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ELECTRIC DISCHARGE OF GAS BUBBLES IN LIQUIDS

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Introduction

For many years physicists in a number of laboratories have been investigating the electric discharge of vapour-gas bubbles in liquids. There are various reasons behind this research. In some cases, an explanation has been given for the effect of a discharge in bubbles on the electric strength of liquids, whilst in others a study has been made of the dynamics of bubble growth in a liquid when there is a steady supply of electric power to the bubbles. In a number of instances, research has been directed towards the formulation of a new method for recording particle tracks in pseudo-boiling liquids. One of the main problems with this type of research is the optimal selection of electric field characteristics for the discharge of bubbles which differ according to the amount, pressure and nature of the gas they contain. It is surprising that at present there is no technique for calculating the parameters of electric fields, despite the obvious need for such a system. A description is given below of a method for calculating fields for the discharge of bubbles by steady, pulsed and high-frequency electric fields. The calculation is based on the main criteria and some of the experimental dependences of the electric breakdown of a gas in small gaps. The methods are investigated by using specific examples of the electric discharge of bubbles in such liquids as helium, hydrogen, xenon and neon. These liquids are, of course, widely used in bubble chambers and at the present time it is particularly interesting to examine the discharge of bubbles in them. It goes without saying that the technique described below is equally suitable for any other liquids.

The discharge of bubbles in steady and alternating electric fields

Let us examine the conditions which have to be met by electric fields capable of producing a discharge in bubbles. In

principle, there are three possible methods for the discharge of bubbles: steady, pulsed and high-frequency fields. However, the disruptive characteristics of steady and pulsed fields of a few msec. duration are similar and we shall not draw a special distinction between them.

To represent the main criterion for calculating the steady or pulsed breakdown voltage in bubbles, we shall use Reuter's well-known empirical condition ad = 20, where a is the first Townsend coefficient, dependent on the type of gas and the ratio E/P, d is the discharge gap value which can be equated to the bubble diameter in the given instance, P is the vapour pressure in the bubble and $E \equiv E_2$. The dependence $a = f(E/P)$ for many gasses is given in the literature on gas discharge. It is clear that for the bubble discharge to be efficient, it is essential that $a > 20/d$.

From now on, we shall assume that the linear size of the bubbles is d and the field intensity is E in the chamber volume and E_2 in the bubble. The dielectric constant will be ε_1 for the working liquid and ε_2 for its vapour. Then the link between E_1 and E_2 will be expressed by the well-known relation:

$$E_2 = E_1 \frac{3\epsilon_1}{\epsilon_2 + 2\epsilon_1}. \qquad (1)$$

As an example, let us examine the method for determining the E_1 value for bubble discharge in a xenon chamber. In this chamber the vapour pressure in the bubbles is approximately 20 atmos. The diameter of the bubbles is taken as $d = 1.10^{-1}$ cm., and then $a \geq 200$ cm^{-1} and $a/p = 200/20.760 = 1.3.10^{-2}$ (cm mm Hg)$^{-1}$. As $a/p = f(E/P)$ from the tables in paper /1/ we find the value $E/P \approx 17$ in (cm mm Hg)$^{-1}$. Hence the field intensity in the bubble is

$$E = E_2 = 17P = 17.20.760 = 260 \text{ kV/cm}.$$

To determine E_1 we shall use formula (1). For liquid xenon $\varepsilon_1 = 1.83$ and for vapour at 20 atm. - $\varepsilon_2 \approx 1$. By substituting these

data into (1), we find that E_2 = 210 kV/cm. Consequently, for bubble discharge in a xenon chamber, the electric field intensity in the liquid must not fall below 210 kV/cm.

The electric fields required for bubble discharge in other liquids may be determined in the same way. Thus, to discharge bubbles of 1 cm. diameter in a hydrogen chamber: $P = P_o (T/T_o) = 4\ (300/27) = 44$ atmos, where P is the vapour pressure in the bubbles of hydrogen at room temperature T and P_o is the vapour pressure in the bubbles at the liquid hydrogen temperature T_o : $a/p = 200/44.760 \cong 6.10^{-3}$ (cm mm Hg)$^{-1}$. According to the value of a/p given in the tables of paper /1/, we find that $E/P \cong 18$ V (cm mm Hg)$^{-1}$. It therefore follows that the intensity of the discharge field in the hydrogen bubble is $E_2 = 18.44.760 \cong 600$ kV/cm. and the field intensity in the liquid according to formula (1) ($\varepsilon_1 = 1{,}18$, $\varepsilon_2 = 1{,}02$) should be $E_1 \cong 500$ kV/cm.

For a bubble discharge in a liquid helium chamber, $P = P_o (T/T_o) = 0{,}3\ (300/2) = 45$ atmos. and $a/P \cong 6.10^{-3}$ (cm mm Hg)$^{-1}$. Then, from /1/, the ratio E/P = 5 V (cm mm Hg)$^{-1}$ and hence $E_2 \cong$ 170 kV/cm., and $E_1 \cong$ 150 kV/cm.

In a number of cases the intensity of the discharge field in bubbles can be more easily calculated by using the experimental dependence of the breakdown voltage E on the Pd value. Here P is the pressure of the gas in the gap being discharged, which can be identified with the pressure of the gas in a bubble of diameter d. For gaseous hydrogen and helium, the dependence $E \cong f(Pd)$ can be found, for example, in /1/. Thus, by using this method to calculate the field intensity for the discharge of hydrogen bubbles, we obtain E_1 = 480 kV/cm. and E_2 = 550 kV/cm. The calculation for helium bubbles gives E_1 = 230 kV/cm. and E_2 = 260 kV/cm.

Calculations using the Meek equation /1,2/ also give discharge fields close to these values:

$$\ln E = \ln ad + 0{,}5 \ln P - 1.5 \ln d + ad - 14{,}46 , \qquad (2)$$

where E_2 is in V/cm., P in mm Hg, d in cm and a in cm^{-1}. ad is defined by Reuter's theoretical condition[1]

$$ad = 17,7 + \ell nd$$

It can be seen that the data obtained by these two methods differ slightly. This has to do with the approximation and extrapolations that had to be postulated using the information on gas discharge for the values a/P and Pd which differ from the tables now in print.

It is appropriate here to compare the accuracy of the calculation of discharge fields with the experimental data. The results of experiment[3] on the discharge of helium bubbles of $\approx$ 0,2 cm diameter and at a gas pressure of $\approx$1 atmos. are now well-known. The intensity of the discharge field at the midpoint on the plateau was 13 kV/cm. The calculation in this case gives:

a/P = 100/760 = 0,13 $(cm\ mm\ Hg)^{-1}$, in [1] we find that E/P = 16 in $(cm\ mm\ Hg)^{-1}$ or $E_2 = 16 \cdot 760 = 12,2$ kV/cm, which is close to the experimental value.

However, despite the approximative nature of these calculations, it can definitely be concluded that the discharge of vapour bubbles in the monatomic liquids used in bubble chambers should set in at an electric field intensity of $\approx$ 200 kV/cm, and in polyatomic liquids at 500 - 600 kV/cm. It can also be shown that discharge field values change slightly when the bubble dimensions vary 1.5 times.

When pulsed fields are used in bubble chambers to discharge bubbles along a particle track, the pulses must be applied to the chamber at the moment when the bubbles reach a specific size. A discharge will be initiated in these bubbles by electrons which are generated in the liquid at the moment when the particles pass through and they remain in the bubbles during vaporization. It can be shown that each bubble which is produced at the tail of a δ electron and

which has a diameter of 0,1 cm contains, on average, up to 10 electrons. These electrons can either be in a free state or linked to vapour molecules if the latter are electronegative. This imposes further conditions on the electric field. Thus, in the case of free electrons, the pulse-shaping time (length of the leading edge) should be sufficiently short to prevent electrons from moving away from the bubble volume to the wall during this time as a result of drift motion. Let us investigate a specific example. The shift of X electrons due to an increase in field equals

$$x = \int_0^\tau v\,dt. \qquad (3)$$

Here v. is the electron drift rate which equals μ E, μ is the mobility of electrons in electric fields and τ is the length of the pulse's leading edge. The growth rate of the electric field intensity can be represented in a first approximation as a linear time dependence:

$$E = \frac{U_{max}}{\ell\,\tau}\,t, \qquad (4)$$

where U_{max} is the pulse height and ℓ is the distance between the electrodes in the chamber. The integration of expression (3) allowing for equality (4) gives:

$$x = \frac{\mu U_{max}}{2\ell}\,\tau^2. \qquad (5)$$

As the electron shift must be less than the bubble diameter, (5) produces the following condition, applied to the τ value:

$$\tau \leq \frac{2\ell d}{\mu U_{max}}. \qquad (6)$$

We shall estimate the τ value for vapour bubble discharge in liquid xenon. Let us assume that ℓ = 1 cm, d = 0,1 cm and U_{max} = 210 kV. Electron mobility in gaseous xenon at 20 atmos. is 10 $cm^2/sec.$ /1/. By substituting these data into 6, $\tau \leq$ 100 nsec. The same calculation for free electrons in hydrogen bubbles gives $\tau \leq$ 90 nsec., and for helium $\leq$ 60 nsec.

In fact, it seems that the demand on the τ value will be less rigid, as the formation of electronic avalanches begins before the field intensity in them reaches its maximum value. This process is accompanied by the production of ultraviolet radiation quanta which in turn will produce electrons throughout the bubble volume due to photoionization. Unfortunately, it is not possible to calculate this process to any degree of accuracy for bubbles.

Let us now examine another case, where the vapour or gas molecules in the bubbles are electronegative and capture electrons. These clusters--negative ions--have 10^3 less mobility then electrons. in electric fields and their rate of escape from the bubbles when the field is applied will be comparatively slow. In this case it is possible not to impose particular requirements on the pulse's value. However, the pulse height must meet a specific condition, that is, it must be sufficient to set up a field in the bubble which is capable of detaching electrons from the ions within a fixed time. As has already been mentioned, these electrons are needed to initiate a discharge in the bubbles. The value of the required field may be determined from the following equation /4/.

$$\lg \tau = -13{,}17 + 0{,}5 \lg \phi - \lg E + \frac{29{,}67}{E} \phi^{3/2}, \qquad (7)$$

where τ is the average life-time of a negative ion in an electric field in seconds, E is the field intensity in the bubbles in MV/cm and ϕ is the potential of electron affinity in gas molecules in eV. Equation (7) is given in paper /4/ in the form of graphs which express the dependence of $\lg \tau$ on E and which are suitable for calculations. This calculation will be necessary whenever electronegative liquids are used, including helium and hydrogen, as these are also slightly electronegative. Thus hydrogen molecules have two resonances in the electron-capture cross-section at interaction energies of 8 and 15 eV /5/. The capture cross-sections at these levels are approximately identical - $\sigma \cong 10^{-21} cm^2$. In this case, electron capture is accompanied by a break-up of the hydrogen molecules into atoms in the reaction $H_2 + e \rightarrow H_2^- \rightarrow H^- + H$. At the

end of the reaction, an electronegative ion of the hydrogen atom is formed, the electron affinity of which is 0,75 eV[5]. If formula (7) is used to estimate the intensity of the electric field capable of inducing the emission of an electron from H^- in a fraction of a second, we find that this field must be of several MV/cm. intensity. This means, in fact, that electrons captured by hydrogen atoms play no part whatsoever in the initiation of a discharge. Only the free electrons in the bubble which have avoided attachment to hydrogen atoms can induce an electric discharge. However, in this case the high-voltage field in the chamber must be shaped in $\tau <$ 90 nsec., as described above.

Electron emission can be induced much more easily from ions of He^-, the binding potential of which equals 0,075 eV. In fields with an intensity of several tens of kV/cm, the electrons leave He^- in $10^{-5} - 10^{-6}$ sec[4]. Electrons can be stripped from helium ions not only directly by means of an electric field but also by colliding ions which have been accelerated up to 0,075 eV. The second process is particularly efficient in a rarefied gas where the ions can easily be accelerated to the required energy. The fact that electrons become slightly attached to helium atoms may be applied in helium chambers and chambers filled with other liquids which contain helium bubbles, and may even be used to advantage as the attached electrons may remain in the bubbles for a considerable time and can be introduced into the discharge process by comparatively weak fields. Bearing this in mind, the requirement for the shaping of the pulse front - $\tau <$ 60 nsec, as calculated above, for helium, may be ignored in principle, if negative ions are present in the bubble.

Atoms of xenon have no electron affinity and only free electrons may be used to produce a bubble discharge in the liquid. Therefore, the condition established above for a pulse-shaping speed of $\tau <$ 100 nsec. is still valid.

We did not investigate the possibilities for an electric discharge of bubbles in chambers filled with organic liquids and liquids whose molecules contain halogen atoms. When using haloid liquids, it seems to be impossible to perform an electric discharge of bubbles as their molecules have a strong electron affinity and a very large cross-section for the capture of slow electrons[6]. Bubbles in these liquids contain no free electrons capable of initiating a discharge. Moreover, it is virtually impossible to free the electrons held in the negative ions by any tolerable electric field.

At present there is hardly any information on the attachment of electrons to the molecules of organic liquids and it is difficult to draw specific conclusions about the possibilities of bubble discharge in these liquids.

From the data concerning the great mobility of negative ions in organic liquids placed in an electric field, it can only be assumed that saturated hydrocarbons may possibly possess slight electronegativity. If so, then a discharge could be initiated in bubbles in organic liquids at field intensities comparable to the one used for bubble discharge in hydrogen.

Bubble discharge in a high-frequency field

At a given gas pressure P in the bubble and a fixed wavelength λ of the high-frequency field, discharge in the gas occurs at the following field intensity[7]

$$E = E_e \sqrt{1 + \left(\frac{78.6}{P}\right)^2}, \qquad (8)$$

where E_e is the so-called effective field dependent on the field frequency and the frequency of collisions between electrons and gas atoms. The E_e value is usually determined by experiment. Thus, in the case of helium in fig. 4.15 of paper [7] the experimental dependence of $E_e \Lambda$ on $P\Lambda$ is given, where Λ is the characteristic

diffusion length of electron shift in a gas subjected to a high-frequency field. When there are bubbles, the Λ value may be assumed to equal approximately the bubble diameter divided into /7/.

Formula (8) is valid when the field frequency is less than the frequency of collisions with the gas atoms. For fields with frequencies of several MHz and gas pressures of over 1 atmos., formula (8) is always valid.

Let us now find the discharge field intensity E for helium. As before, let us assume the following bubble conditions: d = 0,1 cm and $P = P_o (T/T_o) = 45$ atmos. Then $\Lambda = 3.10^{-2}$ cm and $P\Lambda =$ 1026 cm mm Hg. From the experimental dependence of $E_e \Lambda$ on $P\Lambda$ /7/ we find that $E_e \Lambda = 1000$ V, or $E_e \cong 33$ kV/cm. By substituting E_e, P and λ (when f = 10 MHz) into (8), we obtain the value $E \cong 33$ kV/cm.

The same calculation for bubble discharge in liquid hydrogen at $P = P_o (T/T_o) = 44$ atmos. gives $E \cong 300$ kV/cm.

Unfortunately, there is no data available on the dependence of $E_e \Lambda$ on $P\Lambda$ for the calculation of bubble discharge in liquid xenon. However, information on the discharge of gaseous argon in high-frequency fields /7/ may be used instead as the electric discharge characteristics of argon and xenon are similar. Using this approximation we find that discharge in xenon bubbles at 20 atmos. pressure sets in at a field intensity $E \approx 70$ kV/cm.

For the calculations we used the field frequency f = 10 MHz, which fully satisfies the necessary requirement for the rate of growth of a voltage half-wave in the liquid. In fact, in this case the shaping time is $\tau = \frac{1}{4} T = 25$ nsec, which is less than the 100 nsec. calculated above for xenon and the 60 nsec for helium.

It is clear from these calculations that the average intensity of a discharge field at high frequencies in vapourbubbles is as high as in the case of pulsed discharge.

It is obvious that a high-frequency field must be applied to the liquid at the moment when the bubbles along the particle track are reaching the size necessary for photography. For this, the length of the train of high-frequency oscillations may be several milliseconds as track distortion caused by variations in the bubbles' emersion rate during this period will still be low.

Some comments and conclusions

We did not investigate the possibility of initiating a discharge in bubbles by autoelectronic emission from the walls into the gas. This is virtually impossible as the bubbles have no micro-in homogeneities which might have indicated the tunnelling of electrons from the bubble walls into the vapour at the indicated field values.

Moreover the calculations did not take into account the effect on discharge of electrons escaping from the interior of the bubbles to their surface. It is extremely difficult to allow for this process although it is bound to lead to some increase in the values calculated for discharge fields.

The calculations presented in this paper can be used to solve a number of applied problems. In particular, these calculations point to one interesting possibility for the application of electric discharge in bubbles in order to indicate particle tracks in bubble chambers without using the conventional lighting system. This would require an experiment on bubble discharge in an operating chamber.

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