Determination of energy input in barrier discharge excilamps

M.I. Lomaev

Institute of High-Current Electronics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

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This paper presents calculated results on the voltage drop, power, and excitation energy in the barrier discharge excilamps. To verify the validity of calculations of the above parameters the measurements of energy input to the gas-discharge plasma were made, both with the use of common techniques (calorimeter and volt-coulomb discharge characteristics) and by integrating the calculated excitation power. The results obtained well agree that points to the correctness of the calculations of the above-mentioned excitation parameters in the barrier discharge excilamps.

Introduction

The determination of power and energy characteristics acting on an object under study is traditionally significant when investigating different gas-discharge tubes. A peculiarity of discharges, where a current flow is limited by the dielectric layers (including barrier discharges), as regards the determination of these parameters is a capacitance-resistance character of the load – a discharge cell, in this case. Determination of the input energy can be performed by different methods: (a) by the volt-ampere power in a primary circuit of a transformer of a power supply with the account for its losses; (b) by the calorimetric method using the temperature drop in a cooling water jacket of a discharge cell; (c) by the volt-coulomb discharge characteristic depending on the electric theory of ozonizers; (d) by the measured effective values of current and voltage across a discharge cell with the account for their phase shift.[1–3] The first method (a) will most likely be considered as an estimate. The second method (b) needs for the measurements to be carried out under the determined thermal conditions. When using the relations of the electric theory of ozonizers, consideration must be taken of the voltage value on the discharge gap during the discharge current flow, which is not measured directly. The use of the last-named method is limited by the difficulty in the determination of the shape factor in some cases.

The best suited is the calculation of input energy by the volt-coulomb characteristic, since the current in the circuit and the voltage drop on the discharge cell can be determined from direct measurements. The input energy in gas-discharge plasma during a complete discharge cycle (over one period) is calculated as a shape area in the charge-voltage coordinates. The key disadvantage of this method is the lack of information about the time variation of the voltage drop on a gas-discharge gap and of the excitation power. Knowledge of these characteristics may be important, for example, in creating highly efficient Xe_2 excilamps, in which, as expected, the efficiency of excilamp operation is in many ways determined by the regime of power input in the gas-discharge plasma.[4,5] Besides, this can be useful to gain better understanding of the dynamics of different processes in gas-discharge plasma.

The goal of this paper is determination of the time variation of the voltage drop on the gap, as well as the power and input energy in the barrier discharge excilamp and checking the correctness of calculation of the excitation parameters by comparison of the energy contribution determined for the same experimental conditions by standard methods.

1. Main calculation relations

One of the peculiarities of the discharges, limited by dielectric, is a complicated time and space dependence of the discharge current distribution on the voltage applied to the cell. Depending on the conditions a discharge can take different shapes – from a homogeneous volume shape to a sharply inhomogeneous one with isolated current channels in the form of filaments. As an equivalent electric scheme, different scheme are given in the literature. Most simple one includes a power supply with the voltage $U(t)$ and the capacities of the dielectric C_d and gas gap C_g connected in series.[6] Parallel to the capacitance C_g two antiparallel Zener diodes are set up, limiting the voltage at the gas-discharge gap up to values $\pm U_g$ in the case of an AC power supply of the discharge cell. This scheme is adequate in the case of sinusoidal form of the generator voltage. However, when using short excitation pulses with duration of tens to hundreds of nanoseconds, the voltage at the gap during active phase of discharge is not constant as it takes place for the sinusoidal voltage. Therefore, in this case, to analyze the electric characteristics of the discharge, we must use some different, more common equivalent scheme given in Fig. 1. Such schemes were used in the Refs. 2, 7, etc., in modeling of the barrier discharge. A correct calculation of the input energy in the short-pulse excitation regime is important because in a number of papers on different applications the advantage of this regime is shown as compared with the use of generators of sinusoidal voltage.[4,5,8,etc.] At the same time, in Ref. 9 there are indications that it is impossible to use traditional techniques to determine the input energy from the volt-coulomb characteristic in the case of a short-pulse excitation.

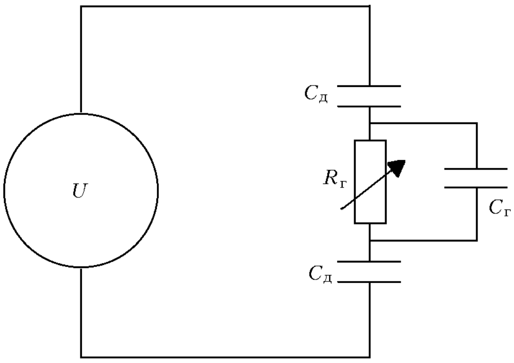


Fig. 1. Equivalent circuit scheme: U is the generator voltage; C_d is the capacitance of dielectric barrier; C_g is the gas discharge gap capacitance; R_g is the gas discharge plasma resistance.

In this paper, the voltage drop at the discharge gap $U_g(t)$ was assumed to be dependent on time during the active discharge phase and varying from the breakdown voltage to the extinction voltage. Prior to the gas gap breakdown the cell is similar to the capacity voltage divider, because in this case, most of voltage is applied to the capacity C_g and the gas discharge gap because in the most cases $C_d \gg C_g$. After the breakdown the capacity C_g is shunted by the discharge gap resistance R_g, in this case the input energy to plasma as an active load takes place. To calculate the input power $P(t)$ into plasma, we need for a knowledge of the voltage drop $U_g(t)$ and the magnitude of an active current component in the discharge gap $I_a(t)$:

$$P(t) = U_g(t)\, I_a(t). \tag{1}$$

The quantity $U_g(t)$ can be found using the second Kirchhoff rule with the use of experimentally measured quantities of the time variation of the voltage at the discharge cell $U(t)$ as well as the voltage drop on the dielectric capacitance $U_d(t)$:

$$U_g(t) = U(t) - U_d(t). \tag{2}$$

It should be noted that the voltage $U(t)$ is equal, at every moment in time, to the difference of the generator electromotive force and the voltage drop on the generator internal resistance. The voltage $U_d(t)$ can be calculated if we know the quantities of a displaced charge $Q(t)$ and the capacitance C_d:

$$U_d(t) = Q(t)/C_d. \tag{3}$$

A charge displaced in circuit can be determined at least by two methods. First, by integrating the current with the account for the initial conditions $Q(t = 0) = Q_0$:

$$Q(t) = \int_0^t I(t')\, dt' + Q_0, \tag{4}$$

Second, $Q(t)$ can be determined if we know the voltage drop $U_{\text{suppl.}}(t)$ at the supplementary capacitance $C_{\text{suppl.}}$ connected in series with the discharge cell:

$$Q(t) = U_{\text{suppl.}}(t)/C_{\text{suppl.}}. \tag{5}$$

The magnitude of C_s is determined based on geometric dimensions of the cell and permittivity of the dielectric used or the slope of appropriate parts of the volt-coulomb loop.[1–3] Using Eqs. (2), (3), (5) we can write equations for $U_g(t)$

$$U_g(t) = U(t) - Q(t)/C_d. \tag{6}$$

It can show that the value of active current component $I_a(t)$ can be determined with the use of experimentally recorded total current $I(t)$:

$$I_a(t) = I(t)\,\frac{C_g + C_d}{C_d} - C_g\,\frac{\partial U}{\partial t} = I(t) - C_g\,\frac{\partial U_g}{\partial t}. \tag{7}$$

The excitation power $P(t)$ is expressed from Eqs. (1) and (6) as

$$P(t) = \{U(t) - Q(t)/C_d\}\, I_a(t). \tag{8}$$

The input energy in the plasma as function of time $E(t)$ is determined by integrating Eq. (8):

$$E(t) = \int_0^t P(t')\, dt'. \tag{9}$$

Equations (6), (8), and (9) were used in the present paper to calculate the voltage at the discharge gap, excitation power, and energy injected in plasma as functions of time using the data obtained in the experiment.

In the specific cases we must consider the validation of Eq. (7) because when deriving this equation it was assumed that the value of plasma permittivity, in the general case of a medium with dispersion, approximately equals to 1. The expression for permittivity of plasma depending on a cyclic frequency of the applied field ω (Ref. 10) is given in the form:

$$\varepsilon(\omega) = 1 - \frac{4\pi e^2 n_e}{m(\omega^2 + v_m^2)} = 1 - \frac{\omega_p^2}{\omega^2 + v_m^2}, \tag{10}$$

ω_p is the plasma frequency, v_m is the effective frequency of the electron collisions, n_e is the electron density, e is the electron charge. The estimation of the value $\varepsilon(\omega)$ for conditions of the experiment performed shows that, first, there is a lack of the dependence ε on ω, since $\omega \ll v_m \sim 10^{12}\ \mathrm{s}^{-1}$. Second, at electron concentration in the range from 10^{12} to $10^{14}\ \mathrm{cm}^{-3}$, typical for a barrier discharge, the value ε is 1–0.9.

2. Experimental conditions

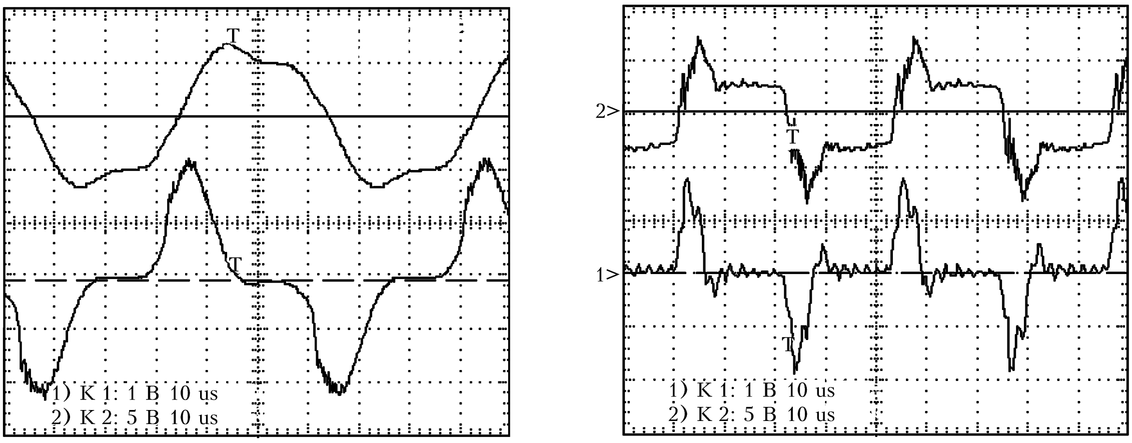
In the experiment we used the excilamps of the coaxial design with two dielectric barriers.[11] For excitation the following regimes were used: regime A – sinusoidal voltage pulses at 17 kHz frequency, and regime B – short (0.1–2 μs at the base) one- or bipolar voltage pulses at 93 kHz frequency. In the first case a lamp of 10 cm length was used, the diameters of external and internal tubes were 4 and 2 cm, respectively. In the second case the corresponding dimensions of the lamp were 47, 6.5, and 4.3 cm. As electrodes the metal foil and grid were used placed on the inner surface of the internal tube and on the outer surface of the external tube. The thickness of quartz tubes, used for preparing excilamps, was about 2 mm. The current pulses $I(t)$ and the voltage across the discharge cell $U(t)$ were recorded with the use of a current shunt and a voltage capacity divider. Electric signals, including those from a supplementary capacity $U_{\text{suppl.}}(t)$ enter in an oscilloscope TDS-220. Figure 2 shows typical oscillograms of the current pulses and voltage on the lamp electrodes taken as the input data for calculating the excitation parameters.

3. Results of determination of the input energy using different methods

To assess the correctness of determination of the excitation parameters, two checks were carried out. First, for regimes A and B the input energy over one period and mean excitation power were determined first by Eqs. (6)–(9), and then for the same experimental conditions – using the commonly accepted method – by the volt-coulomb characteristic. Second, a supplementary experiment was carried out using a two-barrier excilamp of 70 cm length (the excitation regime B). In the course of this experiment, the mean excitation power was determined by three methods, namely, calorimetrically, using the volt-coulomb discharge characteristic, and by Eqs. (6)–(9).

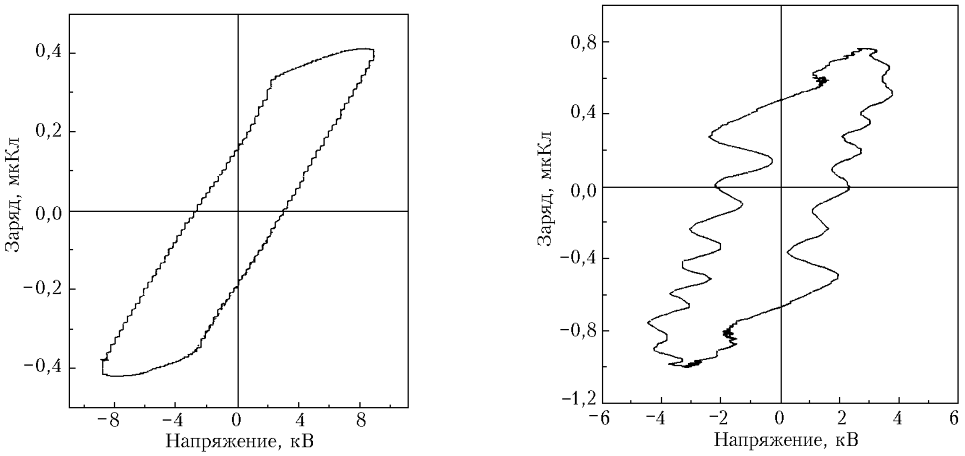
Figures 3*a* and *b* show the volt-coulomb discharge characteristics for both excitation regimes in the first case. The charge integration with respect to voltage enables one to calculate the input energy for one cycle (period), and the product of this energy by the frequency gives mean excitation power. The corresponding values are 4.5 mJ, 76 W (Fig. 3*a*) and 5.7 mJ, 525 W (Fig. 3*b*). A characteristic feature is the relative constancy of the reduced voltage (≈ 2.9 kV) using a harmonic sinusoidal oscillator. And vice versa, in the case of the short pulse excitation (Fig. 3*b*) the charge-voltage loop has a complex shape with the characteristic S-shaped intervals. Besides, we observe a characteristic feature of current flowing in different directions that is evidently a result of the design feature of the excilamp. The values of the capacitances C_{d} and C_{g} are determined from the slopes of the corresponding parts of the volt-coulomb loops. In this case a certain uncertainty occurs for the regime B. The values C_{d} and C_{g} can be tested independently by calculating these values based on the geometric dimensions of the discharge cell as well as by the trial-and-error method using the condition of current and voltage drop cophasing at the gas-discharge gap. The results of calculation using Eqs. (6)–(9) are the following: 4.46 mJ and 75.7 W for the conditions of Fig. 3*a*; 5.65 mJ and 525.5 W for the conditions of Fig. 3*b*. Figure 4 shows the curves of current, voltage on the discharge gap as well as the curves of the excitation power and the energy injected into plasma.

The mean excitation power, obtained from the volt-coulomb discharge characteristic using the calorimetric method (with the account for heat carried away by the water flow cooling the excilamp and dissipated by a heat-insulating layer) and based on Eqs. (6)–(9) in the supplementary experiment, equals 204, 197, and 199 W.



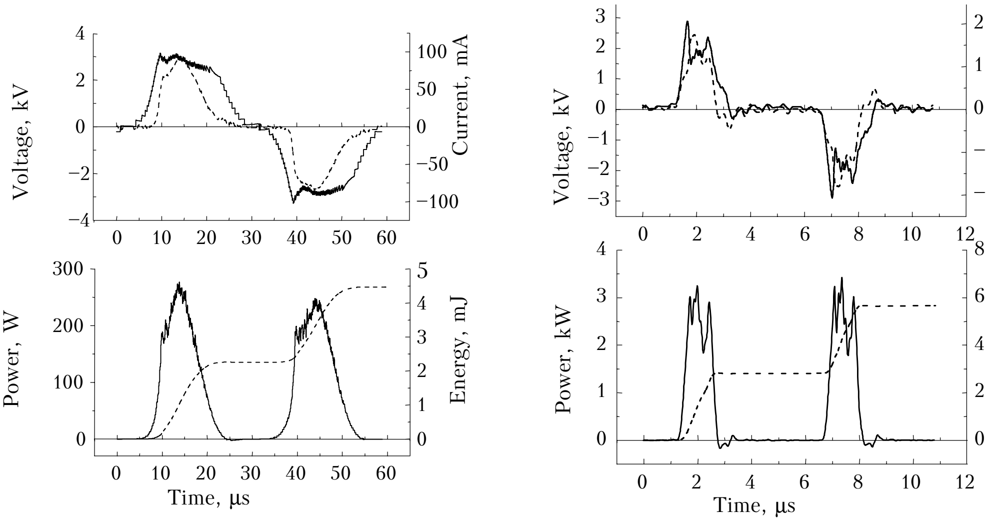
a *b*

Fig. 2. Oscillograms of current pulses $I(t)$ (channel 1>) and voltage $U(t)$ (channel 2>) on the lamp electrodes for sinusoidal (*a*) – regime A and short bipolar voltage pulses (*b*) – regime B.



a *b*

Fig. 3. Volt-coulomb characteristics of the discharges for regimes A (*a*) and B (*b*).



a *b*

Fig. 4. Calculated curves of active current component and voltage at the gas-discharge gap, excitation power and input energy during one period for regimes A (*a*) and B (*b*). Solid curves denote the voltage and power; dashed curves denote the current and power.

Conclusion

The calculations of the excitation parameters, namely, voltage drop, active current component at the discharge gap, excitation power and energy, as well as the measurements of input energy and mean excitation power by different methods in the barrier-discharge-pumped excilamps have shown that the mean excitation power determined by the calorimetric method, volt-coulomb discharge characteristic, and by the method of power integration differs by no more than ~5%. The account for the effect of capacitance of the gas discharge gap C_g is most significant at short-pulse excitation and makes it possible to obtain more information on the parameters of a single excitation pulse and the mean excitation power.

Acknowledgments

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