss, r is the radial coordinate, t is the time, T is the gas temperature.

The radiative loss was calculated using the expression

$$W_{em} = \sigma_{SB} T^4 / l_R \,, \tag{2}$$

where σ_{SB} is the Stefan–Boltzmann constant, l_R is the Rosseland mean free path. The equation (2) was applied when the gas temperature exceeds 8.000 K.

In the model the heat conductivity coefficient was calculated using the expression of

$$k_r = k_{el} + k_{rad} \,, \tag{3}$$

where k_{el} is a coefficient of electronic heat conductivity; k_{rad} is a coefficient of radiative heat conductivity.

The coefficient k_{rad} of radiative heat conductivity was calculated using the expression of

$$k_{rad} = \frac{16}{3} \sigma_{SB} T^3 l_R \,. \tag{4}$$

The numerical model (1-20) can be applied when gas-dynamic pressure exceeds the magnetic pressure by an order of magnitude. Description of the simulation procedure is presented in works [15, 16].

The gradients of thermodynamic gas parameters are assumed to be absent for the spark channel axis. It is assumed that initial conditions have no gas dynamic perturbations in the entire computation region.

The validation of the model for thermal radiation of spark discharge is done in [14].

INFLUENCE OF RADIATIVE THERMAL CONDUCTIVITY ON SPARK EXPANSION

To carry out these studies, the calculation of the change in the temperature and density distribution along the radial coordinate of the spark channel was carried out under conditions when radiative thermal conductivity is included and excluded. Thus, the heat conductivity coefficient was represented by an equation in the form $k_r = k_{el} + k_{rad}$ or $k_r = k_{el}$.

The results of calculating the distribution of the thermodynamic parameters of the gas in the spark discharge for a channel expansion time of 30 and 100 ns and for the discharge of a capacitor with a capacitance of C = 1 μF charged at a voltage of 30 kV over a gap length of 10 mm are shown in Fig. 1. In both simulation variants, it was assumed that the inductance of the discharge circuit is L = 2 μH, and the resistance of the electric circuit is R_c = 0.3 Ω. The calculation was carried out for a discharge in nitrogen at an initial gas temperature T_0 = 300 K and an initial gas pressure p_0 = 101.4 kPa. To form a conductive channel, during 10 ns the energy equal to 22 mJ was deposited into the computational domain with a radius of 0.1 mm.

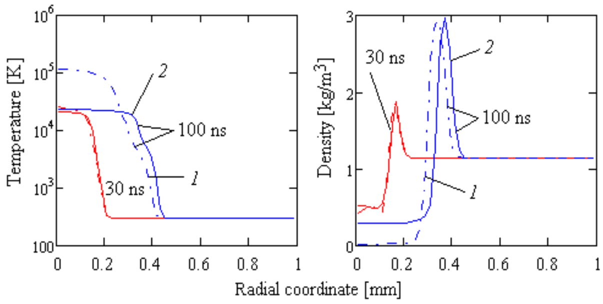

Fig. 1. Distribution of gas temperature and density along the radial coordinate for a time of 30 and 100 ns: 1 – excluding radiative thermal conductivity; 2 – including radiative heat conductivity

According to the simulation results, it was found that if the radiative thermal conductivity is not taken into account, then during 100 ns, 135 mJ energy is introduced into the spark channel, and due to electromagnetic radiation, 35 mJ leaves the discharge. If radiative thermal conductivity is taken into account, an energy of 215 mJ is introduced into the spark channel for a time of 100 ns, and 1.8 mJ leaves with radiation.

From the presented research result follows that if the radiative thermal conductivity is not taken into account, the gas temperature would rises in the spark discharge up to values that not correspond to the of experimental studies results. For example, in calculations, for a time of 100 ns, the gas temperature exceeds 100.000 K. It is observed, on the other hand, that when radiative thermal conductivity is taken into account, the expansion rate of the spark channel increases. As a result of this expansion, there is a decrease in the gas temperature reached in the discharge. In the presented calculation, where radiative thermal conductivity was taken into account, the gas temperature for a time of 100 ns does not exceed 23.400 K. Thus, the intensive expansion of the high-temperature region of the spark channel is provided not only as a result of gas-dynamic processes, but also due to radiative thermal conductivity.

INFLUENCE OF THE CAPACITOR CAPACITANCE ON THE EMITTED ENERGY

This study was carried out for the discharge across a spark gap with a length of l_{sp} = 10 mm using capacitors of different capacitances. In the calculations, the capacitance C of the capacitor was 0.01, 0.05, 0.1, 0.5, and 1 μF. The capacitor charge was equal to U_0 = 30 kV. Thus, the total discharge energy varied in the range from 4.5 to 450 J. The other parameters of the electric circuit did not change. Thus, the resistance of the discharge circuit was R_c = 0.3 Ω, the inductance of the circuit was L = 2 μH. Nitrogen was considered as a working gas at an initial temperature of T_0 = 300 K and an initial gas pressure p_0 = 101.4 kPa. To form a conductive channel, an energy of 22 mJ was deposited into the computational domain with a radius of 0.1 mm for 10 ns.

Calculation results of the energy Q_{rad} emitted by the spark discharge as function of time for different capacitance of the capacitor are shown in Fig. 2.

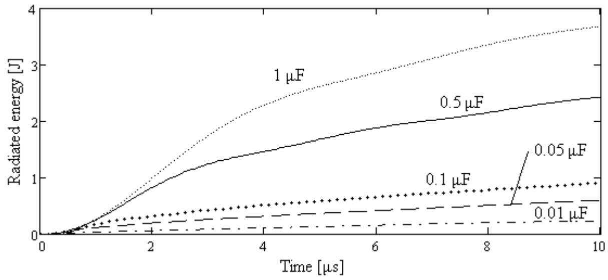

Fig. 2. Time dependence of the energy emitted by the spark discharge for different capacitances of the discharge capacitor

As it can be seen from the obtained result, in the case of an increase in the capacitance of the capacitor there is an increase in the energy emitted by the spark discharge for the same spark development time. We also observe that in the initial period of the spark channel expansion (from 0 to 300…500 ns), a small amount of energy leaves with radiation. This is due to the small volume of gas that radiates in the spark discharge for a given period of time.

Let's estimate instantaneous efficiency η_{rad} of thermal radiation using the following equation

$$\eta_{rad} = \frac{2Q_{rad}(t)}{CU_0^2} \cdot 100\% . \qquad (5)$$

Calculation results for instantaneous efficiency of thermal radiation and different capacitor capacitances is shown in Fig. 3.

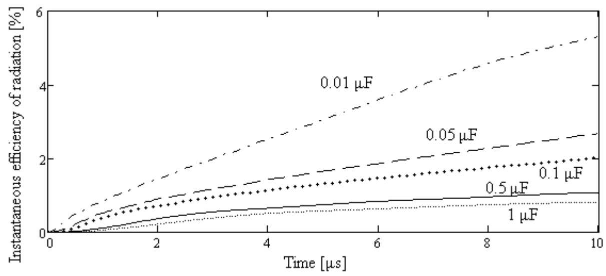

Fig. 3. Instantaneous efficiency of thermal radiation for different capacitances of the discharge capacitor

It can be seen from the obtained results, that in the case of an increase in the capacitance of the capacitor, the instantaneous efficiency of thermal radiation decreases. In particular, when the capacitance is C = 1 μF, we have η_{rad} = 0.82% for the time t = 10 μs, and when the capacitance is C = 0.01 μF, we have η_{rad} = 5.8%. It should be noted that at a fixed time there is a difference in the share of energy released during the discharge for different capacitances. In particular, according to the results of calculations at C = 0.01 μF for a time of 10 μs, about 97 % of the total energy of the discharge is released in the discharge on the resistance of the electric circuit and the spark channel. With a capacitance C = 1 μF for a time of 10 μs, about 77% of the total energy is released in the discharge. Therefore, the total efficiency of thermal radiation may differ from the instantaneous efficiency.

Since the radiated energy is only a part of the energy deposited into the spark channel, the dependence of the energy deposited into the discharge on the capacitance of the discharge capacitor was investigated. The change in the energy released into the discharge versus the discharge time was calculated using the equation.

$$Q_{dep} = l_{sp} \iint E^2 \sigma 2\pi r dr dt . \qquad (6)$$

The results of calculating the energy Q_{dep} introduced into the discharge as function of the discharge time are shown in Fig. 4. We observe that an increase in the capacitance of the capacitor leads to an increase in the energy released into the spark channel. For example, for a time of 10 μs, Q_{dep} = 23.9 J of energy was deposited into the spark discharge at a capacitance of C = 1 μF, that is 5.3% of the total discharge energy. And with a capacitance C = 0.01 μF, Q_{dep} = 2.55 J is released for 10 μs, that is 56.6% of the total discharge energy. It should be noted that the decrease in the efficiency of energy deposition into the spark discharge in the case of an increase in the capacitance of the discharge capacitor was experimentally confirmed in [17].

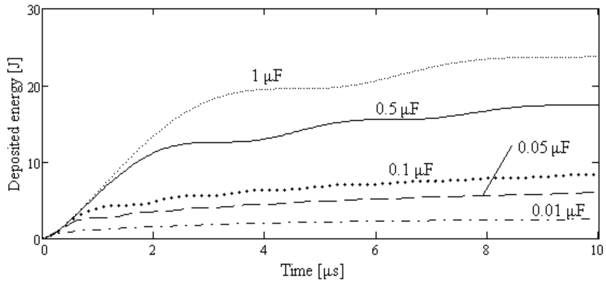

Fig. 4. Dependence of the energy introduced into the spark channel on the discharge time at different capacitances of the discharge capacitor

From the results of comparing the curves of the radiated energy (see Fig. 2) and the corresponding curves of the deposited energy (see Fig. 4), we can conclude that the radiated energy does not linearly depend on the energy released into the spark channel.

To establish the relationship between the deposited energy and the radiated energy at the given time, it was calculated relative efficiency η_{rel} of the thermal radiation

$$\eta_{rel} = \frac{Q_{rad}}{Q_{dep}} 100\% . \qquad (7)$$

Calculation results for relative efficiency are shown in Fig. 5.

It is observed that during the development of the discharge, the share of the radiated energy in the total energy released in the spark channel at the current time increases. Moreover, with an increase in the capacitance of the capacitor, the relative efficiency increases to large values. It was found out that at the initial period of the discharge development, the relative efficiency for the same time interval practically coincides for different capacitor capacitances. This coincidence takes place for capacitance C = 0.01 μF and capacitance C = 1 μF in the time interval from 0 to 400 ns. For capacitors of C = 0.5 and 1 μF, there is a coincidence for 3.5 μs.

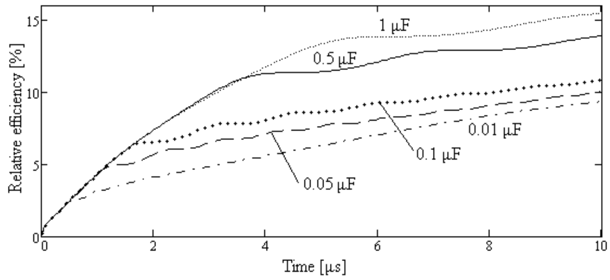

Fig. 5. Dependence of relative efficiency of the thermal radiation from time at different capacitances of the discharge capacitor

To understand the processes that lead to a change in the energy emitted by the spark discharge at different capacitances of the discharge capacitor, we considered the change in the thermodynamic state of the gas in the spark channel. The results of calculating the distribution of gas pressure and temperature for different times along the radial coordinate of the spark channel in the case of capacitor capacitances equal to C = 0.1 and 1 μF are shown in Figs. 6, 7.

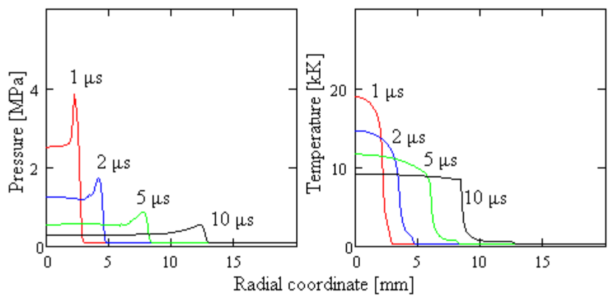

Fig. 6. Distributions of pressure and temperature as function of time, along the radial coordinate of the spark channel when C = 0.1 μF

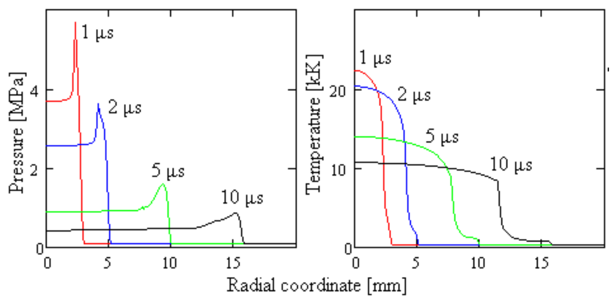

Fig. 7. Distributions of pressure and temperature as function of time, along the radial coordinate of the spark channel when C = 1 μF

As a result of comparing the distributions of the thermodynamic parameters of the gas, it can be concluded that in the case of an increase in the capacitance of the capacitor, the temperature increases, which is reached in the spark discharge for the same time. For example, for a time of 1 μs at C = 0.1 μF, the maximum gas temperature is 19.000 K, and at C = 1 μF, there is a temperature of 22.300 K. An increase in the capacitance of the capacitor also leads to an increase in the expansion rate of the spark channel. For example, for a time of 10 μs at C = 0.1 μF, the radius of the conductive (emitting) spark channel reaches 8 mm, and at C = 1 μF, this radius is 12 mm. As a result of an increase in the volume and temperature of the emitting gas in the spark channel, the energy emitted by the discharge increases.

A decrease in the energy input into the spark channel in the case of an increase in capacitance is associated with a change in the balance of energy release in the spark gap and the resistance of the electrical circuit. Therefore, the study of the effect of the capacitance of the discharge capacitor on the change of the resistance of the spark channel that is changed in time was carried out. The results of calculating the change in the resistance of the spark channel are shown in Fig. 8. For further comparison, Fig. 8 also shows a line reflecting the resistance of the electrical circuit equal to 0.3 Ω. It is observed that only when a capacitor with a capacitance of 0.01 μF is discharged, the spark resistance is practically equal to the resistance of the discharge electric circuit. In this case, 50% of the total discharge energy is released in the spark channel. Therefore, with a decrease in the resistance of the spark channel, which arises in the case of an increase in the capacitance of the capacitor, it leads to a decrease in the share of the energy released in the spark channel from the total discharge energy.

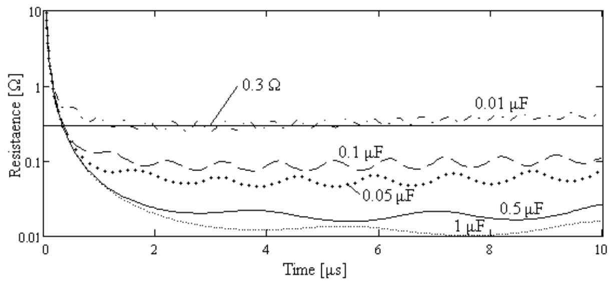

Fig. 8. Change in the resistance of the spark channel as function of time at different capacitances of the discharge capacitor

Let us analyse the relationship between the discharge current and the energy introduced into the spark channel and the radiated energy. The discharge current arising in an electric circuit with a different capacitance that is shown in Fig. 9. Comparison of the time variation of the change in the discharge current from the radiated energy (see Fig. 2) and input energy (see Fig. 4) shows that current pulses are more influenced on the energy input into the discharge than on the radiated energy. In particular, when the current values pass through zero, the termination of energy input into the discharge channel is observed, and at the maximum current we observe a maximum of the energy input power (see Fig. 4).

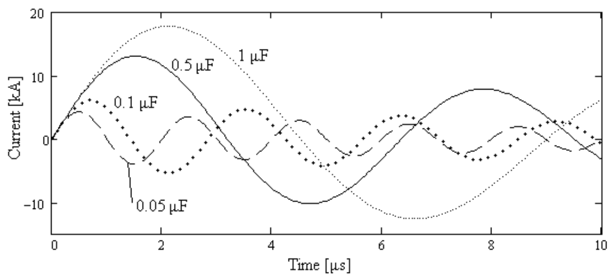

Fig. 9. Discharge current in electrical circuit with a different capacitance of the capacitor

But current fluctuations have less effect on the emitted energy (see Fig. 2) due to the fact that thermal radiation is determined by the current size and thermodynamic state of the emitted gas. And thermogasdynamics processes, under the influence of which there is a change in the size of the radiation region and the gas temperature, are more inert than processes in the electric circuit.

INFLUENCE OF PRESSURE AND GAP LENGTH ON THERMAL EMISSION

Let's consider the situation when the parameters of the energy source do not change, but the parameters of the load change. Thus, we have unchanged parameters of the electrical circuit (R, L, C) and unchanged capacitor charge voltage in this case. A change in the load parameters means a change in the length of the discharge gap and the initial pressure of the working gas. We assume that a uniform electric field is created in the discharge gap due to the shape of the electrodes. Then the dependence of the gap breakdown voltage on the gap length l_{sp} and the initial gas pressure p_0 is represented by Paschen's law in the form

$$U_{br} \sim p_0 l_{sp} . \quad (8)$$

Let's assume that the breakdown of the gas gap occurs under a voltage equal to the voltage of the capacitor charge. Then a fixed voltage of the capacitor charge in the discharge circuit occurs if the increase in gas pressure in the discharge gap is compensated by a directly proportional decrease in the length of the discharge gap, and vice versa.

A numerical study was carried out for an electrical circuit of the following parameters. The capacitance of the capacitor was C = 0.05 μF, the resistance of the discharge circuit was R_c = 0.3 Ω, and the inductance of the circuit was L = 2 μH. The capacitor charge voltage was U_0 = 30 kV. As a working gas it was considered a nitrogen at an initial temperature T_0 = 300 K. In the first calculation variant of this study, it was assumed that the initial gas pressure is p_0 = 101.4 kPa, and the length of the gap is l_{sp}= 10 mm. At the second variant of the study, it was assumed that the initial gas pressure is p_0 = 202.8 kPa, and the gap length is l_{sp}= 5 mm.

The results of calculating the energy emitted by the spark discharge at different load parameters are shown in Fig. 10.

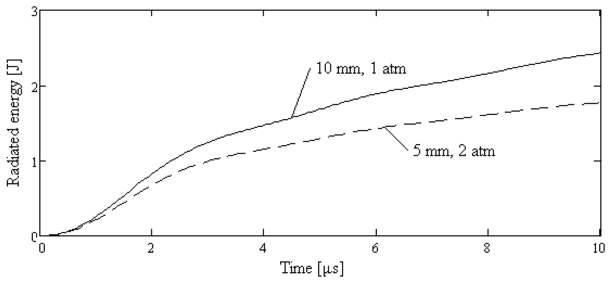

Fig. 10. Time dependence of the energy emitted by the spark discharge for different spark load

It could be find out from the obtained calculation results that an increase in the length of the discharge gap under conditions of a directly proportional decrease in the working gas pressure leads to a decrease in the radiated energy. This result shows that a change in the length of the spark gap affects the change in the radiated energy more intensively than a change in the pressure of the working gas.

According to research presented in the work [6], the energy deposited into the spark discharge, as a rule, is directly proportional to the length of the spark gap. According to the research [16], an increase in the initial gas pressure in two times at an unchanged initial gas temperature leads to an increase in the energy deposited into the spark discharge by no more than 1.2 times. Hence, when the length of the gap is reduced by 2 times and the gas pressure is increased by 2 times, the introduced energy decreases by 2/1.17 = 1.71 times. According to the results of calculations, it was obtained that for a time of 10 μs at p_0= 101.4 kPa and l_{sp} = 10 mm, an energy of 17.76 J is introduced into the spark channel, where 2.43 J of this energy is consumed for radiation. And at p_0 = 202.8 kPa and l_{sp} = 5 mm for a time of 10 μs, an energy of 10.06 J is input into the spark channel, where 1.77 J of this energy is consumed for radiation. Thus, there are changes in the input energy of 17.76/10.06 = 1.76 times. At the same time, in the variants of the study for a 10 μs (see Fig. 10), we have a change in the radiated energy 2.43/1.77 = 1.37 times. Such a deviation of the multiplicity of the change in the emitted energy from the multiplicity of the change in the input energy is explained by the increase in the share of the emitted energy under conditions of increasing gas pressure.

In addition to the radiated energy, an important characteristic of a spark light source is the power of thermal radiation from a unit surface. The calculation of the power of thermal radiation was carried out relative to the surface of the current-conducting channel of the spark by the expression

$$W_{suf} = 2\pi r_{ch} l_{sp} \frac{dQ_{rad}}{dt} . \quad (9)$$

The results of calculating the change in radiative power as function of time for mentioned calculation projects are shown in Fig. 11.

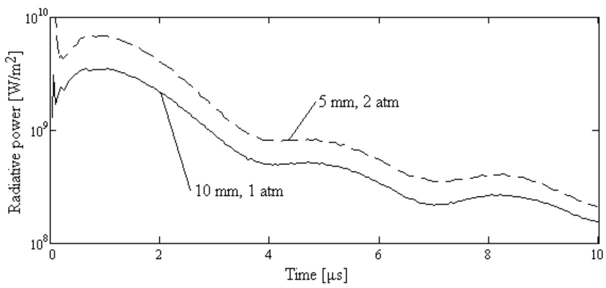

Fig. 11. The power of thermal radiation from a unit of surface in calculating variants

It should be mentioned that in the case of an increase in the gas pressure under conditions of a directly proportional decrease in the gap length, the radiative power increases for the same discharge time. In particular, for a time of 1 μs at p_0 = 202.8 kPa and l_{sp} = 5 mm we have $W_{suf} = 6.805 \cdot 10^9$ W/m^2, and at $p_0 = 101.4$ kPa and $l_{sp} = 10$ mm we have $W_{suf} = 3.55 \cdot 10^9$ W/m^2. We observe a 1.9-times change in radiative power. This effect is explained by the fact that although a reduction in the gap length leads to a decrease in the radiated energy (see Fig. 10), such a reduction in the length also leads to a decrease in the radiation surface area.

CONCLUSIONS

It was established that radiative thermal conductivity together with the gasdynamic process are the main factors leading to the expansion of the high-temperature region of the spark channel. It was found that an increase in the total discharge energy due to increase in the capacitance does not lead to a directly proportional increase in the emitted energy at a fixed time of the spark discharge development. It was established that the decrease in instantaneous efficiency of thermal radiation is caused by a decrease in the efficiency of energy input into the spark discharge. A change in the gap length affects the change in the radiated energy more intensively than a change in the gas pressure. It was found out that in the case of an increase in the gas pressure under conditions of a directly proportional decrease in the gap length, the radiative power increases for the same discharge time.

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ТЕПЛОВОЕ ИЗЛУЧЕНИЕ В ИСКРОВОМ РАЗРЯДЕ

К. Корытченко, Е. Поклонский, Д. Самойленко, Д. Винников, Р. Мелещенко, К. Остапов

Работа посвящена численному исследованию теплового излучения в искровом разряде. Установлено влияние лучистой теплопроводности на расширение искрового канала. Проведено исследование влияния величины емкости разрядного конденсатора на энергию, излучаемую разрядом. Рассмотрено изменение термодинамического состояния газа в искровом канале с учетом следующих факторов: изменения емкости разрядного конденсатора, длины разрядного промежутка и начального давления газа. Изучено влияние начального давления газа и длины промежутка на параметры теплового излучения газа в условиях постоянного напряжения пробоя искрового промежутка.

ТЕПЛОВЕ ВИПРОМІНЮВАННЯ В ІСКРОВОМУ РОЗРЯДІ

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Робота присвячена чисельному дослідженню теплового випромінювання в іскровому розряді. Встановлено вплив променистої теплопровідності на розширення іскрового каналу. Проведено дослідження впливу величини ємності розрядного конденсатора на енергію, що випромінюється розрядом. Розглянуто зміну термодинамічного стану газу в іскровому каналі з урахуванням наступних факторів: зміни ємності розрядного конденсатора, довжини розрядного проміжку і початкового тиску газу. Вивчено вплив початкового тиску газу і довжини проміжку на параметри теплового випромінювання газу в умовах постійної напруги пробою іскрового проміжку.