ORIGIN OF R.F. OSCILLATIONS IN A.C. 'SILENT' DISCHARGES

by S. R. Khastgir, *F.N.I. and* C. M. Srivastava, *Banaras Hindu University*

(*Received December 17, 1953*; *read May 7, 1954*)

1. Introduction

It was Warburg (1903) who concluded that the discharge current in Siemen's ozonizer had components, the frequencies of which were very high compared to that of the exciting voltage. According to him, the frequency components were within 10^5–10^6 cycles/sec. This was supported by Prasad (1949) who in his investigation on Joshi Effect devised a method in which the high frequency components were picked up by an aerial and measured by means of a suitable detecting device. Direct experimental evidence of R.F. oscillations of discrete frequencies set up in some gases and vapour under 'silent' electrical discharge was later given by Khastgir and Setty (1952), using ozonizers and discharge tubes, fitted with external 'sleeve'-electrodes and excited by a suitable high voltage of 50 cycles/sec. The various frequencies appeared to correspond to overtones of an oscillating system. It was observed that for a given distance between the electrodes, the frequency of these oscillations was not dependent on the magnitude of the applied voltage. It was also observed that for a given applied voltage, the frequency was independent of the inter-electrode distance. Further, it was found that for a given discharge tube, the frequency of the R.F. oscillations was independent of both applied voltage and inter-electrode distance. Subsequent experiments of Khastgir and Setty (1953) showed an *increase* in the frequency of the R.F. oscillations in a.c. 'silent' discharges in iodine vapour and hydrogen gas on exposure to visible light. Khastgir and Srivastava (1952) also observed a *decrease* in the frequency of the R.F. oscillations in similar discharges in iodine vapour, hydrogen and chlorine gases on exposure to thermal radiations.

The object of the present paper is to outline a theory as to the origin and nature of the R.F. oscillations set up in a.c. 'silent' discharges and to explain the effects of light and heat on the frequency of such oscillations. As the theory is based on the streamer mechanism of Loeb and Meek (1941), as applied to a.c. 'silent' discharges, we shall first mention very briefly the main features, which we have already developed (Khastgir and Srivastava, 1953), regarding the nature of the 'silent' discharge.

2. Effect of the Intervening Glass Wall in A.C. 'Silent' Discharges

The intervening glass wall in an ozonizer or in a discharge tube fitted with external electrodes introduces certain features which are illustrated in fig. 1(*a*) and are enumerated below:—

(i) A negative surface charge is formed on the inner glass surface (AA) opposite to the anode during the half cycle of the applied field.

(ii) A stationary array of positive ions (GG) is formed very close to the negative surface charge on the glass wall, when the applied field is adequate for Townsend collisions to take place in the enclosed gas or vapour.

(iii) A gap (GGCC) in the discharge channel is set up between the stationary array (GG) of positive ions and the top surface (CC) of the moving column.

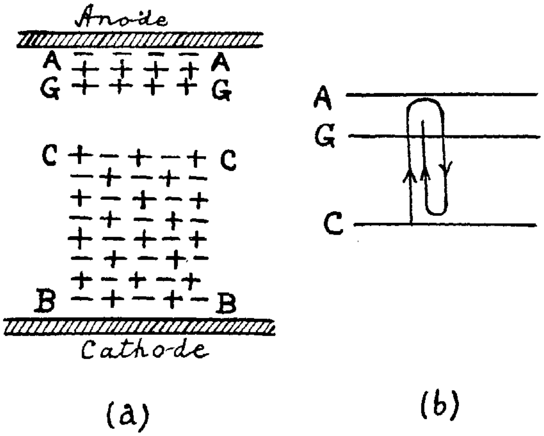

FIG. 1(*a*). AA—Negative surface charge on glass wall.
GG—Stationary layer of positive ions.
GGCC—Gap.
CCBB—Streamer.
FIG. 1(*b*). Electronic oscillation.

(iv) The streamer formation, as the moving column of positive ions attracts to itself neighbouring electron avalanches and photo-ionized electrons, is possible even at a low pressure in an electric field which has been reduced due to the negative charge on the inner surface of the intervening glass wall.

(v) The lower boundary (CC) of the gap may be regarded as the *virtual* cathode. The electrons start from the virtual cathode and being in an adequate field move across the gap towards the anode, producing cumulative ionization due to Townsend collisions. The negative charge on the glass wall is built up in this manner during the half-cycle of the applied field.

(vi) When the density of the negative charge on the glass wall attains a requisite value, the electron avalanches moving towards the anode across the gap are repelled and get mixed up with a large number of positive ions which are already produced due to Townsend collisions during the passage of the electrons through the gap. This makes the gap highly conducting, and the gap gets bridged up.

(vii) The pulse flashing across, when the gap gets bridged up, has been called by us *Townsend pulse.*

3. ORIGIN OF THE R.F. OSCILLATIONS IN A.C. 'SILENT' DISCHARGES

When the applied field is such that the negative charge on the glass surface is less than the requisite value for the *Townsend pulse* to pass, the electrons start from the virtual cathode and move across the gap under an *accelerating* field towards the stationary array of positive ions. After passing through the array of positive ions, the electrons come under a *retarding* field. In spite of the retarding field, some electrons with large velocities reach the glass surface, while others having relatively small velocities turn back and move towards the array of positive ions. Some of these returning electrons pass through this array and come to rest somewhere near CC to be attracted once again towards the array of positive ions due to the accelerating field (see fig. 1*b*). Electronic oscillations of radio frequencies may thus be set up near the glass surface opposite to the anode in a manner similar to the Barkhausen-Kurz oscillations in a triode. It is evident that these electronic oscillations are maintained till the density of the negative charge on the glass wall attains the requisite value for the Townsend pulse to pass, when, however, these oscillations cease and are immediately followed by a Townsend pulse, According to this view, therefore, the R.F. oscillations observed in a.c. 'silent' discharges are electronic oscillations of the B–K type and are maintained intermittently, each train being followed by a pulse.

4. EXPRESSION FOR THE FREQUENCY (OR WAVELENGTH) OF THE ELECTRONIC OSCILLATIONS IN THE A.C. 'SILENT' DISCHARGE

Consider any point in the discharge channel. The total electric field at that point is given by $X-X_1+X_2$ where X is the uniform field due to the applied voltage, X_1 the field due to the negative charge on the glass wall and X_2 the field due to the stationary array of positive ions close to the glass wall. It is evident that at the stationary layer of positive ions, $X-X_1 = 0$ and the entire field is due to the positive ionic concentration and is equal to $2\pi\sigma_p$, where σ_p is the density of surface charge in the array of the positive ions. In considering the accelerating field within the gap, let us suppose that the total electric field at any point at a distance r from the virtual cathode is represented by

$$E = Af(r), \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where A is a constant. Then the potential of the positive ionic concentration with respect to the virtual cathode is given by

$$V_g = A\int_0^l f(r)\,dr \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

where l is the length of the gap. The average field across the gap can be written as

$$\frac{A}{l}\int_0^l f(r)\,dr.$$

The average acceleration acting on the electron charge e and mass m moving towards the array of positive ions is then obtained from

$$a_1 = \frac{e}{m}\cdot\frac{A}{l}\int_0^l f(r)\,dr \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

If v is the velocity of the electron when it reaches the layer of positive ions and t_1 the transit time across the gap then

$$v = a_1 t_1 = \left[\frac{e}{m}\cdot\frac{A}{l}\int_0^l f(r)\,dr\right] t_1 \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

We shall now find the average *retarding* field across the double layer. Let σ_e be the density of negative charge on the glass wall. Then the field close to it may be taken as $4\pi\sigma_e$ which is very much larger than the applied field. The field close to the layer of positive ions is given by $2\pi\sigma_p$. Assuming here a linear field variation, the average retarding field is then approximately equal to $\pi(\sigma_p+2\sigma_e)$. The deceleration acting on the electron in this region of *retarding* field is then obtained from

$$-a_2 = \pi(\sigma_p+2\sigma_e)\cdot\frac{e}{m} \qquad \dots \quad \dots \quad \dots \quad \dots \quad (5)$$

If t_2 is the time when the velocity of the electron is reduced to zero, then the velocity of the electron at the positive ionic concentration is given by

$$v = \pi(\sigma_p+2\sigma_e)\cdot\frac{e}{m}\cdot t_2 \qquad \dots \quad \dots \quad \dots \quad \dots \quad (6)$$

From (4) and (6)

$$t_2 = \frac{\frac{A}{l}\int_0^l f(r)\,dr}{\pi(\sigma_p+2\sigma_e)}\cdot t_1.$$

Since the field $4\pi\sigma_e$ due to the charge on the glass wall is very much greater than the average field

$$\frac{A}{l}\int_0^l f(r)\,dr$$

across the gap, $t_2 \approx 0$, and we can write $t_1+t_2 \approx t_1$.

The frequency f of the electronic oscillation is then given by

$$f \approx \frac{1}{2t_1} \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (7)$$

Again, since $l = \frac{1}{2}a_1 t_1^2$, we get

$$t_1 = \sqrt{\frac{2l}{a_1}}$$

Substituting the value of a_1 from (3), we have

$$t_1 = \sqrt{\frac{2l^2\left(\frac{m}{e}\right)}{A\int_0^l f(r)\,dr}} = l\sqrt{\frac{2m/e}{V_g}} \qquad \dots \quad \dots \quad \dots \quad (8)$$

From (7) and (8)

$$f = \frac{1}{2t_1} = \frac{1}{4l}\sqrt{V_g}\cdot\sqrt{\frac{2e}{m}}.$$

Expressing V_g in volts, the frequency of the electronic oscillation is given by

$$f = \frac{\sqrt{V_g}}{2l}\cdot 3\times 10^7 \qquad \dots \quad \dots \quad \dots \quad \dots \quad (9)$$

The corresponding wavelength in cms. is obtained from

$$\lambda = \frac{3\times 10^{10}}{f} = 2000\,\frac{l}{\sqrt{V_g}} \qquad \dots \quad \dots \quad \dots \quad (10)$$

This is the well-known Barkhausen-Kurz formula for electronic oscillations in a triode with plane electrodes, when the anode is connected to the cathode, V_g being the grid voltage and l the distance between the anode and the cathode.

In the present case when electronic oscillations are set up in the a.c. 'silent' discharge, both l and V_g may vary within certain limits. A frequency band is thus expected when these oscillations are being built up. The predominant frequency should, of course, correspond to the instant when these oscillations cease and the Townsend pulse starts. This happens when the electric field attains a definite value E_0.

5. GAP-LENGTH IN RELATION TO THE POTENTIAL OF THE ARRAY OF POSITIVE IONS

Let v_+ be the velocity of the positive ions moving towards the cathode through the gap; then

$$v_+ \propto \sqrt{V_g}.$$

If now t is the time during which the positive ions in the moving column attract and capture neighbouring electron avalanches and photo-ionized electrons forming thereby the highly conducting streamer, then the limiting length of the gap is given by $(v_+ . t)$. As t depends on the positive ionic concentration and can be taken as some function of the electric field E, the length of the gap may be expressed as

$$l = v_+ . t \propto \sqrt{V_g} . \phi(E)$$

or

$$\phi(E) = K . \frac{l}{\sqrt{V_g}} \quad .. \quad .. \quad .. \quad .. \quad (11)$$

where K is a constant.

At the time when the gap gets bridged up and the field E attains a certain definite value E_0, it is evident from (11) that the ratio $\frac{l}{\sqrt{V_g}}$ should be taken as constant.

6. NON-DEPENDENCE OF THE WAVELENGTH OF THE R.F. OSCILLATIONS IN THE A.C. 'SILENT' DISCHARGE ON THE APPLIED VOLTAGE AND THE INTER-ELECTRODE DISTANCE

In finding the predominant wavelength of the R.F. oscillations in the a.c. 'silent' discharge, as given by (10), we have to consider the ratio $\frac{l}{\sqrt{V_g}}$, when the applied electric field has a definite value E_0. For a given discharge tube, E_0 is constant, so that whatever be the applied voltage and the inter-electrode distance, the values of the gap-length l and the potential, V_g, of the positive ionic concentration must be such that the ratio $\frac{l}{\sqrt{V_g}}$ has always the same value. This explains the constancy of the wavelength of the oscillations observed by us, for a given discharge tube, for any applied voltage and inter-electrode distance.

In considering the particular case, when the magnitude of the applied a.c. voltage is kept fixed and the inter-electrode distance varied, we have to note that the applied voltage varies sinusoidally and we are concerned with only those instantaneous values of the applied voltage which give the requisite electric field E_0 for the different inter-electrode distances. In considering the wavelength of the electronic oscillations, we have to take the values of the potential V_g of the positive ionic-concentration corresponding to these different instantaneous values of the applied voltage and also the corresponding values of the gap length l. Since $\frac{l}{\sqrt{V_g}} = \text{const.}$, for $E = \text{const.}$, it follows that the wavelength of the electronic oscillations should be the same for different inter-electrode distances, even when the applied voltage is kept constant. This is what has been actually observed.

In the other particular case, when the inter-electrode distance is kept constant and the applied voltage varied, it can be seen that the wavelength of the electronic oscillations should be independent of the applied voltage. Even though the applied voltage is varied, there is a definite value of the applied voltage for which the electric field attains the requisite value E_0. For this fixed value of the applied voltage, the potential V_g of the positive ionic concentration must also have a fixed value. Further, since $\frac{l}{\sqrt{V_g}} = \text{constant}$ for $E = E_0$, the gap length l for the particular inter-electrode distance should also be constant. The wave-length of the oscillations for a given inter-electrode distance should therefore be the same for different applied voltages. This has been substantiated by our experimental results.

7. EFFECT OF LIGHT AND HEAT ON THE FREQUENCY OF THE R.F. OSCILLATIONS

The effect of light and heat on the frequency (or wavelength) of the R.F. oscillations in a.c. 'silent' discharges can be explained in consideration of the formula given by (9) or (10). When the negative charge on the glass surface is exposed to light, there is photo-electric emission and these photo-electrons come near the array of positive ions. Due to closer proximity with the photo-electrons, the attracting field increases resulting in an increase in the positive ionic concentration. This should increase the potential V_g of the array of positive ions, so that according to the formula (9) the frequency of the electronic oscillations is expected to increase on exposure to light. Such photo-increase in the frequency of the R.F. oscillations in a.c. 'silent' discharges has been actually observed.

On exposure to thermal radiations, the temperature of the gas or vapour in the discharge tube is raised. With the rise of temperature the diffusion of the positive ions increases, reducing thereby the concentration of the positive ions. Thus the potential V_g of the stationary array of positive ions is expected to be reduced, causing thereby, according to the formula (9), a decrease in the frequency of the electronic oscillations on exposure to thermal radiations. This has been actually observed in our experiments on the effect of heat on the frequency of the R.F. oscillations. It is interesting to note that at very high temperature when there is thermionic emission from the negative charge on the glass surface, an increase in frequency is expected in the same way as in the case of photo-electric emission. Thus when the temperature of the gas or vapour in the discharge tube is raised sufficiently, the effect of thermionic emission should increase the frequency, whereas greater diffusion of the positive ions due to higher temperature should decrease the frequency of the electronic oscillations. The decrease of frequency due to the latter cause may be counter-balanced to some extent by the increase of frequency due to thermionic emission. This may explain the observed fact that the decrease of frequency of the R.F. oscillations in a.c. 'silent' discharges is not as much as is expected at a comparatively high temperature.

8. Modulation of R.F. Oscillations by A.F. Pulses in a.c. 'Silent' Discharge

Attention will now be drawn to the fact that any current pulse during a discharge does not pass at all points on the surface. With regard to the Townsend pulses which are preceded by the R.F. electronic oscillations in an a.c. 'silent' discharge, it can be said that they pass at a finite number of points on the glass surface. Considering random distribution of these points on the glass surface over a finite interval of time, it is evident that the pulses occurring at a number of points may occur simultaneously with the R.F. oscillations which are set up prior to the pulses, which will occur at other points at some subsequent instant. The R.F. oscillations can, therefore, be modulated by the Townsend pulses. Such modulated R.F. oscillations are actually detected by the galvanometer in the anode circuit of the detector valve of a radio-receiver and also by the loud speaker at the receiver output.

9. Conclusions

Considering the streamer mechanism of Loeb and Meek, as applied to the a.c. 'silent' discharge, an electronic theory has been developed in the paper. According to this theory, the observed R.F. oscillations in the a.c. 'silent' discharge is regarded as trains of electronic oscillations of the Barkhausen-Kurz type maintained intermittently, each train being followed by what has been called a *Townsend pulse.* The expression for the frequency (or wavelength) of the electronic oscillations which has the same form as the Barkhausen-Kurz formula for electronic oscillations in a triode, has been taken as the basis for explaining the observed non-dependence of frequency (or wavelength) of the R.F. oscillations set up in a.c. 'silent' discharges on the inter-electrode distance and the applied voltage. The observed effects of light and heat on the frequency (or wavelength) of the R.F. oscillations in a.c. 'silent' discharges have also been explained. The statistical consideration of the fact that a current pulse during a discharge passes at a number of points distributed at random on the glass surface can also explain the observed modulation of the R.F. oscillations by the Townsend pulses.

Abstract

An electronic theory of the origin of R.F. oscillations in a.c. 'silent' discharges is given in the paper. According to Loeb and Meek's streamer theory, when the applied field is adequate for Townsend's cumulative ionization, there is a conical distribution of positive ions drifting towards the cathode. In an a.c. 'silent' discharge, the negative charge formed on the intervening glass surface attracts the positive ions of the conical column and forms a stationary array of positive ions close to the glass surface. A gap is also set up between this stationary layer of positive ions and the moving column of positive ions which soon becomes highly conducting by attracting to itself electron avalanches and photo-ionised electrons. The gap is subsequently bridged up when the density of the negative charge on the glass surface attains a requisite value producing what has been called a Townsend pulse. Before this requisite density is attained, the gap exists and electronic oscillations of Barkhausen and Kurz type are set up near the glass surface opposite to the anode. These oscillations are maintained till the gap is bridged up. Accordingly we get electronic oscillations which are maintained intermittently, each train being followed by a Townsend pulse. The expression for the frequency (or wavelength) of the electronic oscillations has been shown to be of the same form as the Barkhausen-Kurz formula for electronic oscillations in a plane triode.

The theory explains the general features of the R.F. oscillations observed in a.c. 'silent' discharges. The effects of light and heat on the frequency of the oscillations recently observed by Khastgir, Setty and Srivastava are also explained.

10. REFERENCES

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Issued June 25, 1954.