Drift velocity of electrons and ions in dry and humid air and in water vapour

1965 Proc. Phys. Soc. 85 1283

(http://iopscience.iop.org/0370-1328/85/6/327)

PROC. PHYS. SOC., 1965, VOL. 85

Drift velocity of electrons and ions in dry and humid air and in water vapour

H. RYŻKO

Institutet för Högspänningsforskning vid Uppsala Universitet, Uppsala, Sweden

MS. received 7th September 1964

Abstract. The avalanche current resulting from the release of a short (30 nsec) pulse of photoelectrons (5×10^4) at the cathode of a uniform field gap (5 cm) is observed experimentally. By this technique the drift velocities of electrons (v_-) and of positive ions (v_+) are measured. In dry air in the range

$$E/p = 50\text{–}100 \text{ v cm}^{-1} \text{ torr}^{-1}$$

at temperature 20 °C, $v_- = 256 \times 10^3 E/p + 5 \times 10^6$ and in water vapour in the range $E/p = 55\text{–}85$ v cm^{-1} torr^{-1} at 20 °C, $v_- = 255 \times 10^3 E/p + 8{\cdot}9 \times 10^6$, with units cm sec^{-1} and v cm^{-1} torr^{-1}. The values of v_- obtained for dry air fit the values calculated by Heylen and are higher than those measured with the magnetic-deflection method by Townsend and Tizard.

The mobility of positive ions in dry air, which is constant in the range $E/p = 45\text{–}70$ v cm^{-1} torr^{-1} and is equal to $2{\cdot}2 \times 10^3$ cm^2 v^{-1} sec^{-1} (at 1 torr and at 20 °C), gradually decreases at higher E/p values. In water vapour the mobility of positive ions was constant over the measured range $E/p = 50\text{–}90$ v cm^{-1} torr^{-1} and is equal to $0{\cdot}61 \times 10^3$ cm^2 v^{-1} sec^{-1} (at 20 °C and at 1 torr). In humid air the value of mobility is lower than the value calculated from Blanc's law. This suggests a clustering of ions.

1. Introduction

This paper describes new results concerning the drift velocities of electrons and positive ions in dry air, humid air and water vapour. In this investigation an improved experimental method primarily developed by Hornbeck (1950) was used.

We record the transient current following an illumination of the cathode of a uniform field gap for a short interval of time with ultra-violet light. During the light pulse a current i_0 of photoelectrons flows in the gap under the influence of a static field. At a suitable field strength ionization through the gap increases the current. It is observed by means of an oscilloscope connected via an amplifier across a resistor in series with a discharge gap.

Since the drift velocity of electrons is much larger than that of ions the front of the current pulse depends on the electron component of the avalanche. The tail of the pulse is of much lower value and depends on the ionic component of the avalanche. From the duration of each component the drift velocities of electrons or positive ions can be derived.

2. Ionization chamber and electrode arrangement

The ionization chamber housing the uniform-field electrodes was made from a glass cylinder 50 cm in diameter and 75 cm in length, covered at both ends with steel plates 15 mm thick. The plates were polished on a lathe and were then electroplated with

about 0·05 mm of nickel. As the edges of the glass cylinder were polished too, the chamber could be made vacuum-tight by using suitable gaskets.

The anode was insulated by means of three Nylon brackets fixed to the metal ring, which was provided with three screws. These screws enabled the anode to be made parallel to the cathode. The screws were accessible through the opening in the lower plate of the chamber. The cover of this opening was provided with a quartz window 50 mm in diameter, through which ultra-violet light could pass into the chamber.

The cathode could be moved vertically through a distance of 10 cm. The bracket of the cathode electrode was movable in a guide tube fixed directly to the upper plate of the chamber. This bracket was connected to the micrometer screw which enabled the gap to be set to within 0·01 mm from the outside of the chamber. The movable steel bracket of the cathode was carefully polished and a special type of gasket was used to make the construction vacuum-tight.

The brass electrodes to the Stephenson profile (Bruce 1947) had an overall diameter of 24 cm and a plane central area about 8 cm in diameter. Both electrodes were carefully machined and polished on a lathe. The central area of the anode was provided within a circle 3 cm in diameter with holes each 0·75 mm in diameter. The cathode was illuminated through these holes and the window in the lower plate of the chamber.

3. Source of photoelectrons

In our experiment a spark in compressed gas was used as a source of the cathode illumination. The spark was produced in a gap pulsed to 17 kv and spaced 0·3 mm. The spark gap was arranged in a small metal chamber with a quartz window and a bushing. The chamber was filled with nitrogen compressed to 9 atm. The discharge capacity was of 50 pF and the series resistor was 10 Ω. The approximate shape of the photopulse recorded with a photomultiplier (Philips model 56 AVP) and oscilloscope (Tektronix model 517) is shown in figure 1. As the front duration of this photopulse is about the

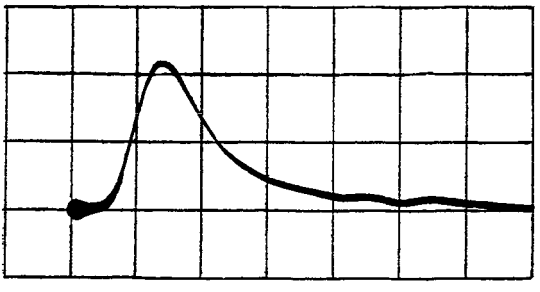

Figure 1. Photopulse illuminating the cathode; time base 10 nsec/div.

same as the rise time of the measuring system (7 nsec), the actual duration of the front is, of course, shorter than 7 nsec. We assume as a first approximation that the pulse is a 10 nsec square wave followed by a 'tail', the time constant of which is about 6 nsec, and that photoelectrons are liberated from the cathode at a rate proportional to the instantaneous value of the light pulse.

In our experiment the cathode is illuminated for a time interval of about 30 nsec, which is of the same order of magnitude as the time constant $T = 1/\alpha v_-$, where α is the first ionization coefficient and v_- is the drift velocity of the electrons. This influences

considerably the current growth in the gap. The considerations of the case are briefly summarized above.

We examine an avalanche in a uniform field gap started by n_0 photoelectrons released from the cathode and we assume that the electron diffusion coefficient $D = 0$. If all photoelectrons are released simultaneously the electron current is

$$i'(t) = \frac{\epsilon n_0}{T_-} \exp\left(\frac{t}{T}\right) \qquad 0 \leqslant t \leqslant T_- \tag{1}$$

where ϵ and T_- are the electronic charge and the electron transit time respectively.

Let us assume now that n_0 photoelectrons are released by a square light pulse of length T_0, followed by an exponential 'tail', the time constant of which is $-T_1$ and the maximum value of which is equal to the value of the square pulse. In this case the electron current is

$$i(t) = \left\{\left(\frac{T_0}{T} + \frac{T_1}{T}\right)^{-1}\left\{1 - \exp\left(-\frac{T_0}{T}\right)\right\} + \left(1 + \frac{T_0}{T} + \frac{T_1}{T} + \frac{T_0}{T_1}\right)^{-1} \times \left[\exp\left(-\frac{T_0}{T}\right) - \exp\left\{\frac{T_0}{T_1} - t\left(\frac{1}{T_1} + \frac{1}{T}\right)\right\}\right]\right\} i'(t), \quad T_0 \leqslant t \leqslant T_-. \tag{2}$$

In our experiment $T_0 = 10$ nsec, $T_1 = 6$ nsec and $T = 30$–60 nsec. Using equation (2) we find that at $t \geqslant T$ the deviation of the current growth from an exponential growth is less than 1% and that the instantaneous values of this current are reduced if compared with the values calculated from equation (1) by a factor 0·75 and 0·86 if $T = 30$ nsec and 60 nsec respectively.

As on our oscillograms the curve rises above the zero line at $t > 3T$, the distortion of this curve (at $t \leqslant T_-$) due to a non-simultaneous release of photoelectrons can not be observed. The only result is that the signal is now lower.

In order to estimate the necessary amplification of the signal at different αd values the number n_0 must also be known. It was measured in the following way. The cathode was illuminated by a spark at a frequency of occurrence of 15 per second and the current in the gap was measured with a d.c. amplifier and electrometer (type 1230 A, General Radio Co., Cambridge). The measurement was made at a potential which was below the ionization potential. As at this potential a saturation current was measured we assumed that the effect of back scattering was avoided. The result was $n_0 = 5 \times 10^4$ electrons. The accuracy of this measurement was to 20% or better.

4. Vacuum system and pressure measurement

The ionization chamber was evacuated by means of an oil-diffusion pump backed by a rotary pump. The housing of the diffusion pump was fixed directly to the lower plate of the chamber. The highest vacuum which could be obtained was 3×10^{-5} torr and was measured with an ionization gauge (Edwards High Vacuum). When the ionization chamber was isolated from the pumps (by means of a valve built into the housing of the diffusion pump) the pressure rose from 3×10^{-5} to 3×10^{-3} torr in about 2·5 hours.

The pressure in the range 2·6–100 torr was measured with an oil manometer, the vapour pressure of which was 2×10^{-7} torr at 25 °c. The readings were accurate to within 1 mm of oil. In the range 100–650 torr the pressure was measured with a mercury manometer isolated from the chamber by a cold trap with liquid nitrogen.

5. Potential measurement

The static potential applied to the gap from a highly stabilized d.c. voltage supply was measured by means of a resistor in series with a microammeter (Hartman and Braun, 0·2%). The resistor (180 MΩ) was built up from 18 sections of wire-wound resistor (temperature coefficient 2×10^{-5}) immersed in an insulating oil. The highest and lowest temperatures of the oil could be measured with thermometers, so that a correction for the change of resistance with temperature could be introduced if desired. In these experiments this correction could be disregarded, as the highest temperature of the oil was 26 °C and the calibration temperature was 21 °C. Each section of the resistor was calibrated with a sub-standard coil and with a standard cell with an accuracy to 0·1% or better.

6. Electron transit-time measurement

The electron transit time T_- was measured as being equal to t_1-t_0. Here t_0 denotes the instant at which the first electrons in a time interval Δt of the cathode illumination leave the cathode, and t_1 is the instant at which they reach the anode.

In order to determine t_0 and t_1, we use a Tektronix dual-beam oscilloscope, type 551, with two fast rise-time preamplifiers, type L. One beam recorded the photopulse illuminating the cathode. The phototube used here was of type 6255S (EMI Electronics). With the second beam the avalanche current was recorded. It was additionally amplified by means of a Tektronix preamplifier, type 121A, with a band pass 5 c/s to 17 Mc/s. The mutual time base, which we calibrated with an accuracy to 2% or better, was triggered by the photopulse itself.

The supply voltage of the phototube was adjusted so that the delay of the signal through the phototube was equal to the delay of the signal via the preamplifiers. Thus the instant t_0 was identical with the instant at which the curve of the photopulse ascends above the zero line. The instant t_1 was taken from the curve of the avalanche current. This current grows exponentially until the instant t_1, at which the first electrons of the electron cloud near the anode reach the anode.

The value of T_-, measured as above, could be checked by comparing it with the time interval T_g between successive avalanches produced by a secondary photoelectric process on the cathode (Raether 1961).

The initial successive avalanches give pronounced peaks of voltage if the time constant RC of the measuring system is considerably lower than the electron transit time. In addition, if the requirement is fulfilled that

$$RC \ll 1/\alpha v_- \tag{3}$$

the instantaneous values of electron current are proportional to the instantaneous value of the measured voltage drop. In our experiment this requirement was not fulfilled as R should be of very low value, and consequently the sensitivity of the measuring system would not be sufficiently high. We have chosen $R = 1\ \text{k}\Omega$, and as C was equal to 70 pF, RC was 70 nsec. This value was of the same order of magnitude as the time constant T of the exponential current rise. In this case the capacitance C 'deforms' the voltage curve if compared with the exponential current curve only at the beginning of the exponential pulse. In our experiment the curve of voltage drop rises above the zero line at $t \geqslant 3T$. Thus we are justified in assuming that this curve represents the current curve in scale.

The rise time of the system used for measurements of the avalanche current was 22 nsec. It was measured by applying square-wave pulses produced by a mercury-wetted relay. As the system was 4–6 times faster than the pulse being measured, the system could be regarded as infinitely fast.

The rise time of the system used for recording photopulses was 16 nsec, so that the rate of rise of the photopulse was slowed down. However, this effect did not reduce the accuracy of the T_- measurement.

7. Measurement of the positive-ion transit time

The positive-ion transit time T_+ in humid air and water vapour was measured as being equal to the duration of the positive-ion component of a primary avalanche. However, in dry air, because of the high value of the secondary ionization coefficient, we could not record a primary avalanche, the duration of which could be measured with satisfactory accuracy. Therefore the values of T_+ in dry air were derived from short series of avalanches.

8. Procedure

8.1. *Dry air*

First the ionization chamber was evacuated to the limiting vacuum and filled with dry air. Then the cathode was 'cleaned' by running a low-pressure glow discharge for about 15 minutes.

Pre-dried, compressed air, supplied in a cylinder, was employed throughout the present work. To check the air supplied, the breakdown potentials and the avalanche current pulses were studied, using room air dried in a liquid N_2 trap and cylinder air dried in a liquid N_2 trap. Results agreeing closely within the limits of experimental error were obtained from both samples, thus justifying the use of cylinder air for this study.

8.2. *Humid air and water vapour*

A small Pyrex glass vessel, 2 cm in diameter and 10 cm in length, was connected to the chamber through a valve. Pure distilled water was introduced into the vessel and frozen by arranging a liquid N_2 bath around the vessel. After the ionization chamber and the vessel had been evacuated to the limiting vacuum, the diffusion pump was isolated and the liquid N_2 bath was removed. Now the warm bath was arranged around the vessel so that water was evaporated to the desired pressure into the ionization chamber, the pressure being measured on an oil manometer. Then the dry air from the cylinder was leaked in until the desired total pressure was reached. In order to avoid condensation of the water vapour, the air was pre-heated to about 100 °C, as in the experiments of Prasad and Craggs (1960).

9. Results

9.1. *Limitation of the E/p range for electron transit-time measurements in dry air*

Figure 2 (lower beam) represents the avalanche pulses in dry air started by about 5×10^4 electrons from the cathode separated from the anode by a distance of 5 cm. Gas amplification was in all cases (figure 2) lower than 10^4.

In order to record the avalanche pulses in a large range of E/p values the pressure of gas was changed from 5 torr to 650 torr. An investigation of the avalanche pulses at constant E/p values and at different gas pressures could not be performed with our experimental arrangement because the sensitivity of the measuring system was too low.

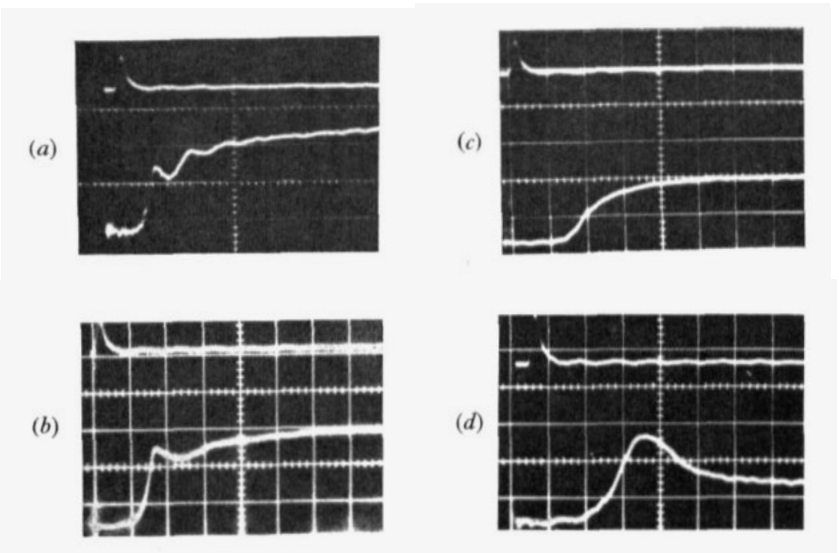

Figure 2. Avalanche pulses (lower beam) in uniform field gap at different pressures p of dry air: plate separation $d = 5$ cm; time base 188 nsec/div.; $RC = 70$ nsec; $n_0 = 5 \times 10^4$ electrons; gas amplification lower than 10^4; temperature 22 °C.

	p (torr)	E/p(v cm^{-1} torr^{-1})	pd (cm torr)
(*a*)	5	79·1	25
(*b*)	50	46·4	250
(*c*)	125	40·1	625
(*d*)	650	34·1	3250

Upper beam, photopulse illuminating the cathode.

At higher E/p values (figure 2(*a*) and (*b*)) the front of the pulse is exponential, as predicted by theory, and its duration is of the range which would be expected on the basis of an estimated electron transit time of the order of 10^{-7} sec. After the first peak we observe the subsequent ones, which appear more distinctly at higher E/p values. The time interval between the successive peaks (oscillogram (*a*)) is in agreement with that predicted by theory if the secondary avalanches are produced by a photoelectric process on the cathode. At gradually lower E/p values the shape of the pulse differs more and more from that predicted by theory, and at $E/p \simeq 40$ v cm^{-1} torr^{-1} looks like that on oscillogram (*c*). At still lower E/p values (oscillogram (*d*)) the front of the pulse is also not exponential and much longer than would be expected.

Avalanche pulses of very long front duration were observed earlier at high gas amplification (Vogel 1957, Blair *et al.* 1961, Tedford and Blair 1962) and at a gas amplification as low as 300 (Frommhold 1960). This observation suggests that at lower E/p values additional processes, such as secondary ionization, which starts in the gas itself, and an attachment–detachment process (Frommhold 1963), interfere with primary ionization started by electrons leaving the cathode.

At higher E/p values these additional processes seem to be of little importance since they do not disturb appreciably the current growth predicted by theory. Therefore we are justified in assuming that at higher E/p values a duration of the front of an avalanche pulse depends only on the electron transit time, providing the radius of electron diffusion is very small compared with the plate separation. The electron current in air can be calculated from equation (1) or (2) if, instead of α, $\alpha-\eta$ is substituted. η is defined here as the electron attachment coefficient.

9.2. *Drift velocity of electrons*

We analyse the front of the avalanche pulse at different E/p values, using oscillograms as shown in figure 3. Converting the pattern of the front into a semi-logarithmic plot, we obtain ln u as a function of time (figure 4). We assume that the curvature of the straight line (departure from the exponential rise of the voltage) starts at the instant t_1, when the tip of an avalanche reaches the anode and the electrons enter the anode. As t_0 is known, and since at t_0 the curve of the photopulse rises suddenly over the zero line (see § 6), we obtain the electron transit time $T_- = t_1 - t_0$. The results, combined with the plate separation, yield the drift velocity of electrons.

The small oscillations during the first 150 nsec recorded on oscillogram (*a*) (figure 3) originate in the instrument and are due to imperfect screening of the spark gap used for the illumination of the cathode. They start at the same instant as the front of the photopulse recorded with the upper beam. In this way we could check that the delay of the signal in the photomultiplier was matched to the delay of the signal in the amplifiers. The oscillations disappear on the oscillograms (*b*) and (*c*) because in these cases the sensitivity of the measuring system was diminished.

It should be mentioned that the duration of the photopulse recorded with the upper beam is longer than the actual duration given in figure 1. The reason is that the supply voltage to the phototube was relatively low and the time constant of the phototube discharge circuit relatively large.

The electron transit time in dry air combined with a plate separation of 5 cm yields the drift velocities given in figure 5, where the drift velocity is plotted against the ratio of field strength to pressure.

In the range E/p = 50–100 v cm^{-1} torr^{-1} the drift velocity of electrons in dry air at a temperature of 20 °c can be expressed by the formula

$$v_- = 256\times10^3 E/p + 5\times10^6 \tag{4}$$

where the units are cm sec^{-1}, v cm^{-1} torr^{-1}.

The drift velocity of electrons in water vapour (figure 5) at a temperature of 20 °c in the range E/p = 50–85 v cm^{-1} torr^{-1} is expressed by the formula

$$v_- = 255\times10^3 E/p + 8{\cdot}9\times10^6 \tag{5}$$

with the same units. Below $E/p = 50$ the value of v_- quickly decreases. These values of E/p correspond to the pressures above 12 torr.

In humid air, when the ratio of partial water pressure to total pressure was 0·16, the drift velocity of the electrons, as shown in figure 5, was slightly higher than in dry air.

It is considered that the values of v_- are subject to an error of less than 7% and of less than 4% at highest and lowest E/p values respectively.

An additional experiment was performed to check whether a leakage of room air ($p_w \simeq 9$ torr) into the ionization chamber influences the results obtained in dry air. At a pressure of dry air equal to 2·5 torr the first set of measurements was performed and

then air was left in the chamber for 3 hours. This time interval was more than 10 times longer than a time interval necessary to perform the first set of measurements. Then the second set of measurements was performed. The results obtained from both sets agreed

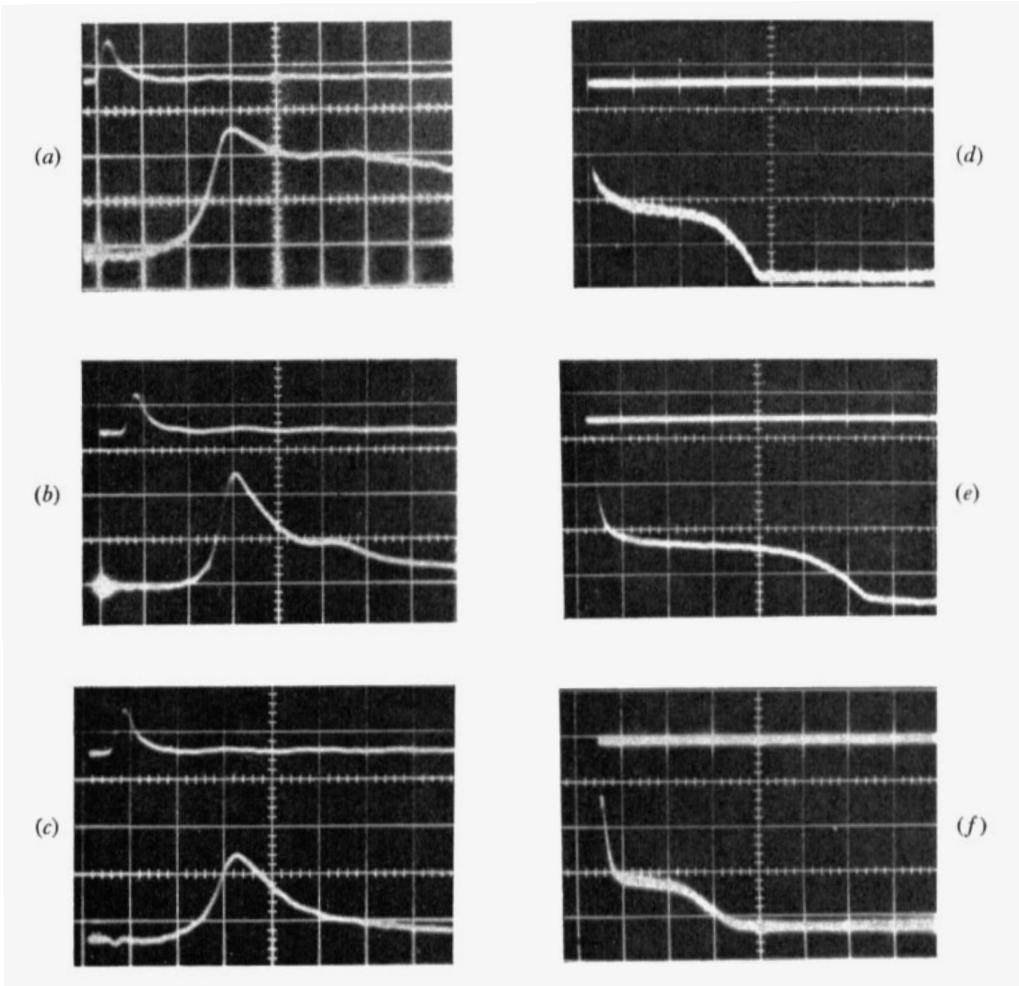

Figure 3. Avalanche pulses (lower beam) in uniform field gap spaced 5 cm: $n_0 = 5 \times 10^4$ electrons; temperature 22–23 °C; p, total pressure; p_w, partial water pressure.

	E/p (v cm^{-1} torr^{-1})	p (torr)	p_w(torr)	Time base (1/div.)	RC
(*a*) Dry air	47·4	31	—	99 nsec	70 nsec
(*b*) Humid air	55·8	16	2·5	99 nsec	70 nsec
(*c*) Water vapour	47·6	15·8	15·8	99 nsec	70 nsec
(*d*) Dry air	106·0	2	—	9·6 μsec	0·88 μsec
(*e*) Humid air	53·3	16	2·5	9·6 μsec	0·88 μsec
(*f*) Water vapour	48·8	15·8	15·8	48 μsec	70 nsec

Upper beam, photopulse illuminating the cathode.

closely within the limits of experimental error. Thus we concluded that the influx of impurities into the chamber could not affect the results given in figure 5 and figure 6.

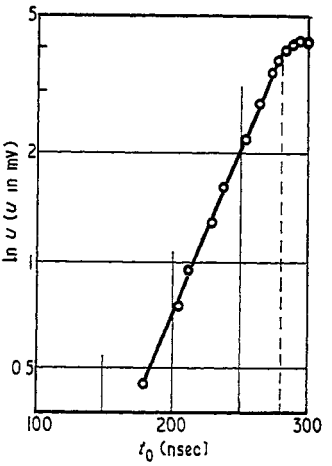

Figure 4. Front of the avalanche pulse from figure 3(*a*) presented in semi-logarithmic plot.

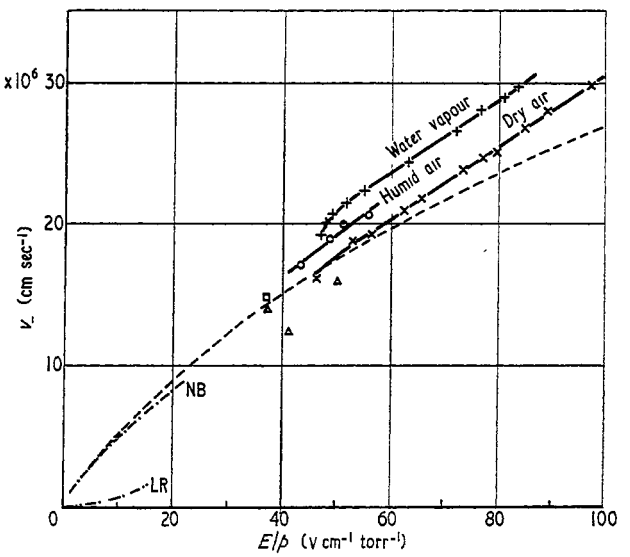

Figure 5. Electron drift velocity in dry air, humid air and water vapour as a function of reduced electrical field. Pressure readings reduced to temperature of 20 °C; humid air, $p_w/p = 16\%$. Broken line, Townsend and Tizard 1913; △, Raether; □, Rieman 1944; NB, Nielson and Bradbury 1937; LR, Lowke and Rees 1963.

9.3. *Error due to the electron diffusion*

Let us consider the error of T_- due to the diffusion of electrons. The diffusion of electrons has the effect of slowing down the rate of rise of the current of an avalanche which approaches the anode because the electrons which have diffused towards the anode earlier enter the anode. However, this effect does not result in any appreciable error if the radius $\bar{r}(d)$ of the electron diffusion in an avalanche which has crossed the gap is much

lower than the plate separation d:

$$(4DT_-)^{1/2} \ll d \tag{6}$$

where D is the electron diffusion coefficient and T_- the electron transit time. Assuming for a rough calculation a Maxwellian distribution of the velocities, one obtains

$$D = 2\bar{\epsilon}\mu/3\epsilon$$

where $\bar{\epsilon}$ is the mean random energy of electrons, μ is the mobility of electrons and ϵ is the charge of the electron. Since $E = U/d$ the requirement can be written

$$U \gg 8\bar{\epsilon}/3\epsilon. \tag{7}$$

The diffusion of electrons also has the effect of slowing down the rate of the current rise if these electrons which diffuse in the direction of the cathode produce over the same time interval fewer new electrons than those which have diffused towards the anode. In order to avoid this effect the requirement concerning the first ionization coefficient can be written

$$\alpha \ll v_-/D. \tag{8}$$

We shall now see whether both requirements are fulfilled in our experiment. For dry air at lowest pressure $p = 2{\cdot}6$ torr, $U = 1270$ v, $v_- \simeq 30 \times 10^6$ cm sec^{-1} and $\alpha \simeq 1{\cdot}3$. Assuming that the random electron energy is 6 ev (Townsend and Tizard 1913), we find that $u \gg 16$ v and that $\alpha \ll 30$. Assuming the same order of magnitude for the random electron energy in water vapour, we find that both requirements are fulfilled in experiments in water vapour.

If the photoelectrons are released from the cathode for a time interval T_0 not negligible compared with T_-(see § 3), the delay of the avalanches started from the cathode should be taken into account. In this case the number of electrons which, owing to diffusion, enter the anode in times shorter than the mean transit time diminishes for each successive avalanche. Consequently the influence of the diffusion on the electron current is not as pronounced as in the case of a sudden release of photoelectrons from the cathode.

9.4. *Drift velocity of positive ions*

The drift velocities of positive ions plotted against the ratio of field strength to pressure are given in figure 6. The results were obtained at a plate separation of 5 cm. The values of T_+ were taken from oscillograms such as oscillograms (*d*), (*e*) and (*f*) in figure 3. Here the series resistance was 12·2 kΩ or 1 kΩ. As the resultant capacitance was 70 pF, the time constant was 0·84 μsec and 70 nsec respectively. These values were much lower than the time constant $1/\alpha v_+$. Thus we were justified in assuming that T_+ was equal to the duration of the positive-ion component of an avalanche given on the oscillogram.

At larger t values, for instance at $t > 0{\cdot}5\ T_+$, where T_+ is the transit time of positive ions, the current of negative ions of an avalanche is very small if compared with the current of positive ions equal to

$$i_+(t) \simeq \frac{n_0\epsilon}{T_+}\,\frac{\alpha}{\alpha-\eta}\,[\exp\{(\alpha-\eta)d\} - \exp\{(\alpha-\eta)v_+t\}], \quad T_- \leqslant t \leqslant T_+. \tag{9}$$

Consequently at larger t values the recorded curve in figure 3(*d*), (*e*) and (*f*) should be exponential in accordance with equation (9). This is the case when we analyse the oscillogram in figure 3(*e*) and (*f*). The curve in figure 3(*d*) is typical for the current of a short series of the avalanches produced by a photoelectric secondary effect on the cathode. This could be confirmed by observing the front of the pulse with a short time base.

The reason that we could not record single avalanches in dry air was the low sensitivity of the recording system. It was sufficiently high only in the case of humid air and of water vapour, as in these mixtures of gases the secondary ionization coefficient is much lower than in dry air.

From figure 6 it follows that in dry air the mobility of positive ions is constant in the range 45 v cm^{-1} $torr^{-1}$ to about 70 v cm^{-1} $torr^{-1}$ and at 20 °c and 1 torr is equal to about $2{\cdot}2 \times 10^3$ cm^2 sec^{-1} v^{-1}. At higher E/p values this mobility has lower values.

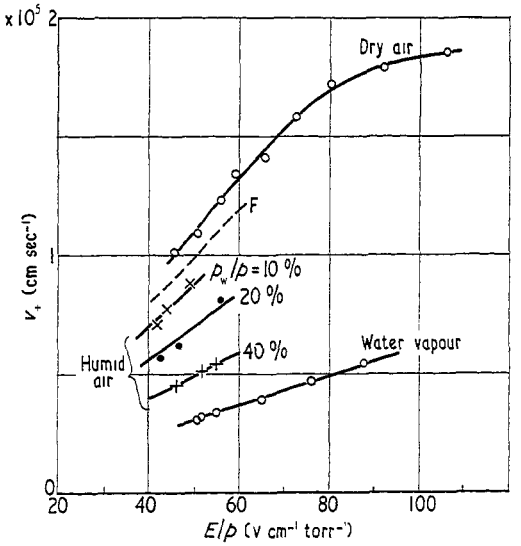

Figure 6. Drift velocity of positive ions in dry air, humid air and water vapour as a function of reduced electrical field. Pressure readings reduced to temperature of 20 °c; p_w, partial pressure of water vapour; p, total pressure; F, Frommhold.

In water vapour the mobility is constant over the measured range from 50 to 85 v cm^{-1} $torr^{-1}$ and at a temperature of 20 °c and 1 torr is equal to $0{\cdot}61 \times 10^3$ cm^2 sec^{-1} v^{-1}.

It is considered that the values of v_+ as a function of E/p are subject in dry air to an error of less than 8% and less than 4% at the highest and lowest E/p values respectively. In humid air v_+ values are subject to an error of less than 3%, and in water vapour to an error of less than 7% and less than 3% at the highest and the lowest values of E/p respectively.

10. Concluding remarks

The drift velocity of electrons in dry air obtained in our experiments is in agreement with the data by Townsend and Tizard (1913) only at E/p = 40–50 v cm^{-1} $torr^{-1}$. If we extrapolate our results, we find that at E/p = 100 v cm^{-1} $torr^{-1}$ the drift velocity of electrons is 13% higher than that given by Townsend and Tizard.

It is worth stressing that the calculated drift velocity of electrons in dry air (Heylen 1962) at E/p > 50 v cm^{-1} $torr^{-1}$ is also higher than the velocity given by Townsend and Tizard. At E/p = 100 v cm^{-1} $torr^{-1}$ it is about 12% higher.

Our experiments show that in humid air the drift velocity of electrons is somewhat higher than in dry air. This result is likely but not quite certain, as the difference is within the range of measurement accuracy. The drift velocity of electrons in humid air obtained here is in fairly good agreement with the results of Blair *et al.* (1961), as the differences are also within the range of the measurement accuracy. The value obtained earlier in a cloud chamber by Rieman (1944) is in good agreement if we extrapolate our results. Raether's (1937) results show lower values.

At $E/p > 55$ v cm^{-1} torr^{-1} the drift velocity of electrons in water vapour grows linearly with an increase in E/p. The departure from a linear dependence is observed at pressures above 12 torr.

The values of the drift velocity of positive ions in dry air obtained in our experiment are about 10% higher than the values of Frommhold (1960), which were measured with a plate separation of 3 cm, and about 30% higher than the values of Vogel (1957), which were measured with a plate separation of 2 cm.

In order to verify the results obtained for the plate separation of 5 cm, we performed the experiments in the range $E/p = 45$–55 v cm^{-1} torr^{-1} for a plate separation of 3 cm. The results were the same as at a plate separation of 5 cm within the limits of experimental error. Thus we assume that, if the transit time of positive ions in dry air is of the order of tens of microseconds, ageing of the ions does not occur. Here it can be mentioned that Bradbury (1932) did not find any ageing of the positive ions in dry air even when the age of the ions was as great as 70 msec. However, his value for the mobility is lower than ours.

Since, as regards water vapour, the measurements until now have been performed only at E/p values lower than those in our experiments, we have no comparative data. The newer results for the range $E/p = 1$–15 v cm^{-1} torr^{-1} (Lowke and Rees 1963), which are in fairly good agreement with those of Pack *et al.* (1962), are shown in figure 5.

As could be expected (Blair *et al.* 1961), the positive ion drift velocity in humid air is lower than in dry air. From our experiments it follows that it is higher than the drift velocity in water vapour. However, if we consider air and water vapour as two gases and humid air as their mixture and if we calculate the respective mobilities and the fractional concentration of air and water vapour in humid air, we see that here Blanc's law cannot be applied. This result suggests that in humid air a clustering of ions takes place.

It is difficult to compare our results for the drift velocity of positive ions with the results obtained by Blair *et al.* (1961). We kept a constant ratio of partial water pressure to total pressure. In the experiments of Blair *et al.* the partial water pressure was kept constant while the total pressure was changed. In such experiments one can obtain an apparent independence of the drift velocity on the reduced electrical field.

Acknowledgments

It is a pleasure to acknowledge discussions concerning this work with Dr. R. Siksna. Thanks are due to Professor S. Lundquist for providing part of the work facilities.

References

Blair, D. T. A., McNaull, J., Tedford, D. J., and Bruce, F. M., 1961, *Proc. 5th Int. Conf. Ionization Phenomena in Gases, Munich*, Vol. 1 (Amsterdam: North-Holland), p. 162.
Bradbury, N. E., 1932, *Phys. Rev.*, **40**, 508, 522.

BRUCE, F. M., 1947, *J. Instn Elect. Engrs*, [II], **94**, 138.
FROMMHOLD, L., 1960, *Z. Phys.*, **160**, 554.
—— 1963, *Proc. 3rd Int. Conf. Physics of Electronic and Atomic Collision, London*, 1963 (Amsterdam: North-Holland), p. 556.
HEYLEN, A. E. D., 1962, *Proc. Phys. Soc.*, **79**, 284.
HORNBECK, I. A., 1950, *Phys. Rev.*, **80**, 297.
LOWKE, J. J., and REES, J. A., 1963, *Aust. J. Phys.*, **16**, 448.
NIELSEN, R. A., and BRADBURY, N. E., 1937, *Phys. Rev.*, **51**, 69.
PACK, J. L., VOSHALL, R. E., and PHELPS, A. V., 1962, *Phys. Rev.*, **127**, 2084.
PRASAD, A. N., and CRAGGS, J. D., 1960, *Proc. Phys. Soc.*, **76**, 223.
RAETHER, H., 1937, *Z. Phys.*, **107**, 91.
—— 1961, *Ergebn. exakt. Naturw.*, **33**, 224.
RIEMAN, W., 1944, *Z. Phys.*, **122**, 216.
TEDFORD, D. J., and BLAIR, D. T. A., 1962, *Proc. Phys. Soc.*, **79**, 310.
TOWNSEND, J. S., and TIZARD, H. T., 1913, *Proc. Roy. Soc.* A, **88**, 336.
VOGEL, J. K, 1957, *Z. Phys.*, **148**, 355.