GRADES OF VACUUM IN ELECTRONIC AND IONIC TUBES

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Abstract

The problems of vacuum are of great importance both for electronic and ionic devices. In this paper it is shown that the most important factor that qualifies the grade of vacuum is not the pressure of the residual gases but the ratio of the mean free path of the molecules to the distance between the cathode and the anode of the device, namely λ/r. This ratio, designated as the relative grade of vacuum, is to be preferred as an index of the vacuum properties of the tube, to the pressure of the residual gases. A higher relative grade of vacuum will ensure better vacuum properties. The ways of achieving high relative grades of vacuum are discussed.

I. Introduction

Electronics is finding increasing application in many spheres of human activity. Many new developments are under way. This subject, which has developed due to the application of high vacuum electronic and ionic devices, has lately received an impetus through the emergence of semi-conductors. But it is fairly evident that semi-conductors cannot replace vacuum and ionic tubes in many important fields of application. Consequently great importance must continue to be attached to the study of vacuum electronics. A major problem of interest in this regard is the increase of the life-time of electronic and ionic tubes. On its satisfactory solution rests the vital question of whether vacuum tubes can survive in the face of the competition offered by semi-conducting devices. It is clearly important to investigate in detail the ways and means of improving the vacuum and reducing the harmful effects of residual gases in vacuum devices. These two needs are interrelated and their solution will be mutually helpful.

II. Grades of Vacuum of Electronic and Ionic Tubes

There must be a high vacuum inside the vessel of the electronic tube. Ionic tubes contain gas, but the inside of the tube must be rarefied to a great extent relative to the atmosphere surrounding the tube. In electronic tubes such rarefaction is much more intense. Any pressure of gases lower than the atmospheric pressure is usually called a vacuum. The higher the rarefaction, the larger will be the mean free path of the molecules of the gas inside the tube, λ. The ratio λ/r, where r is the minimum essential dimension of the vessel, is dependent on the vacuum.

The following main grades of vacuum can be distinguished:

(*a*) low vacuum, characterised by $\frac{\lambda}{r} \ll 1$,

(*b*) medium vacuum, characterised by $\frac{\lambda}{r} \backsimeq 1$,

(*c*) high vacuum, characterised by $\frac{\lambda}{r} \gg 1$.

For high vacuum, corresponding to a pressure of 10^{-8} to 10^{-9} mm. of mercury due to the residual gases in the vessel, this ratio has a value expressed by

$$\frac{\lambda}{r} \gg 1 \leq 10^5.$$

A high vacuum of this order has been hitherto regarded as quite satisfactory. But lately the need has been felt for higher vacua. These may be referred to as super-high vacua, and will be characterised by the relation:

$$\frac{\lambda}{r} \gg 10^5.$$

If the ratio λ/r exceeds unity, the mean free path of the molecules becomes larger than the minimum essential tube-dimension. The number of collisions of the molecules with each other inside the vessel becomes smaller than the number of their collisions with the walls of the vessel. As a result, the character of heat conductivity of the gas will change. Besides the electronic discharge will predominate over the ionic discharge.

It is convenient to classify vacuum roughly into four grades; Low, medium, high and super-high. For engineering calculations, the characteristic of the vacuum must be stated in precise terms; the numerical value of the real pressure or the ratio λ/r should be specified. These two ways of characterizing the vacuum are not identical but describe different aspects of the state of the vacuum. The numerical value of the pressure characterizes the general state of the vacuum, corresponding to a certain pressure, independently of the kind of vessel or gas used. On the other hand, the ratio λ/r is a characteristic of the vacuum in terms of some relative numerical units and not in units of pressure. As will be shown later in this article, it is a more important index of the state of the vacuum in the internal space of an electronic or ionic device than the actual pressure. On this consideration rests the practical necessity of increasing this ratio especially for electronic tubes.

The term "relative grade of vacuum" may be introduced to describe this numerical index which characterizes the vacuum inside a vessel of a certain size with certain gases. This numerical value pertains to vacuum in a vessel of which r is the minimum essential dimension, electrode-gap for instance. As the mean free path, λ, depends not only on the pressure of the gas in the vessel but its composition as well, the notion of the relative grade of vacuum applies only to the gases present inside the tube. It is to be used to study the state of the vacuum in vessels of constant size.

III. Practical Importance of the Relative Grade of Vacuum

The relative grade of vacuum is a function of λ and r. An increase in its value may result from a decrease in pressure and r, individually or simultaneously. In both of these cases, the collisions of the molecules with each other or with the electrons in the electrode gap become less. A number of important consequences follow.

It is to be borne in mind that the inequality $(\lambda/r) > 1$ does not mean that there are no collisions of the molecules with each other or with the electrons inside the device. When the mean free path of the molecules is bigger than the minimum size of the electrode gap, it is only a certain number of the molecules that escape collision, not all. But of a total number n, the number of molecules having a free path-length equal to or greater than χ is

$$n_\chi = n . e^{-\chi/\lambda}.$$

$$\text{If } \chi = \lambda,\ n_\chi = \frac{n}{e} = 0{\cdot}368n.$$

Thus, approximately a third of the total number of molecules have free paths longer or equal to the mean free path. The majority of molecules have free paths shorter than the mean free path. Still the narrower the electrode gap, the more rare will be the collisions of molecules with each other and with electrons.

An increase in the relative grade of vacuum causes a reduction in the heat transfer that takes place through the gas in the interelectrode space by virtue of the collisions of molecules with each other. While the heat radiation from the cathode remains unchanged, the heat conductivity of the electrode gap will be lessened by the increase of λ/r. There is also a reduction in the ionization of the residual gases, owing to the fewer collisions which take place. Such a lessening of ionization has salutary effects: decrease in the sputtering and poisoning of the thermo-cathodes by ions, decrease in the ion currents in the grid circuit of grid-controlled devices, lesser distortion of tube characteristics, etc.

IV. Vacuum Modulus of Electronic or Ionic Tubes

The mean-free path of molecules, λ, is given by

$$\lambda = \frac{1}{\sqrt{2}\pi\sigma^2 N_0}, \tag{1}$$

where σ is the effective diameter of the molecules and

N_0 is the number of molecules per unit volume of the gas.

It is also well known that for any gas

$$N_0 = \frac{p}{KT}, \tag{2}$$

where p is the pressure of the gas,

T is its absolute temperature in degrees Kelvin, and

K is Boltzmann's Universal gas constant.

On examining the relation between λ and p, we have,

$$\lambda = \frac{C}{p}, \tag{3}$$

where

$$C = \frac{K.T}{\sqrt{2}\pi\sigma^2} = f(T, \sigma). \tag{4}$$

The relative grade of vacuum is,

$$\frac{\lambda}{r} = \frac{C}{p.r} = \frac{K.T}{\sqrt{2}\pi\sigma^2 p.r} \tag{5}$$

It is clear from the above that the relative grade of vacuum is a function of the gas pressure p, the electrode gap, r, the gas temperature, T, and the effective diameter of the gas molecule, σ. Of these factors the gas pressure stands out being dependent on evacuation, gettering, infiltration of gases into the tube, evolution of gases from the internal parts, and so on. All the other factors are entirely dependent on the tube itself and influence its vacuum properties. It is convenient to unite them and arrive at the general notion of the vacuum modulus of the tube, defined by

$$K_v = \frac{C}{r} = \frac{K.T}{\sqrt{2}\pi\sigma^2 r}. \tag{6}$$

The relative grade of vacuum now becomes

$$\frac{\lambda}{r} = \frac{K_v}{p}. \tag{7}$$

It is seen to be directly proportional to the vacuum modulus of the tube and inversely proportional to the pressure of the residual gases. The vacuum modulus K_v comprises all the vacuum properties of the tube. If it is high, the relative grade of vacuum is high. This parameter of the tube has to be considered separately.

It is clear from equation (6) that the higher the temperature of the residual gas in the tube, the bigger is the vacuum modulus. At present, this property cannot be put to practical use, as the temperature of the residual gas cannot be maintained high, being dependent to a large extent on anode and cathode heating. The vacuum modulus of the tube increases with the decrease of the effective diameter of the molecules of the residual gases.

$$\sigma = r_1 + r_2,$$

where r_1 and r_2 are the effective radii of the colliding molecules. It may be concluded that gases with the minimum size of molecules are desirable as residual gases. Gases having molecules of big effective diameters are to be preferentially evacuated. Steps must be taken to improve the adsorption of residual gases as these gases cause ionisation inside the tube and poisoning, and sputtering of the cathode by ions. As the square of σ is involved in the proportionality, it is obvious that the decrease of effective diameter of molecules results in a considerable increase of the vacuum modulus. It is evident that the minimum possible interelectrode distance has to be chosen to obtain the biggest value of the vacuum modulus.

V. Ways of Increasing the Relative Grades of Vacuum

In order to improve the relative grade of vacuum, either pressure p must be decreased or the vacuum modulus K_v must be increased. Both possibilities may be utilized to secure a big change.

The decrease in pressure is achieved by efficient evacuation of the tube vessel with the help of pumping systems designed to produce super-high vacuum. It is important to remove the residual gases with getters, and to use a technology of degassing of the internal parts of the tube that ensures the minimum evolution of gases from them during the working of the tube. The evacuation and adsorption of gases by getters are facilitated if the internal tube space is small. The specific volume of the tube, namely the volume per sq. cm. of the working surface area of the cathode,

$$K_d = \frac{V_{vessel}}{S_{cathode}}.$$

should be considered as a very important factor from the point of view of the design of the tube with a high relative grade of vacuum. As the decrease of the overall dimensions of the tube is desirable, the necessity for achieving the minimum value of the design-parameter, K_d is underlined. It is clear that the design-parameter depends on r, that is

$$K_d = f(r).$$

K_d decreases with r. From equation (6), we may write:

$$K_v = f(K_d).$$

It is essential to get the minimum value of the design-parameter, K_d, in order to achieve the maximum value of the vacuum modulus K_v, and consequently a high relative grade of vacuum λ/r. Thus the question of the optimum shape of the tube and its electrodes arises. It is evident that thin prismatic or elliptical shapes of electrodes and of the tube will be conducive to the minimum value of the design-parameter, K_d. In the tube the anode may be made to coincide with the envelope. It has been previously mentioned that, all other conditions being the same, the numerical value of the vacuum modulus, K_v, will be high with minimum effective diameter of the molecules of the residual gases. Effective gettering may be arranged in such a way that the gases with the molecules of bigger size are absorbed first.

Such are the main ways of increasing the relative grades of vacuum in electronic and ionic tubes. They are capable of leading to designs of tubes of small overall dimensions, improved electrical characteristics and prolonged life-periods.

REFERENCES

1. G. A. Tyagunov .. *Some Problems of Electronics*, 1955, Moscow Institute of Physical Engineers.
2. A. A. Ivanov .. *Electrovacuum Technique*, 1944, Moscow, Leningrad
3. S. Dushman .. *Scientific Foundations of Vacuum Technique*, 1949, New York, London.
4. Y. Yarwood .. *High Vacuum Technique*, 1955, London.

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