An Investigation of High-Frequency Discharge

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The striking and maintaining voltages have been investigated in argon, neon and hydrogen as a function of gas pressure and geometry of discharge space in the frequency range from 57 to 500 mc. It has been established that boundary conditions at the electrodes and walls of the discharge tube have a substantial influence on the striking and maintaining voltages. As the frequency of the a-c field is increased from 57 to 500 mc, the curves showing striking and maintaining voltages vs. pressure in hydrogen, argon and neon are displaced into the high voltage region, and the minima of these curves are displaced into the high gas pressure region. A region of critical frequencies has been found for hydrogen within which the dependence of striking voltage on gas pressure remains practically constant with changes in field frequency. Results of the present investigation are in accord with conclusions of the diffusion theory of high-frequency discharge[1,2].

INTRODUCTION

It is known that when pressure in a high-frequency discharge is reduced, the striking and maintaining voltages diminish as the frequency of the electrical field is increased from the order of 10^5 to the order of 10^6 cycles[3-6]. At the same time the minima of $V_s(p)$ and $V_m(p)$ curves (showing striking and maintaining voltages vs. gas pressure) are displaced into the low pressure region.

Study of high-frequency discharge in hydrogen has shown that minimum striking voltage occurs at a frequency of 4×10^7 cycles, above which striking voltage again increases with increased frequency. This frequency will be referred to as the critical frequency. Aside from the frequency of the electrical field, the striking and maintaining voltages in high-frequency discharges are significantly affected by the geometry of the discharge space[5,7].

In the literature there is a dearth of data on research in high-frequency discharge at frequencies above the critical. The present study comprises an experimental investigation of striking and maintaining voltages as a function of gas pressure under conditions of several different discharge space geometries and boundary conditions in a frequency region above the critical frequency.

APPARATUS AND METHODS OF MEASUREMENT

High-frequency fields were obtained with the use of tuned-grid tuned-cathode push-pull oscillators over a frequency range from 54 to 750 mc. A diode voltmeter was used for high-frequency voltage measurements. Calibration and checking of diode voltmeter for resonances were conducted with the aid of a dielectric voltmeter developed in the laboratory. The diode voltmeter permitted high-frequency voltage measurements with a relative error not over 10-12 percent at 750 mc. Field frequency was measured with a two-conductor line as well as with a resonant wave-meter.

In conducting the experiments special attention was paid to shielding all elements of electrical circuits, to cleanness of electrodes and discharge tubes, and to oscillator stability.

For the basic measurements, four types of tubes (A,B,C,D) were used, as shown in Fig. 1. In the type A tube, plane electrodes of electrolytic nickel, 30 mm in diameter, were used. The operating surfaces of the electrodes were thoroughly polished. The edges of the electrodes were rounded off to eliminate edge effects. In order that the discharge not extend outside the discharge space, the leads and the back areas of electrodes were covered with glass insulation. One of the electrodes in the tube was movable. The internal diameter of the tube was 40 mm, and its length was 80 mm.

In the type B tube the electrodes were similar to those of type A but were covered with a thin layer of glass (0.2 to 0.3 mm). The internal diameter of

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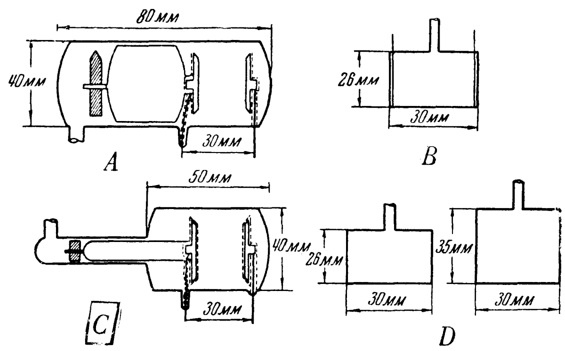

FIG. 1. Types of experimental discharge tubes.

the tube B was 40 mm, its length 50 mm.

Type C tube was a cylindrical glass tube with parallel plane ends. Electrodes consisting of thin sheet nickel discs were tightly soldered to the inside of these tube ends. The diameter of these electrodes was equal to the inside diameter of the tube. The high-frequency voltage could be applied to this type of tube either through these internal nickel electrodes or through external electrodes consisting of round discs tightly bound to the parallel plane tube ends.

Type D tubes (26 and 35 mm in diameter and 30 mm long) were cylindrical tubes with parallel plane ends. The external electrodes were round discs of copper sheet tightly bound to the plane tube ends from the outside. The voltage indicated just prior to striking was taken as the striking voltage of the high-frequency discharge. The maintaining voltage of the high-frequency discharge was considered the minimum voltage indicated just prior to extinguishing of the discharge.

RESULTS OF EXPERIMENTS

To determine the effect of the size as well as the boundary conditions of the discharge space, and, in particular, to find the effect of electrode material on striking and maintaining of a high-frequency discharge, the striking and maintaining voltages were studied in neon in type A and B tubes, at a frequency of 158 mc, and with different electrode spacings (L=20 and 5 mm).

Figures 2 and 3 curves show striking voltages (solid lines) and maintaining voltages (dotted lines for L=20 and 5 mm) vs. gas pressure for clean metal electrodes (Fig. 2), and for glass-covered electrodes (Fig. 3). On these curves the abscissa shows the gas pressure in mm of mercury, and the ordinate shows striking and maintaining voltages. In all curves the voltages shown are peak values.

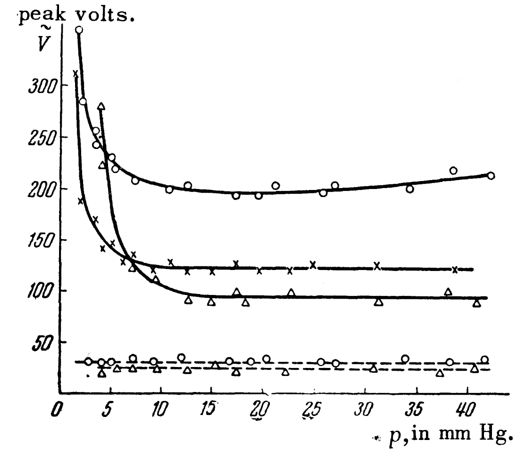

FIG. 2. Striking and maintaining voltages vs. pressure in neon with different electrode spacings using clean nickel electrodes. ν=158 mc.
O L=20mm
x L=10 mm
Δ L=5mm

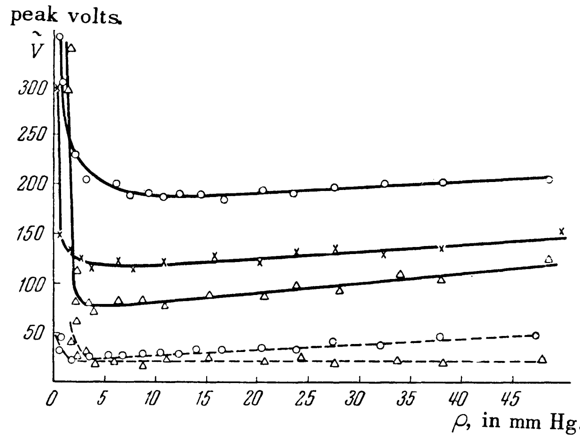

FIG. 3. Striking and maintaining voltages vs. pressure in neon for glass-covered nickel electrodes. O--L=20mm, X-L=10mm, Δ-L=5 mm, ν=158mc

The curves of Figs. 2 and 3 show that an increase in electrode spacing is accompanied by an increase in striking and maintaining voltages, and that curve shape is similar to the striking characteristic for a d-c discharge. However, the curves show that under the present conditions Paschen's law is not obeyed, a conclusion also reached on the basis of theoretical considerations.[8]

The left ends of the curves showing the relation between striking voltage and pressure, $V_s(p)$, for

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electrode spacing L=5 mm pass through a pressure region considerably higher than the left ends of $V_s(p)$ curves for L=20 and 10 mm. In the low pressure region the shape of $V_s(p)$ curves differs for nickel electrodes and for glass-covered electrodes. The left ends of curves for glass-covered electrodes are steeper and pass through considerably lower pressure regions than those for nickel electrodes.

To ascertain the effect of discharge tube diameter on striking and maintaining of high-frequency discharge, measurements were conducted in neon at 158 mc field frequency in type D tubes (Fig. 1) 26 and 35 mm in diameter. Figure 4 shows curves

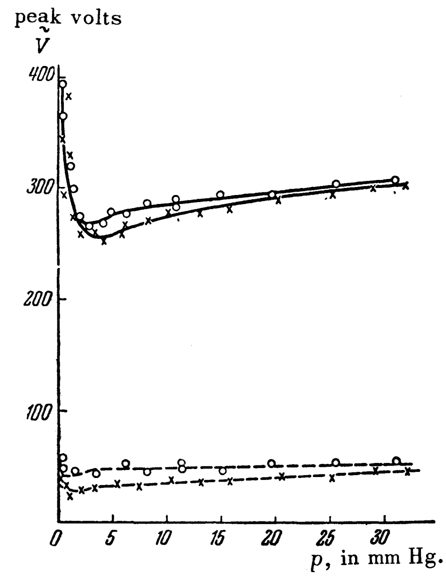

FIG. 4. Striking and maintaining voltages vs. pressure in neon for tubes of different diameters. O--d = 26mm; X --d=35mm; ν=158mc.

of striking and maintaining voltages vs. gas pressures, $V_s(\rho)$ and $V_m(p)$, for these two tubes. Experimental points for the smaller discharge tube are indicated by circles and for the larger tube by x's. Dotted lines indicate maintaining voltages.

Curves of Fig. 4 show that for equal gas pressures, the striking and maintaining voltages in the smaller tube are higher than in the larger tube.

A certain modification of striking and maintaining conditions was obtained as a result of simultaneous application of a d-c field and a high-frequency field to the discharge space. Measurements were made of striking and maintaining voltages of high-frequency discharge in argon with a field frequency of 500 mc in type C discharge tube (Fig.1). High-frequency voltage was applied to the external electrodes, which consisted of round discs tightly pressed to the plane ends of the discharge tube, and the d-c voltage was appled to the internal electrodes.

Figure 5 shows the results of measuring striking and maintaining voltages of high-frequency discharge as a function of gas pressure, with a d-c field of 0, 50 and 100 volts applied simultaneously to the discharge space. The $V_s(p)$ curves are shown as solid lines and the $V_m(p)$ are dotted.

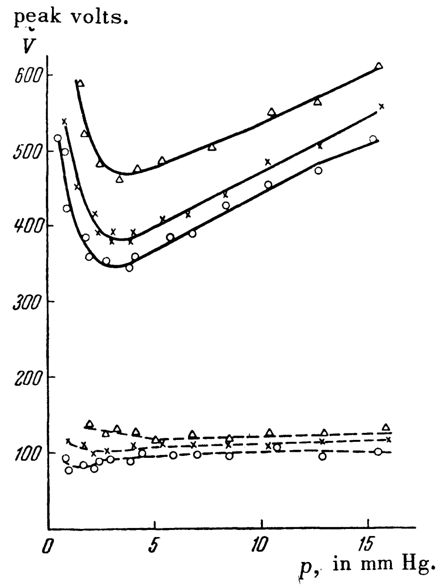

FIG. 5. Striking and maintaining voltages of high-frequency discharge vs. pressure in argon with simultaneous application of a d-c field. o-v=o, x-v=50v, Δ-v=100v; v=500mc

Figure 5 curves show that with a simultaneous application of a d-c field to the discharge space, $V_s(p)$ and $V_m(p)$ curves display considerably higher voltages than in the absence of the d-c field (curves when v=0). The effect of more difficult striking of high-frequency discharge in the presence of simultaneously applied d-c field is clearly evident. This effect, as the curves show, considerably increases the striking and maintaining voltages, and the higher the d-c voltage, the higher the striking and maintaining voltages of the high-frequency discharge.

To clarify the character of $V_s(\rho)$ and $V_m(\rho)$ curves as functions of field frequency, investigation of striking and maintaining voltages was carried out in hydrogen and argon with field frequencies of 57.7, 78.9, 136, 167, and 500 mc in a type D discharge tube (Fig. 1), 30 mm long and 35 mm in diameter. Figure 6 shows the relation between striking and maintaining voltages (the latter dotted) and pressure in hydrogen for the above field frequencies. In order not to make the drawing too complicated, curves for $V_m(p)$ are shown only for the extreme frequencies of 57.7 and 500 mc. For intermediate frequencies, the $V_m(p)$ curves lie between the 57.7 and 500 mc curves. These curves show that in raising the field frequency from 57.7 to 500 mc the striking and maintaining voltages increase. The minima of the $V_s(p)$ curves are displaced into the high-pressure region as the frequency increases. For hydrogen, the $V_s(p)$ curves are practically identical for frequencies of 57.7 and

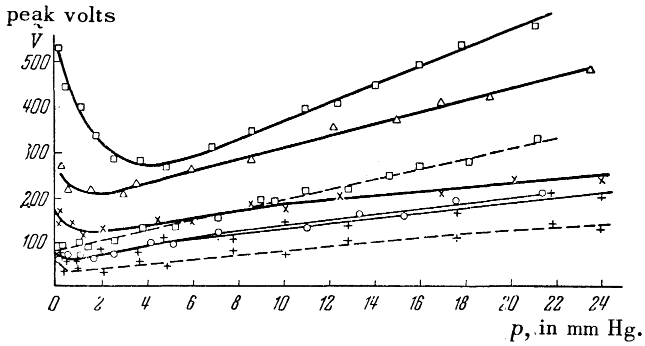

FIG. 6. Striking and maintaining voltages vs. pressure in hydrogen for several field frequencies. +-ν=57.7 mc; o-ν=78.9 mc; x-ν=136 mc Δ-ν=167 mc; □ -ν=500 mc.

79.9 mc, i.e., in changing the field frequency from 57.7 to 79.9 mc, the striking voltages undergo practically no change.

Thus, in investigating striking and maintaining voltages in hydrogen a region of critical frequencies has been determined (57.7 to 79.9) mc). For argon a similar critical frequency region must obtain at lower frequencies.

DISCUSSION OF EXPERIMENTAL RESULTS

The experimental results obtained can be explained in the following fashion on the basis of the initial assumptions of the diffusion theory of high-frequency discharge.[1,2] In the high pressure region the cause of the increase in striking and maintaining voltages with increase in gas pressure is the same as for d-c discharge. As the pressure is increased, the mean free path of the electron, as well as the energy of the electron on this path, are decreased. In order that the electron receive from the field the energy required for ionizing a gas molecule, higher and higher voltages must be applied to the electrodes as the pressure is increased. At high pressures, diffusion of electrons to the electrodes and to the walls of the tube is insignificant.

At low pressures the main factor which determines the striking and maintaining voltages is the departure of electrons from the discharge space to the electrodes and tube walls as a result of diffusion, and not the increase in electron energy along the free path. Therefore, at low pressures it is necessary to increase the voltage on the electrodes to replace the increasing depletion of electrons due to diffusion. The minima of $V_s(p)$ curves correspond to optimum conditions for starting the high-frequency discharge.

With decreased spacing between electrodes, on the one hand the high-frequency field intensity is increased, and therefore the energy which electrons acquire along the free path is increased, which in turn leads to increased gas ionization; on the other hand, with decreased spacing between electrodes loss of electrons takes place due to diffusion to the electrodes. With large electrode spacing and high gas pressure the fundamental part in striking and maintaining voltages is played by the first factor--the high-frequency field intensity; with small spacing and low pressure the other factor begins to play the fundamental role, i. e., loss of electrons by diffusion.

The curves in Figs. 2 and 3 show that striking voltages at 20 mm spacing are considerably higher than at 10 and 5 mm. These curves also show that for 5 mm electrode spacing the left ends of $V_s(p)$ curves pass through a region of considerably higher pressures than the left ends of curves for 20 and 10 mm spacing. The displacement of left ends of $V_s(p)$ curves at 5 mm into the region of higher pressures is caused by high electron losses due to diffusion to the electrodes.

With glass-covered electrodes (Fig. 3) the left ends of V_s (p) and V_m(p) curves are considerably displaced in the direction of low pressures as compared to similar curves for nickel electrodes shown in Fig. 2. This displacement of V_s (p) and V_m (p) curves in the direction of low pressures is due to the lower electron losses with glass-covered electrodes. Accordingly, the balance of charged particles resulting from ionization and diffusion in the case of glass-covered electrodes takes place at lower pressures than in the case of nickel electrodes.

In a d-c discharge, because of secondary processes affecting the electrode material, the latter plays an important part in the very mechanism of the starting and development of the discharge. The role of electrodes in high-frequency discharge fundamentally comes down to the conditions of maintaining a balance of charged particles in the discharge space.

The curves in Fig. 4 show that striking and maintaining voltages are affected not only by boundary conditions near the electrodes, but also by conditions at the walls of the discharge tube. In the small tube, under otherwise identical conditions, more electrons leave the discharge space due to bi-polar diffusion to the walls of the discharge tube. Therefore, for initiating and maintaining high-frequency discharge in a narrow tube, under otherwise identical conditions, considerably higher electrode voltage is required than for a wide tube.

In the presence of only an a-c field, loss of electrons in the discharge space is fundamentally determined by diffusion to the electrodes as well as by bi-polar diffusion to the walls of the discharge tube. In the simultaneous presence of high-frequency and d-c fields, electron loss from the discharge space also increases as a result of withdrawal of electrons to the electrodes caused by the d-c field. Accordingly, in the presence of a d-c field considerably higher electrode voltage is required for initiating and maintaining high-frequency discharge, as has already been shown in reference 10. Thus, the boundary conditions of the discharge space substantially affect the striking and maintaining voltages of high-frequency discharge.

The increase of striking and maintaining voltages with an increase in frequency (at frequencies higher than critical) is explained fundamentally by the decrease of average energy received by electrons from the field at high frequencies.[9]

In conclusion, the author takes this opportunity to express his gratitude to Prof. N. A. Kaptsov for suggesting the subject matter and for his constant interest in the work.

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Translated by K. Amatneek
3