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Investigation of the corona current in a vacuum bulb

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Abstract. The dependence of the negative corona current on the gas pressure was studied experimentally and theoretically in view of designing a gas-pressure sensor to be applied in the production of light bulbs. The gas pressure was varied in the range 1×10^{-2} Torr – 7.4×10^{2} Torr. The dependence of the current on the gas pressure is characterized by a strong heterogeneity. This allowed the implementation of a prototype of a high-speed sensor for a wide range of gas pressures. A mathematical model was developed of the negative corona current behavior by taking into account the ionization of the gas molecules, the attachment and detachment of electrons, the charge drift and the surface ion-electron emission. The results of the numerical simulations describe satisfactorily the experimental dependences.

1. Introduction

Studying of the negative corona current dependence on the gas pressure is of importance, particularly in what concerns the problem of implementing sensors for fast measurement of the gas pressure (air, nitrogen, argon, etc.) in the manufacture of light bulbs. Such measurements must be performed in the pressure range of 1×10^{-2} Torr – 1×10^{3} Torr within a time interval not exceeding 0.1 s – 0.2 s. This requirement has to do with the fact that the time of pumping and filling the light bulb gas at one position on the factory carousel is in the order of 1.8 s. At present, the gas pressure in light bulbs on a production line is not measured under dynamic conditions due to the large inertia of the known industrial sensors and their narrow operating range. For example, the thermal sensors of the VT-3 and FAB-1 type [1] have a time constant in the order of several seconds and cover a low gas-pressure range (in the order of 0.01 Torr – 30 Torr). The Pirani thermal-conductivity sensor [2] has the same inertia characteristics. Low-inertia sensors, such as the PMDH-1 deformation-discharge type [3] and the Baratron membrane-capacitive type [2] do not cover the pressure range required. Choosing the negative corona as a gas-pressure sensor is related to its characteristic property of undergoing pulsations and to the strong dependence of its parameters on the concentration of electronegative gases [4-7]. In particular, the corona pulses charge and current significantly decrease as the oxygen concentration in argon and nitrogen is increased.

2. Experimental setup

The measurements were carried out on the setup presented schematically in figure 1. It consists of a corona-discharge unit, a high-voltage power supply U, a measuring unit, intermediate memory and an inverter. The discharge unit is a metal bulb whose volume is equal to the volume of a typical light bulb. The cathode is a thin needle with a radius of 20 μm – 100 μm made of refractory metal. The anode is a flat metal disk with a diameter of 35 mm. The length, *d*, of the discharge gap is in the order of 0.6 cm. Vacuum-tight leads allow the high voltage to be fed in (through the limiting resistance R_o) and the output signal to be fed out (through the measuring resistance R_m). The high-voltage power supply provides a maximum discharge current of 70 mA and a minimum current of 0.1 mA with an accuracy of 0.3%. The measurement unit and intermediate memory consist of an analog-digital converter (ADC) type ADS1286 and a PIC16F876 processor-controller. The corona current detected, which can be as low as a few μA at low gas pressures, is amplified and digitized; the data obtained is stored in the intermediate memory and red by the inverter, which converts them into gas-pressure readings and displays them. The bulb is connected to a vacuum system equipped with a high-precision manometer and a PMT-2 type vacuum sensor. The system is evacuated by a 2NVR-5DM type vacuum pump; the air inflow is controlled precisely by a needle valve.

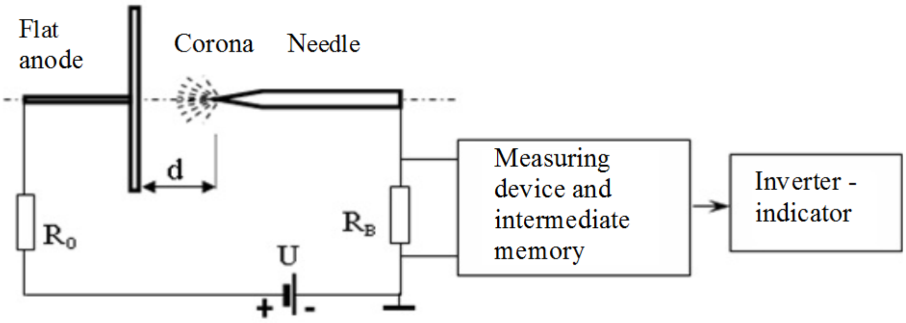

Figure 1. Schematic of the experimental setup**.**

3. Measurement results

Periodical pulsations were observed when a constant high voltage in the range 1500 V – 2000 V was applied to the anode-cathode gap. The average current reachs values in the order of 10^{-6} – 10^{-5} A. The fluctuations in the pulse rate and current amplitude were minimized by selecting optimal values of the voltage and the limiting resistance. Under such conditions, we recorded the pulse shape and duration and the peak and average currents. The shape and the other parameters of the negative-corona current pulses, as well as their dependence on the concentration of oxygen, differed substantially in the different gases. Thus, the current amplitude and the pulse duration and charge in N_2 were considerably greater than in air, whith the pulse rate being lower.

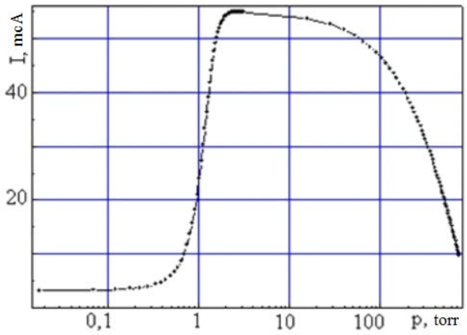

Figure 2. Typical measured dependence of the corona current on the air pressure.

Figure 2 presents a typical dependence of the corona current on the air pressure measured in the range 10^{-2} – 740 Torr. As one can see, the shape of curve $I(p)$ is complex. As the pressure is raised, the current rises sharply from a few to several tens of μA around an air pressure of 1 Torr. Then it forms a slightly inclined plateau in the range of 1 – 10 Torr, to fall gradually to a level in the order of 10 μA at an air pressure of 740 Torr.

Figure 3 shows a typical time dependence of the corona sensor current at one position on the factory lamp carousel. It is recorded every 0.2 seconds during the lamp being purged on the gas-vacuum line. As can be seen, within the time limits of the bulb residing at one position on the carousel (1.8 s), the current reaches maximal and minimal values and an exponential "saturation" of the current is observed. This is indicative of the possibility of applying this technique of fast gas pressure measurements to industrial production of light bulbs.

4. Modelling the corona discharge

Below we describe a simplified model of the negative corona current pulsation in a sharply non-uniform electric field. The following elementary kinetic processes were taken into account: ionization, excitation of gas molecules by electron collisions, ionization by photons, attachment of electrons to oxigen moleculs, their detachment from the O_2^- ion due to collisions, charge drift and surface photo- and ion-electron emission. The numerical computation was based on the differential continuity equations for fluxes of positive and negative ions and electrons, supplemented by Poisson's equation for an electrical field in a quasi-one-dimensional space:

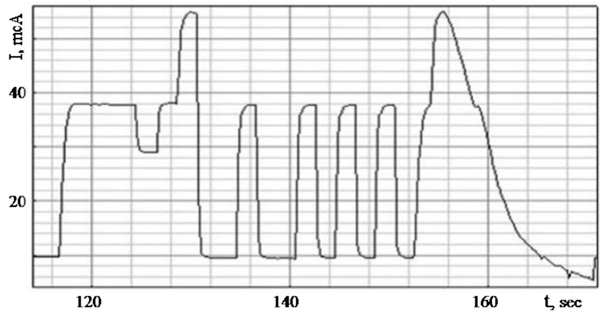

Figure 3. Typical plot of measured corona current in gas sensor on time of its recording.

$$\frac{\partial n_e}{\partial t} + div(w_e n_e) = \alpha n_e w_e - \eta n_e w_e + k_d n_n n_0 \quad , \tag{1}$$

$$\frac{\partial n_p}{\partial t} - div(w_p n_p) = \alpha n_e w_e \, , \tag{2}$$

$$\frac{\partial n_n}{\partial t} + div(w_n n_n) = \eta n_e w_e - k_d n_n n_0 \, , \tag{3}$$

$$divE = 4\pi e(n_p - n_e - n_n) \, . \tag{4}$$

Here n_e, n_p, n_n are the densities of electrons and positive and negative ions and w_e, w_p, w_n are their drift velocities; α, η, k_d are the ionization, attachment and detachment coefficients of the main gas molecules of density n_0. The boundary conditions for positive and negative ions are self-evident: their number density is equal to zero at the anode and the cathode. The boundary condition for electrons at the cathode ($x = 0$) is formulated in terms of the secondary ion emission coefficient, γ_i:

$$j_e(0,t) = \gamma_i \cdot j_p(0,t) \, , \tag{5}$$

where $j_e = n_e \cdot w_e$ and $j_p = n_p \cdot w_p$ are the electron and the positive ion current densities.

Because of the very low current density of the negative corona, it was assumed that, during the pulsation period, the gas temperature is constant at all discharge points. Under this condition, the coefficients of kinetic processes involving neutral particles are constant in time, while those related to ionized particles depend on the local field intensity only. The shape of the current channel was set by choosing two discharge gap regions: the cathode (generating) one as cylindrical, and the drift one, as parabolic. The dependence $F \sim n_p^{2/3}$ was assumed for the current channel cross-section on the positive ion density n_p.

Taking into account that the main current pulse characteristics in a negative corona are determined by the cathode generating region [4-7], for this region we used formulas only for the positive ion flow current $I_p = j_p \cdot S$ and the displacement current $I_{dc} = dE/dt$, where S is the square of the cathode surface and E is the electrical field strength on the cathode surface. Thus, the cathode current I_c at any point in time is defined as $I_c(t) = I_p(t) + I_{dc}(t)$. The total corona current was obtained by the summation $I_{total} = \Sigma I_c(t)\Delta t$ for several tens of current pulses. Bearing in mind the characteristic times of the various processes, the time step Δt for the numerical solution of the equations was set within the range 10^{-11} s – 10^{-9} s. The differentiations were carried out on a non-uniform spatial grid with 160 cells and a minimal step of 10^{-4} cm on the cathode surface.

5. Numerical modelling results

The numerical simulation yielded the dependence of the average current on the air pressure in the discharge gap. The corona parameters used were set close to the experimental ones: d = 0.6 cm, r_0 = 0.004 cm, U = 2300 V, $R = 10^6$ Ω. Figure 4 shows typical dependence of the current on the air pressure in the range of 200 Torr– 740 Torr. In case 2, the cathode tip radius and the current-channel radius in the cathode zone increase in an inverse proportion to the gas pressure, in contrast with case 1, where they are constant.

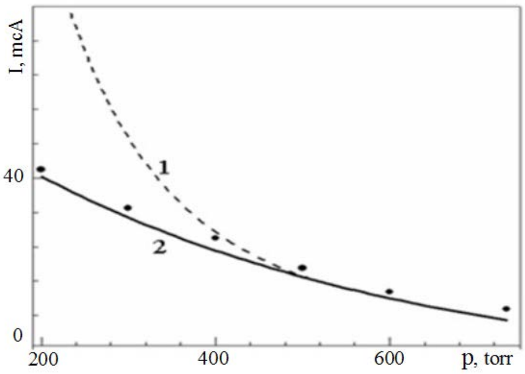

Figure 4. Corona discharge current dependence on air pressure: dots - measured values, 1, 2 - the data of numerical simulations.

As it can be seen, the current values calculated (curve 2) are sufficiently close to the measured ones within the entire range of air pressures. At lower gas pressure (240 – 400 Torr), a better agreement between the simulation and the experimental results was achieved by increasing the working area of tip radius and the cathode-current channel to values in the order of 0.05 cm.

6. Conclusions

The complex dependence of the negative corona current on the air pressure was measured and its nature was partly explained. The technique of measuring the gas pressure based on the corona current is suitable for use in the production of light bulbs. A more detailed description of the corona-current dependence on the gas pressure would require a detailed analysis of the dynamics of the variation of the working cathode surface size during the discharge transition to a glow mode.

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