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The variation with temperature of positive streamer properties in air

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Abstract. Measurements are reported of the variation of the electric field required for propagation of positive streamers in air as a function of ambient temperature. Propagation velocities have also been measured as function of field and temperature. The results are discussed in terms of changes of air density consequent upon the temperature changes and comparisons are made with other work in which density has been changed by variation of pressure at constant temperature. There is some evidence that specific temperature effects exist. The variation of streamer velocity with air density indicates that a constant reduced total field E/N is maintained in the avalanches, replicating the streamer tip as the density is changed.

1. Introduction

The implicit variation with air density of the electric gradient required for positive streamer propagation is employed in the correction procedure adopted in 1989 by the IEC [1] for the measurement of high voltages. A study of this variation also provides insight into the mechanism of streamer propagation; results in which density has been changed by changing the air pressure at constant temperature have been reported by Phelps and Griffiths [2] and Tang [3], but in no previous work has density been changed by means of temperature changes at constant pressure.

Such a study might be expected to show specific effects depending on temperature, since propagation depends upon the detachment of electrons from the negative ions in the atmosphere and upon the efficiency of attachment in the streamer trail. Both of these depend on the composition of the negative ion species in the atmosphere, which is temperature-dependent [4].

Preceding papers [5, 6] have discussed the minimum field needed for the propagation of a streamer under the condition of minimum attainable space charge due to branching. This measurement, as in the previous cases [2, 3], has been made in a plane-parallel electrode arrangement in which streamers are initiated by a voltage pulse at a sharp point placed in the earthed plane. It has been shown that the absolute threshold field measured depends upon the conditions of voltage pulse length and amplitude, but that variations in, for example, streamer velocity, depend only on the uniform field in which propagation takes place. It follows that meaningful measurements can be made, as a function of temperature, of the relative changes in the field required for propagation and in the velocity of propagation in a uniform field. The present paper describes such measurements and discusses their implications for measurements of high-voltage spark-over at high temperatures and low densities.

2. The technique

The experimental technique has been described earlier [5, 6]. Positive streamers were initiated by application of a voltage pulse to an electrode set in a small aperture in an earthed plane; the point of the electrode was level with the plane. The streamers passed in a uniform field to a parallel-plane electrode 18 cm away from the earthed plane. The system was enclosed in an insulated enclosure equipped with internal electric heaters. Temperature could be raised to > 450 K. There was no control of atmospheric pressure or humidity, which were ambient.

The uncertainty in measurements is now considered. The gap between plane electrodes was determined to an accuracy better than 0.5 mm and the voltage measurement (checked against a standardized resistor) was accurate and repeatable to within 0.2%. Thus, the maximum uncertainty in field measurement was less than ±0.5%. uncertainty in pressure measurement was estimated at 0.13% and in temperature measurement (by means of a digital thermometer) at 0.16%. Adjustment was made for pressure variation [1]. Humidity varied between 10 and 12 g m^{-3} during the experiments. Results were adjusted to a standard humidity of 11 g m^{-3} [1], but there was a remanent uncertainty of the order of 0.25%. Thus, an overall uncertainty in repeatability of

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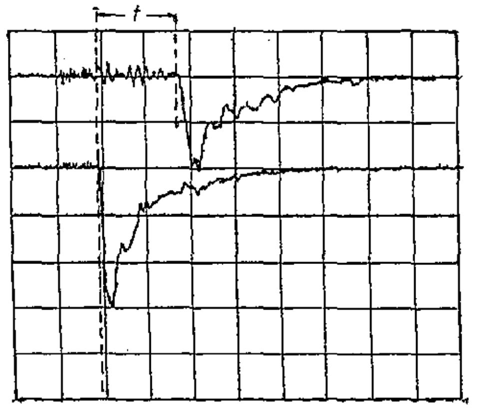

Figure 1. Oscillograms from photomultipliers directed at the point of origin of positive streamers (lower trace) and at the cathode (upper trace). The scale is 250 ns per division.

experimental conditions of not more than ±1.0% in the results is considered likely.

3. Experimental results

3.1. The variation of minimum field with temperature

The minimum field for propagation was measured in the temperature range 294 K< T < 421 K. The previous paper [6] has shown that a meaningful minimum field could be measured, at room temperature; distortion of the ambient, uniform field at the level of the earthed plane near the point was not more than 7% and was less than 1% at axial distances towards the cathode greater than 10 mm away from the point. Procedures were the same in the present work: the pulsed voltage at the point was reduced, progressively, from 4.5 to 3.0 kV and, at each voltage level, the uniform field was raised in small intervals until streamer traverse of the gap was detected by photomultipliers directed towards the point and towards the cathode, which was 15 cm distant. An example of the oscillograms obtained is shown in figure 1.

The voltage pulses were repeated 20 times for each field value by raising the latter over a narrow range; the probability of streamer traverse thus increased. Results obtained at three temperatures are shown in figure 2. 'Threshold' (defined for practical purposes as a probability of 0.025) and 'stability' (probability of 0.975) fields could be identified. At room temperature, with a pulsed voltage of 3.0 kV, the threshold field was 434 kV m^{-1} (curve 1) and the stability field was 440 kV.

In this group of experiments, carried out at an ambient pressure of 999 mbar, the measured fields were adjusted to values that would be expected on the basis of a linear pressure- or density-dependence, at a standard pressure of 1013 mbar, by multiplying by the ratio of 1013/999. This adjustment is in line with the standard IEC procedure [1] for normalizing non-uniform field spark-over voltages, where streamer pre-discharges

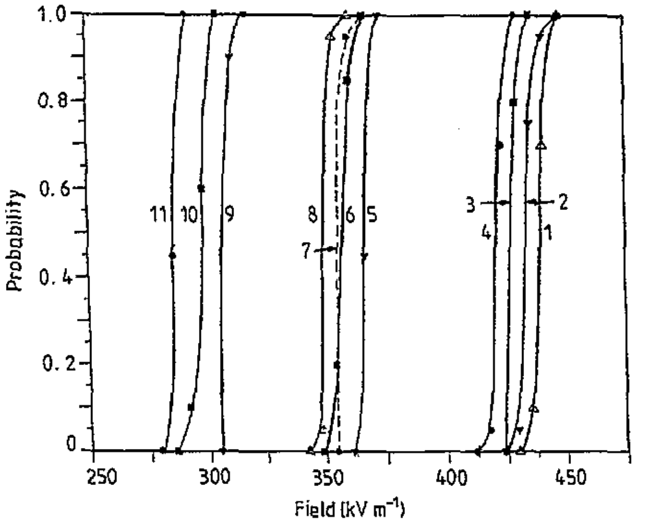

Figure 2. The effect of the pulse voltage at the point on the probability of streamer propagation in the uniform field at three different temperatures: T = 294 K 1, 0.3 kV; 2, 3.5 kV; 3, 4.0 kV; 4, 4.5 kV; T = 323 K 5, 3.0 kV; 6, 3.5 kV; 7, 4.0 kV; 8, 4.5 kV; and T = 373 K 9, 3.0 kV; 10, 3.5 kV; and 11, 4.0 kV. The uniform field gap is 15 cm, with pressure 999 mbar and humidity 10 g m^{-3}. (Results are normalized to a density corresponding to a pressure of 1013 mbar using IEC procedure [1]; no adjustment for humidity was made).

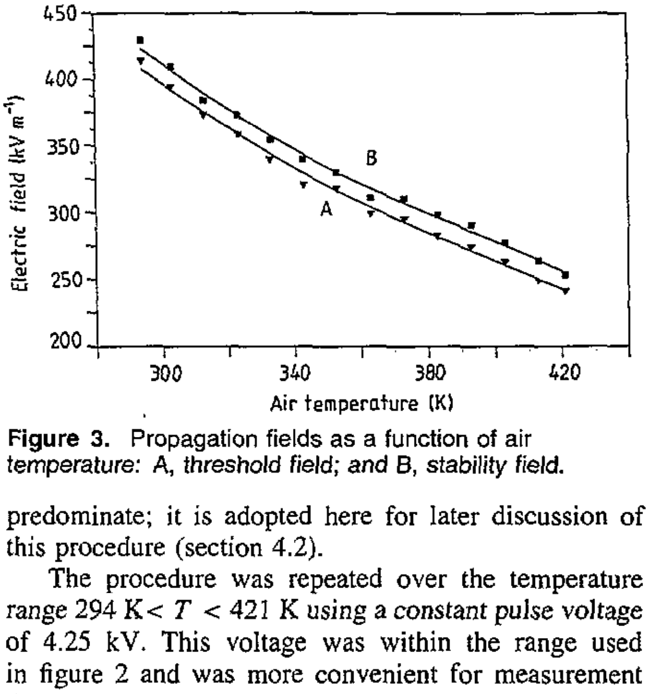

Figure 3. Propagation fields as a function of air temperature: A, threshold field; and B, stability field.

predominate; it is adopted here for later discussion of this procedure (section 4.2).

The procedure was repeated over the temperature range 294 K< T < 421 K using a constant pulse voltage of 4.25 kV. This voltage was within the range used in figure 2 and was more convenient for measurement than were lower voltages. The previous work [6] had shown that, over the whole voltage range, there was no evidence of significant effects due to space charge caused by streamer branching at higher voltages and that experimental trends represented intrinsic streamer behaviour. Threshold and stability fields are shown in figure 3. The two curves are parallel, within the limits of experimental accuracy; the parallellism confirms the lack of influences due to space charge by branching.

Photographs of the streamer system at constant field and at two temperatures are shown in figure 4. Light emission, in the ultra-violet, was low, especially at room

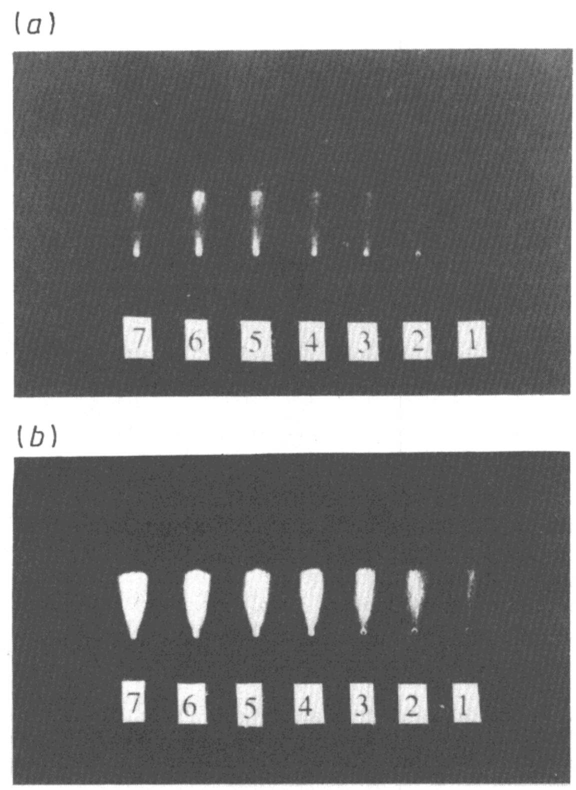

Figure 4. The effect of temperature on streamer propagation. Numbers indicate the number of superimposed shots: (*a*) $T = 290$ K and (*b*) $T = 373$ K. The applied electric field was 500 kV m^{-1}; with pulse voltage 4.25 kV and gap length 15 cm.

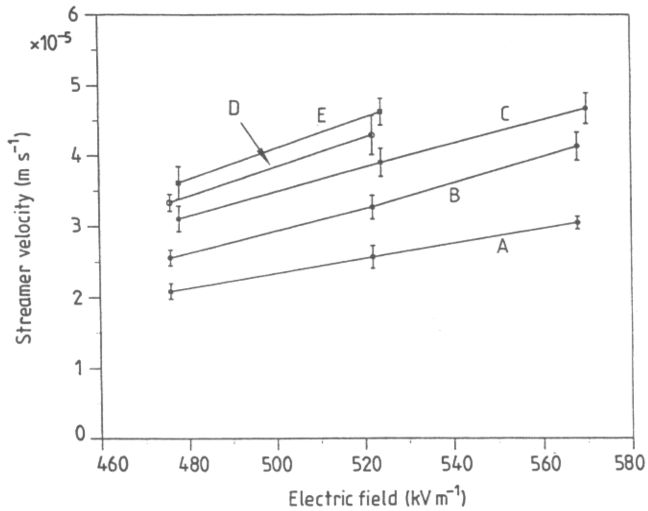

Figure 5. The streamer velocity as a function of electric field at various temperatures: A, 288 K; B, 313 K; C, 333 K; D, 353 K; and E, 363 K. The gap length was 15 cm with humidity 7 g m^{-3} and pressure 998 mbar. Field values were normalized to a density corresponding to a pressure of 1013 mbar. No adjustment for humidity was made.

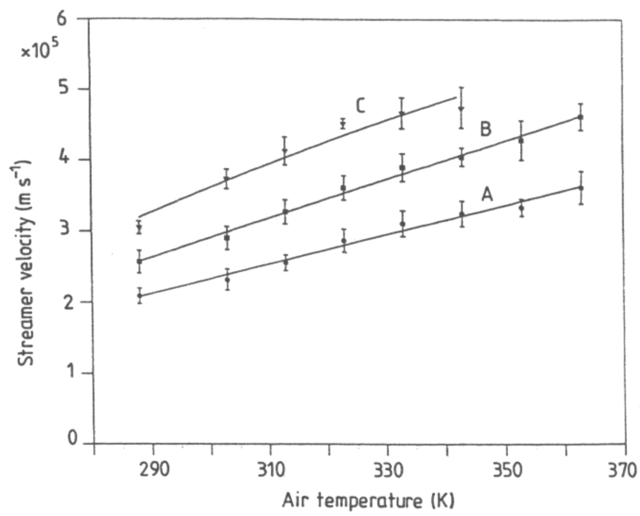

Figure 6. The streamer velocity as a function of air temperature at three electric fields: A, 467 kV m^{-1}; B, 522 kV m^{-1}; and C, 568 kV m^{-1}. Conditions were as in figure 5.

temperature, and superposition of up to seven shots is shown. At higher temperature, and constant field, light emission is increased; it is not possible to determine whether this is a function of intensity emitted from individual streamers, or due to some branching.

3.2. Streamer velocity as a function of temperature

Streamer velocities were determined from the time intervals between the start of the rise of the detected light in each of the oscillograms such as those in figure 1. The field of view of each photomultiplier (of identical associated circuitry) was 1.4 cm at the position of streamer transit; the start of the light signal was assumed to correspond to the entry to the field of view of the first streamer.

Uncertainty in positioning of the field of view of the photomultipliers is estimated at ±0.2 cm, leading to a maximum uncertainty in absolute velocity measurement of about 2.2%. However, since the photomultiplier positions were constant throughout a given set of experiments, uncertainties in relative measurements were less than this, and were limited mainly to uncertainties in field measurements.

Figure 5 shows streamer velocities as a function of electric field at each of five temperatures in the range 228 K$< T <$ 373 K. No adjustment is made, for pressure variation, to the velocity measurements but adjustment of field values has been made by the procedure described in section 3.1. Velocities are re-plotted in figure 6 as a function of air temperature for three values of electric field. The points show mean values of ten shots, with error bars showing the total spreads. Within the ranges studied, streamer velocity is thus a linear function of both electric field and temperature.

4. Discussion

4.1. The propagation field

Comparison is now made with previous work, which has been expressed in terms of the relative air density

$$\delta = \frac{p}{1013}\frac{293}{T} \quad (1)$$

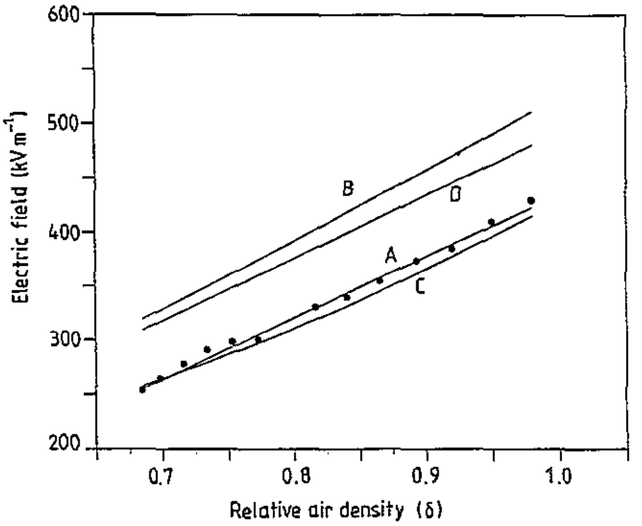

Figure 7. The streamer propagation field as a function of relative air density, δ: A, present results; B, Phelps and Griffiths [2], re-arranged by Geldenhuys [7]; C, Tang [3]; and D, Geldenhuys [7]. All results were normalized to standard atmospheric humidity, 11 g m^{-3}, using the IEC procedure [1].

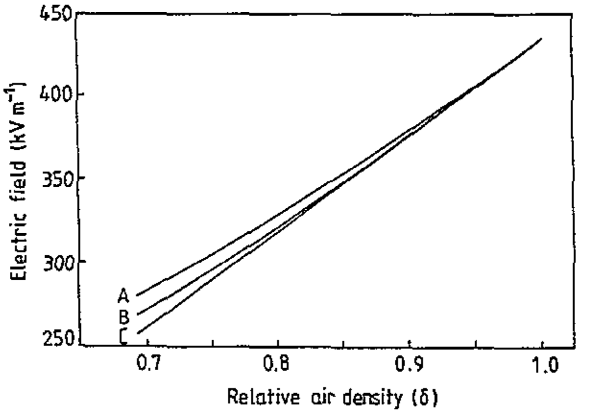

Figure 8. The variation of propagation field with density: A, Geldenhuys [7], $E_S = E_{S0}\delta^{1.2}$; B, Phelps and Griffiths [2], $E_S = S_{S0}\delta^{1.31}$; and C, the present results, $E_S = 567\delta - 133$. Conditions were as in figure 7.

where p is the pressure in millibars and T is the temperature in kelvins. Experimental conditions are expressed relative to a value of $\delta = 1$, that is, the standard atmospheric condition $p = 1013$ mbar and $T = 293$ K; this reference is also used in IEC spark-over measurement procedures [1]. The present experiments have covered the range $0.68 < \delta < 1.0$.

The threshold values are re-plotted as a function of δ in figure 7 (points), together with the results of Phelps and Griffiths, curve B and of Tang, curve C; both of these sets were obtained in experimental arrangements basically similar to the present one.

Curve A is drawn through the points; the equation of the straight line so obtained is

$$E_S = 567\delta - 133 \text{ kV m}^{-1}. \quad (2)$$

Comparison with previous work is made as follows. Phelps and Griffiths found a variation in propagation field according to

$$E_S = E_0\delta^m \quad (3)$$

where E_0 is the propagation field at standard atmospheric density condition and $m = 1.5$. Geldenhuys [7] re-evaluated this result and added a humidity adjustment factor, giving

$$E_S = 524\delta^{1.31}[1 + 0.17\delta^{0.72}(h - 11)] \text{ kV m}^{-1} \quad (4)$$

where h is the absolute humidity in g m^{-3} ($h = 11$ g m^{-3} is taken as standard atmospheric humidity), curve B. On the basis of his own experimental results, obtained by corona measurement in a rod–plane arrangement, but also by varying pressure at constant temperature, Geldenhuys [8] proposed the relationship

$$E_S = 489\delta^{1.2}[1 + 0.13(h - 11)] \text{ kV m}^{-1} \quad (5)$$

This is shown in curve D.

Where experiments are carried out at $h = 11$ g m^{-3} or alternatively, corrected to that value by the use of the factors in equations (5) and (6), then the variations of E_S with δ simplify to $\delta^{1.31}$ or $\delta^{1.2}$. The curvature implicit in these relationships contrasts with the linearity of the present results, expressed in equation (2).

The results of Tang, curve C, obtained by change of pressure at constant temperature, show disagreement with curves B and D under similar atmospheric changes, but show close agreement with the present results where temperature was varied. Overall accuracy was not estimated in this case. Agreement between curves C and A suggests the absence of a temperature effect, but the disagreements noted indicate that a fully satisfactory situation has not yet been achieved.

The reality of any difference between the density-dependences at constant pressure and at constant temperature thus depends on the accuracies inherent in the experiments. In the present case, the experimental uncertainty in repeatability has been set out in section 2; in [2] a figure of ±3.5% is quoted. Comparison between results is made by using the indices $m = 1.31$ and 1.2 in equations (4) and (5) ($h = 11$ g m^{-3}) and normalizing the respective coefficients in each case to the present value of 434 kV m^{-1}. These results are shown, as curves A and B respectively, in figure 8, where they are compared with the present results, curve C. Significant differences of up to 7% appear for low values of δ. Tests show that the use of the index $m = 1.42$ gives a curve agreeing to within 1.5% with the straight line of curve C (equations (2) and (3)).

It is worthwhile to note here that a 1% uncertainty in the measured value of the field results in a 15% uncertainty in the value of 'm' at $\delta = 0.95$ and a 2% uncertainty at $\delta = 0.70$ when the curves are calculated in the way described. Thus, any of the index values used could be applicable in the range above $\delta \simeq 0.85$, but the results show that a possible divergence between temperature and pressure effects, which is worthy of further experimental investigation, develops at lower densities.

4.2. The relation to atmospheric efforts on spark-over

It is established that spark-over in, for example, a rod–plane gap is determined by the traversing of streamers across the gap and, therefore, by the streamer propagation field. Thus, in such a gap 1 m long, the breakdown voltage is taken to be approximately 500 kV; the average gradient in the streamers is 500 kV m^{-1}. This has resulted in the use of this value as the basis of a normalizing procedure to relate measurements of spark-over voltages made at different atmospheric densities and humidities [8, 1].

The procedure uses the analogue of equation (4), at constant humidity, namely

$$V_M = V_0\delta^m \qquad (6)$$

where V_0 is the spark-over voltage under standard atmospheric conditions, $\delta = 1$ and V_M is the voltage measured at relative air density δ. Under a lightning impulse, it is assumed that $m = 1$, and that this value should be used for normalizing over the range $0.9 < \delta < 1.1$. For $\delta < 0.9$, a different 'high-altitude' correction procedure is adopted [9] and it is readily shown that an approximation in which $m = 0.80$ is valid over the range $0.65 < \delta < 0.90$, for a lightning impulse.

These values of m, which are derived from spark-over experiments, are significantly lower than those discussed in the foregoing, which were obtained by the experiments with streamers.

However, the normalizing procedure specifically includes a correction to an assumed streamer gradient of 500 kV m^{-1}, using equation (4), in which m is put equal to 1. The accuracy of the procedure is not, however, fully established and is examined in more detail in a further publication [10]. Breakdown involves a cathode mechanism, the variation of which, with δ, is not known and a weakness of the present normalizing procedure is that no account is taken of this factor, There is a need for further work to reconcile the density variations of streamer propagation fields and of spark-over voltages.

4.3. Streamer velocities

The points in figure 6 have been re-plotted in terms of δ in figure 9, using equation (1), covering the range $0.78 < \delta < 1.0$. Since δ varies as $1/T$, some curvature would be expected, though this is small.

Further interpretation is made by plotting the streamer velocity as a function of δ at a constant value of E/δ, which scales linearly with the parameter E/N used for discussion of electron swarm behaviour, where N is the neutral gas molecular density. Figure 10 shows that the slope is close to zero, suggesting that the velocity depends linearly on the electron ionizing process occurring in the successive avalanches that replicate the streamer and that there is negligible change with density in the combined effects of the field near the head of the streamer and the applied field.

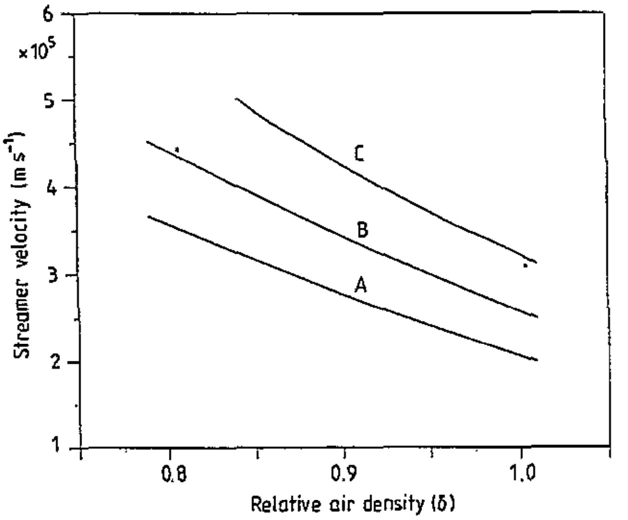

Figure 9. The streamer velocity as a function of relative air density, δ. The applied electric fields were A, 476 kV m^{-1}; B, 522 kV m^{-1}; and C, 568 kV m^{-1}. Conditions were as in figure 5.

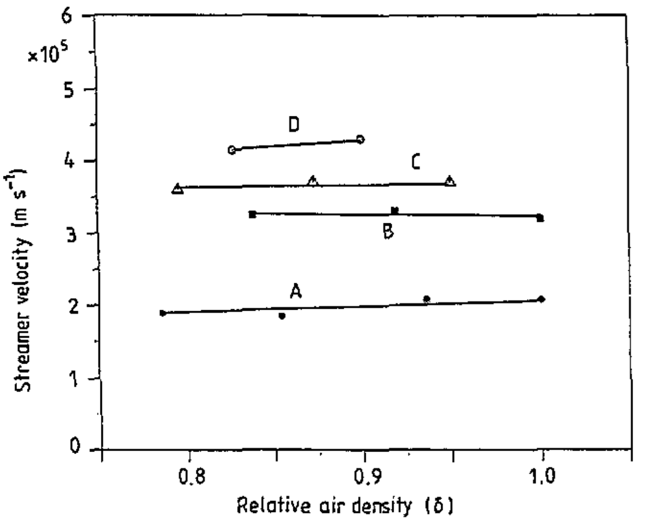

Figure 10. The streamer velocity as a function of relative air density for constant values of E/δ:
A, $E/\delta = 479$ kV m^{-1} per unit of density; B, $E/\delta = 568$; C, $E/\delta = 598$; and D, $E/\delta = 631$. Conditions were as in figure 5.

4.4. The variation of streamer properties with E/δ

Ionization and diffusion processes in an electric field E depend on the parameter E/N. In figure 11, the threshold applied field per unit of air density E/δ has been plotted against δ. The results of figure 2 of [2] have been normalized to the present value of the applied field of 434 kV m^{-1} at $\delta = 1$ and are also shown. In both cases, E/δ increases with δ, but differences that are just significant occur at values of δ below about 0.8. Since the values of Phelps and Griffiths were obtained at a constant temperature of $-14\,°C$, the comparison again suggests that a real temperature effect may exist.

These trends contrast with the constant values obtained when the velocities are plotted against δ at constant values of E/δ, figure 10. Since the streamer velocity depends upon the electron transit times in the

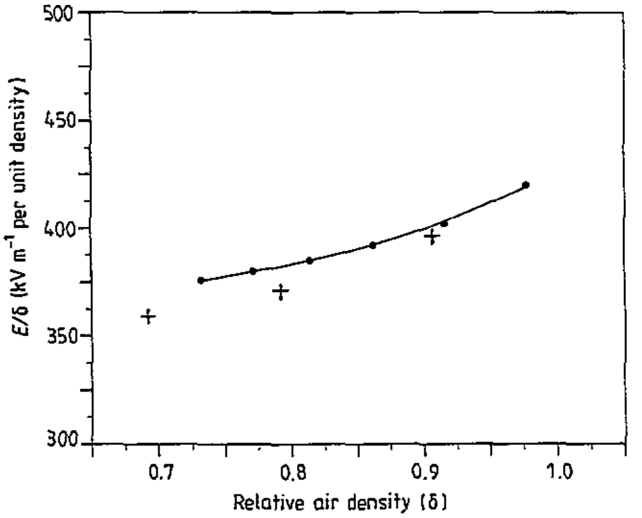

Figure 11. Values of E/δ at thresholds, plotted against δ: (●), the present results (conditions were as in figure 2); and (+), Phelps and Griffiths [2].

consitituent avalanches, this result shows that values of E/N (made up of the applied and streamer tip space-charge fields) in the avalanche region remain constant as δ decreaes and that the thermal energy, kT/e, which partly governs the diffusion, is also constant under constant velocity conditions. At constant E/N, the ionization coefficient λ varies with N.

The variation with N of the charge Q in the avalanche head is not known, but since the space-charge field component is proportional to Q/r_A^2, where r_A is the diffusion radius of the head, r_A^2 is proportional to E/N at constant N, but increases with decreasing N, so that, to maintain a critical avalanche and constant E/N, Q increases as N decreases. However

$$Q = \exp(\lambda x_c) \quad (7)$$

where x_c is the mean length of the critical avalanche. Since $\lambda \propto N$, it follows that x_c increases as N decreases.

Thus, the constancy of velocity is consistent with an increase in the length of the critical avalanches as the gas density decreases. At the threshold field, on the other hand, for which no velocity measurement is available, the condition of constant velocity and E/N is not necessarily a condition of propagation. Thus, since measured values of field form only a minor component of the total field round the streamer tip, it is probable that the reduction of E/N, as δ is reduced, results in less diffusion and smaller values of charge Q at threshold.

5. Conclusions

(i) The field required for propagation of a streamer in air, and its velocity as a function of field, have been measured in conditions of changing air density achieved by variation of temperature at constant pressure.

(ii) The minimum field for propagation shows a linear dependence on relative air density δ. Comparison is made with other results, in which density was changed by variation of pressure at constant temperature, and in which the dependence was not linear. The differences are considered significant at low values of δ, suggesting that a specific temperature effect exists.

(iii) The dependence of propagation field on density suggests approximation to a power law, as δ^m, where $m = 1.42$. The relation between this and the law used for normalization of spark-over voltages in non-uniform fields, where m is put equal to 1.0, is considered; the discrepancies suggest that a reconsideration of the latter procedure is needed.

(iv) Streamer velocities vary linearly with uniform field in the range 476 kV m^{-1} < E < 568 kV m^{-1} at constant temperature, and linearly with temperature in the range 288 K< T < 368 K at constant field.

(v) At a constant value of the parameter E/δ, streamer velocities are constant over the range $0.78 < \delta < 1.0$, indicating an adjustment of space charge with density at the streamer tip to maintain a constant reduced field E/N within the avalanche region.

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