

CORONA-TYPE SENSOR FOR MEASURING GAS PRESSURE AND VACUUM

Annotation – Negative corona current dependence on gas pressure was studied experimentally and theoretically in view of designing a gas-pressure and vacuum sensor. The gas pressure was varied in the range $1 \cdot 10^7 - 7.4 \cdot 10^2$ Torr. The dependence of corona current on 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 numerical simulations describe satisfactorily the experimental dependences.

Keywords: corona, vacuum sensor, numerical simulation, ionization, electron attachment.

ВАСИЛЬ ЧИГІНЬ

Національна академія сухопутних військ України ім. гетьмана Петра Сагайдачного

ДАВАЧ КОРОННОГО ТИПУ ДЛЯ ВИМІРЮВАННЯ ТИСКУ ГАЗУ І ВАКУУМУ

Експериментально і теоретично вивчалась залежність струму негативної корони від тиску газу з метою створення давача тиску газу і вакууму. Тиск газу змінювався в області $1 \cdot 10^2 - 7,4 \cdot 10^2$ тор. Залежність струму корони від тиску газу характеризується сильною неоднорідністю. Це дозволило створити макет швидкісного давача в широкій області тиску газу. Математична модель струму негативної корони передбачає іонізацію молекул, прилипання і відлипання електронів, дрейф зарядів і поверхневу іонно-електронну емісію. Результати числового моделювання задовільно описують експериментальні залежності.

Ключові слова: корона, давач вакууму, числове моделювання, іонізація, прилипання електронів.

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 $1 \cdot 10^2$ Torr – $1 \cdot 10^3$ 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 concentration of oxygen 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, the measuring unit, the intermediate memory and the inverter. The discharge unit is the metal bulb whose volume is equal to the volume of a typical light bulb. The cathode is the thin needle with the radius of 20 μm - 100 μm made of refractory metal. The anode is the 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 read by the inverter, which converts them into gas-pressure readings and displays them. The bulb is connected to the vacuum system equipped with the high-precision manometer and the PMT-2 type vacuum sensor. The system is evacuated by the 2NVR-5DM type vacuum pump; the air inflow is controlled precisely by a needle valve.

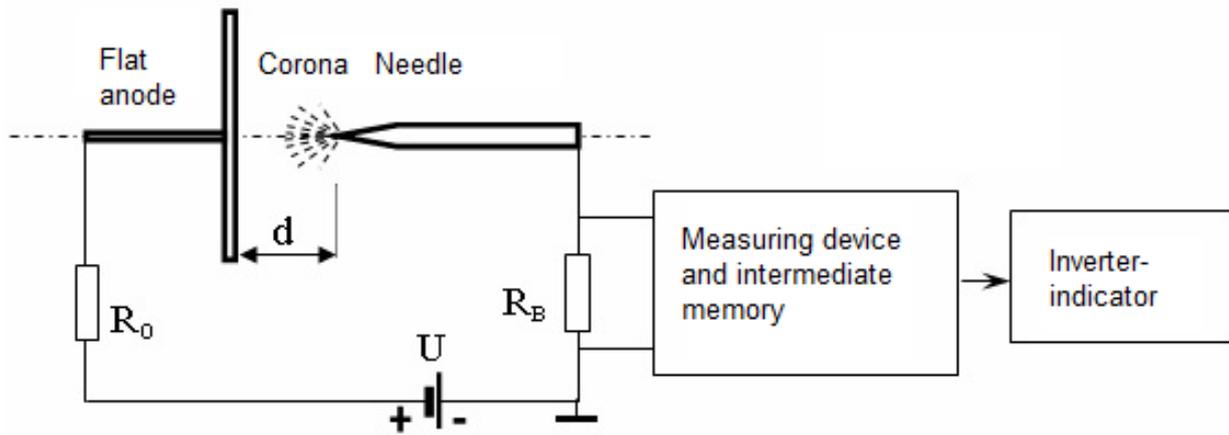


Figure 1 – Schematic of the experimental setup

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 reaches 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, the pulse shape and duration and the peak and average currents were recorded. 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, which the pulse rate being lower.

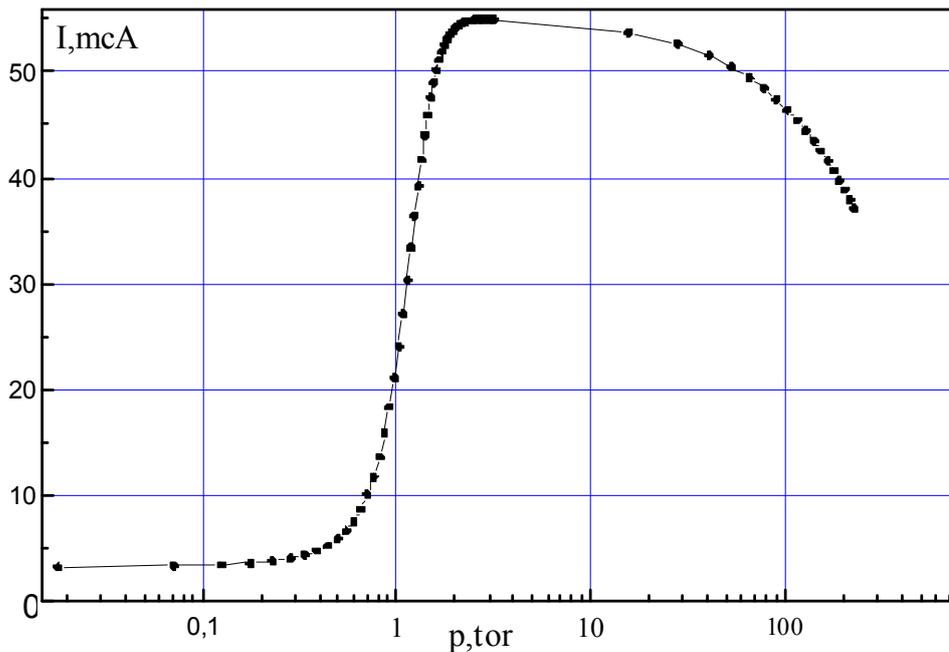


Figure 2 – Typical measured dependence of the corona current on air pressure

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 $10 \mu A$ 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.

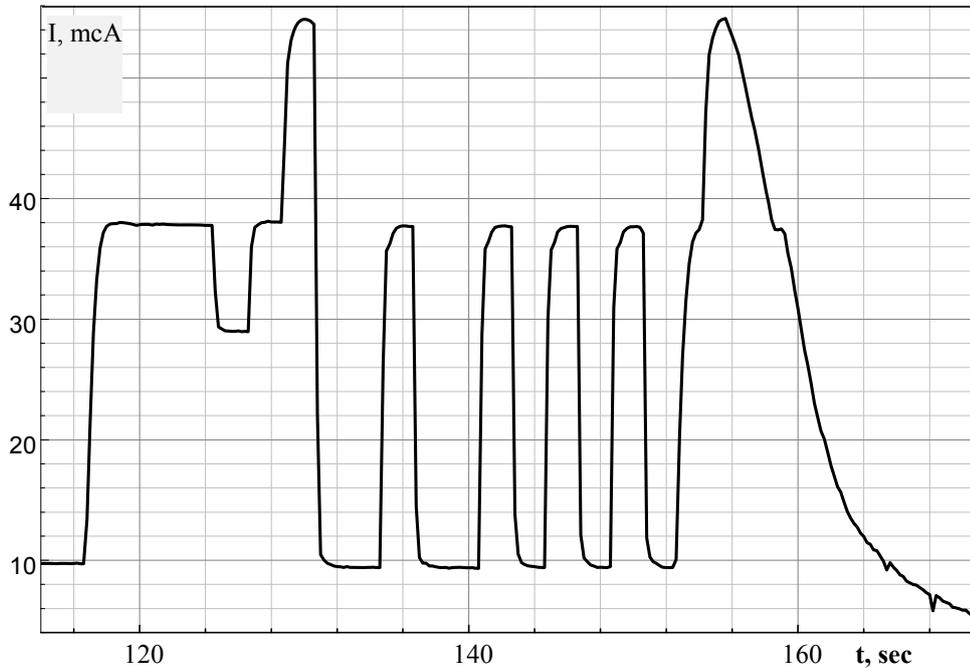


Figure 3 - Typical plot of measured corona current in the gas sensor on time of its recording

3. Modelling the negative corona current

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: an ionization, an excitation of gas molecules by electron collisions, an ionization by photons, an attachment of electrons to oxygen molecules, their detachment from the O_2^- ion due to collisions, a charge drift and a 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:

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

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

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

$$\text{div}E = 4\pi e(n_p - n_e - n_n). \quad (4)$$

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 an ionization, an attachment and a 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 an anode and a cathode. The boundary condition for electrons at cathode ($x = 0$) is formulated in terms of a secondary ion emission coefficient, γ_i :

$$j_e(0, t) = \gamma_i j_p(0, t), \quad (5)$$

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

It was assumed, that the basic kinetic gas-discharge processes develop according to the next schemes:

- a molecule and atom ($M = N_2, Ar$) ionization by an electron impact



- an attachment of electron due to a collision of three particles (M is third one, N_2 or Ar)



- an electron detachment from O_2^- ion by a molecule impact ($M = N_2, Ar$)



Formulas and coefficient constants of kinetic processes

№	Coefficient			Constant		Energy range	Literature
	Process Particle	Symb. Dimen	Formula	A	B		
1	Ionization N ₂	α cm ⁻¹	$\alpha / p = A \exp(-Bp / E)$	8.8	275	E/p, V/(cm·torr) 27-200	8
2				12.0	342		
	Ar			0.01	31	5-22	
				12.0	180	22-600	
3	Attachment N ₂ + O ₂	k_a cm ⁶ /s	$k_{aN_2} \cdot n_{N_2} \cdot n_{O_2} +$ $+ k_{aO_2} \cdot (n_{O_2})^2$	k_{aN_2} $0.16 \cdot 10^{-30}$		T=300° K	8
4	Ar + O ₂		$k_{aAr} \cdot n_{Ar} \cdot n_{O_2} +$ $+ k_{aO_2} \cdot (n_{O_2})^2$	k_{aAr} $0.1 \cdot 10^{-30}$		T=300° K	9
5	Detachment N ₂ + O ₂ ⁻	k_d cm ³ /s	$f(E/n)$, graphic & tabular data	$2 \cdot 10^{-14}$		E/n=100 Td	10
6	Ar + O ₂ ⁻		$f(E/n)$, graphic data	$3.8 \cdot 10^{-9}$		E/n=1000 Td	
				$2.1 \cdot 10^{-13}$		E/n=150 Td	11
				$1.1 \cdot 10^{-9}$		E/n=3800 Td	

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 .

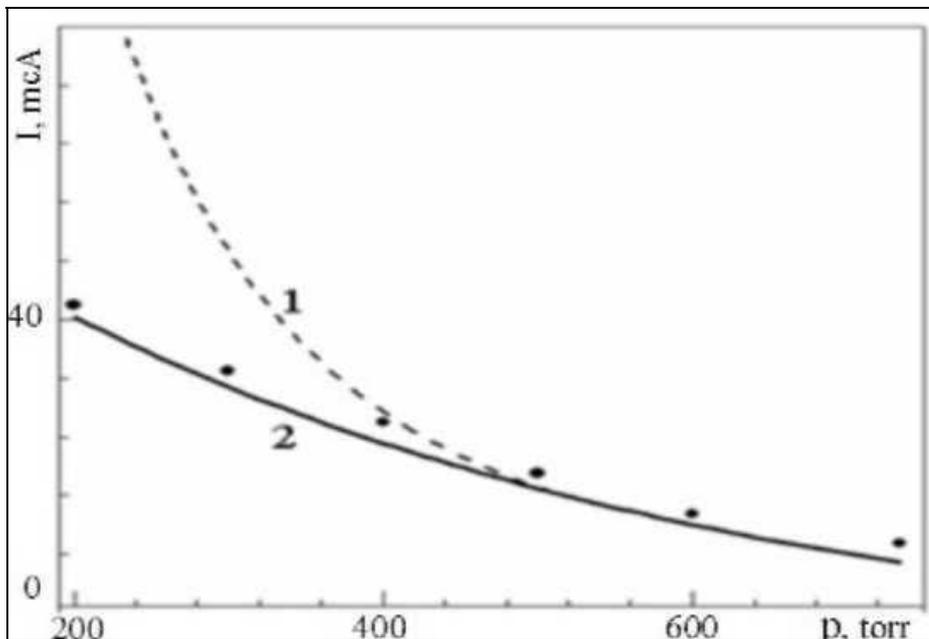


Figure 4 - Corona discharge current dependence on air pressure: dots - measured values, 1, 2 - the data of numerical simulations

Taking into account that the main current pulse characteristics in a negative corona are determined by a cathode generating region [4-7], for this region we used formulas only for a positive ion flow current $I_p = j_p \cdot S$ and the displacement current $I_{dc} = dE/dt$, where S is a square of cathode surface and E is the electrical field strength on 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 a summation $I_{total} = \sum I_c(t) \Delta t$ 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^{-1} s- 10^{-9} s. The differentiations were carried out on the non-uniform spatial grid with 160 cells and the minimal step of 10^{-4} cm on the cathode surface.

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 the 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.

As it can be seen, the calculated current values (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.

Conclusion

The complex dependence of the negative corona current on the gas 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 of gas discharge.

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