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Dynamics of streamer propagation in air

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Abstract. Results concerning the dynamics of streamer propagation in air under a uniform electric field are presented and discussed. Experiments were performed in a plane-parallel electrode arrangement with positive streamers initiated at a sharp point in the earthed anode. The basic properties of streamers are described in terms of the electric field required for a stable propagation and the associated propagation velocity. Critical parameters are the ambient electric field, the voltage used for streamer initiation and the distance of traverse. The present experiments permit the separation between the effects of the above parameters upon streamer advancement and propagation over the whole path up to the cathode. It is shown that an intrinsic propagation field with an associated velocity can be defined, which determine the propagation of streamers of a limiting, minimum energy. The propagation velocity is a power function of the electric field and, with the aid of an empirical equation, values can be expressed accurately in terms of these intrinsic streamer properties.

1. Introduction

Streamer propagation determines the breakdown characteristics of many electrode configurations in air. For example, under lightning impulse or direct voltages, the sparkover voltage gradient is closely related to the gradient required for streamer propagation. Also, the IEC procedures for correcting sparkover voltages in air for both air density and humidity variations [1] are based on this parameter, adopting a value of 500 kV m^{-1} as a working figure. Knowledge of streamer characteristics in air is thus important to the interpretation of a number of practical problems arising in insulating systems.

Several workers have investigated the propagation of streamers in air; a plane-parallel electrode arrangement with streamers initiated at a sharp point in an earthed anode plane has been found useful [2–6]. This arrangement offers the benefit that basic properties can be studied and careful control exercised on the energy with which streamers can be initiated, so that a range of conditions, from the threshold for propagation to those for streamer-induced breakdown, can be studied.

The present paper reports more detailed studies than have been made hitherto of the limiting conditions of field required for stable propagation of a single streamer, of the relation between the velocity of propagation and electric field and of the influence of the energy imparted to a streamer at the point of origin. It also reports on the dynamics of streamer advancement over the whole path up to the cathode, as the distance of traverse from the point was considered as another parameter influencing the streamer properties. The results have led to the definition of an 'intrinsic' propagation field and its related velocity, and place the basic streamer properties on a sounder and more useful quantitative basis than before.

2. The experimental arrangement

2.1. The general settings

The electrode arrangement consists of two parallel planes with a gap clearance of 12 cm. A sharp point was located in a small aperture of radius 5 mm at the centre of the lower earthed plane at the same level (figure 1). The gap was stressed by negative direct voltage applied to the upper plane; in this way a uniform electric field was applied to the gap. There is a distortion of the uniformity of the electric field caused by the aperture of the earthed plane; however, this recovers to within 2% of the ambient field value at a distance of 1.5 cm above the earthed plane [6].

Positive streamers were initiated at the point by applying a fast high-voltage square pulse, with 20 ns rise time, variable in amplitude, u, and duration. The pulses were produced by discharge of a coaxial line and were monitored via a coaxial capacitive divider that was used to trigger a digital storage oscilloscope. Two pulse durations were used, of 135 ns and 270 ns, by changing the length of the line.

To observe the streamers traversing the gap three identical battery driven photomultipliers (EMI type 9781 B) were used (figure 1). Each photomultiplier had a vertical field of view of 0.6 cm along the axis and was horizontally levelled with respect to the ground. Two of the photomultipliers were directed at grazing incidence to the cathode and the earthed plane respectively. The third photomultiplier, starting from a distance of 1 cm above the earthed plane, was raised gradually in 1 or 2 cm steps, viewing different positions along the axis of the gap. The photomultiplier outputs were displayed simultaneously with the HV square pulse on the screen of the oscilloscope.

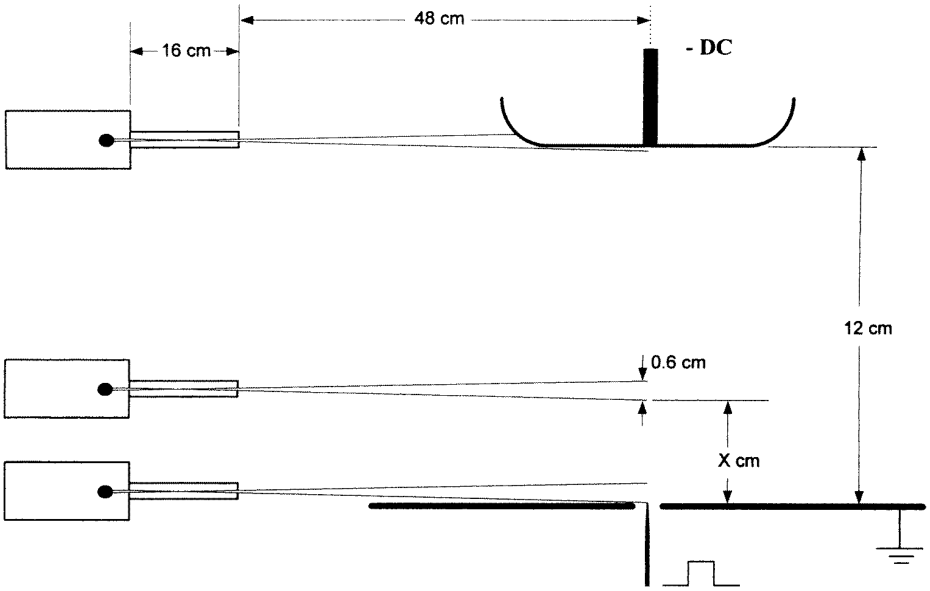


Figure 1. Schematic diagram of the electrode arrangement.

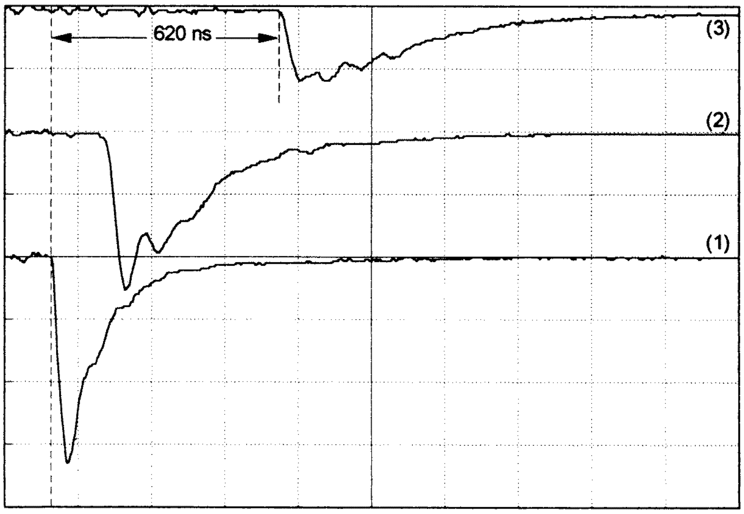


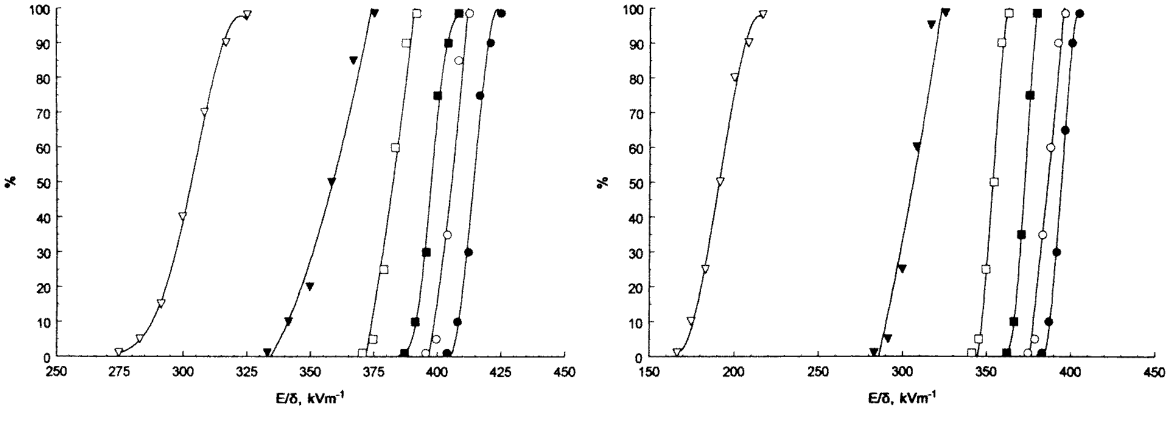
Figure 2. Typical photomultiplier outputs, 450 kV m^{-1}, 270 ns/4 kV pulse voltage, 5 V div^{-1}, 200 ns div^{-1}: trace 1, PM directed at the anode plane; trace 2, PM directed at 4 cm above the anode plane; trace 3, PM directed at the cathode plane.

2.2. Measurement procedures

The first step was to measure the electric fields required for streamer propagation, in the region of and just above the threshold. It was found that the probability of propagation increased with increasing electric field according to an approximately normal distribution. Thus, class 1 (multiple-level) tests analogous to those used for sparkover measurements [1] were performed for propagation to seven different streamer traverse distances, namely 2, 4, 6, 8, 10, 11 and 12 cm from the point. At each field level 20 voltage pulses were applied at the point, at time intervals of around 10 s; successive field levels differed by ~1% from the previous one.

The inception times of the streamers at the point were obtained from the time delay between the start of the pulse voltage waveforms and the first appearance of light detected at the point. Streamer transit times were measured using the start of the rise of each light signal (figure 2); thus the corresponding propagation velocities could be calculated. Transit times were also measured at electric field levels in the range of 450 to 800 kV m^{-1}, each level differing by 50 kV m^{-1} from each other, and for 11 different traverse distances along the axis (in steps of 1 cm). This yielded information about the streamer advancement over the whole path up to the cathode.

All the field measurements were adjusted to standard air density according to IEC correction procedures [1] and results are expressed as a function of the ratio of applied electric field E and relative air density δ. The absolute humidity h varied between 8 and 11 g m^{-3}.



(*a*) (*b*)

Figure 3. Propagation probability distributions, $u = 4$ kV, $h = 9.2$ g m^{-3}: (*a*) 135 ns pulse duration, (*b*) 270 ns pulse duration. Symbols show traverse distances from the point of origin: —▽—, 2 cm; —▼—, 4 cm; —□—, 6 cm; —■—, 8 cm; —○—, 10 cm; —●—, 12 cm.

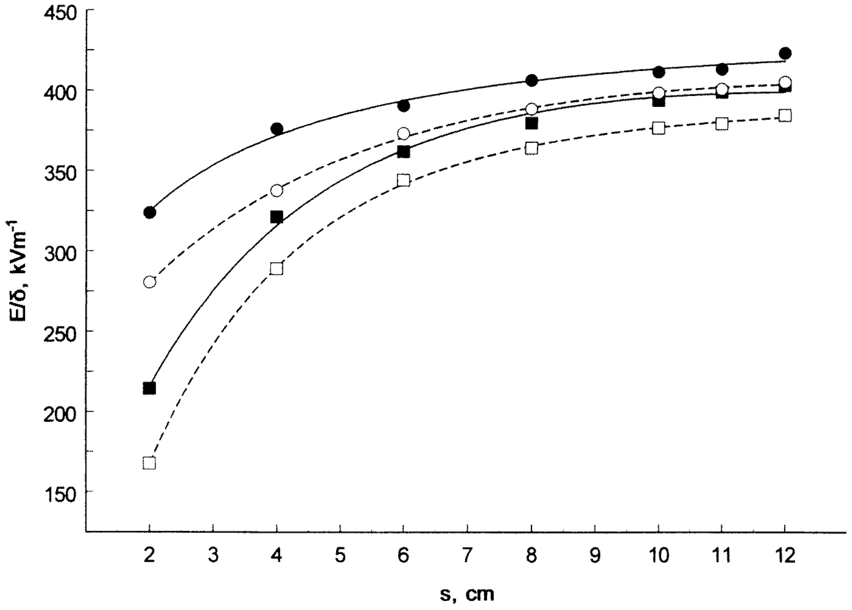


Figure 4. Threshold and stability fields as a function of the traverse distance with the pulse duration as parameter, $u = 4$ kV, $h = 9.2$ g m^{-3}: - - □ - -, 270 ns, E_{th}; —■—, 270 ns, E_{st}; - - ○ - -, 135 ns, E_{th}; —●—, 135 ns, E_{st}.

3. Experimental results

3.1. Streamer propagation fields

The propagation probability distributions, when plotted on normal probability paper, were found to follow a Gaussian distribution. From each distribution the mean propagation field and the corresponding standard deviation σ were computed. In a similar way to reference [6] the required electric fields for propagation, corresponding to 0.025 and 0.975 propagation probability were calculated, termed 'threshold' field E_{th} and the 'stability' field E_{st} respectively.

Figure 3 displays typical distributions of the probability of propagation to various distances from the point; these are on a linear scale. The field required for streamers to propagate to a given point increases as they advance within the gap, especially at the beginning of their travel; the effect is stronger for the longer pulse duration, but is less pronounced near the cathode. These results are more clearly demonstrated in figure 4 where the threshold and stability fields are plotted as a function of the distance of traverse. The propagation fields are smaller for longer pulse duration, especially for short travelling distances (figures 3 and 4), and, as figure 5 indicates, for higher pulse amplitude. For a given value of electric field the propagation probability increases with pulse duration and/or pulse amplitude and for shorter streamer traverse.

It is noteworthy that the slopes of the curves in figure 3 increase with the length of streamer traverse and with pulse duration.

3.2. Streamer propagation velocities

The time to distance curves and the corresponding streamer velocities at the stability fields, appropriate to the observation

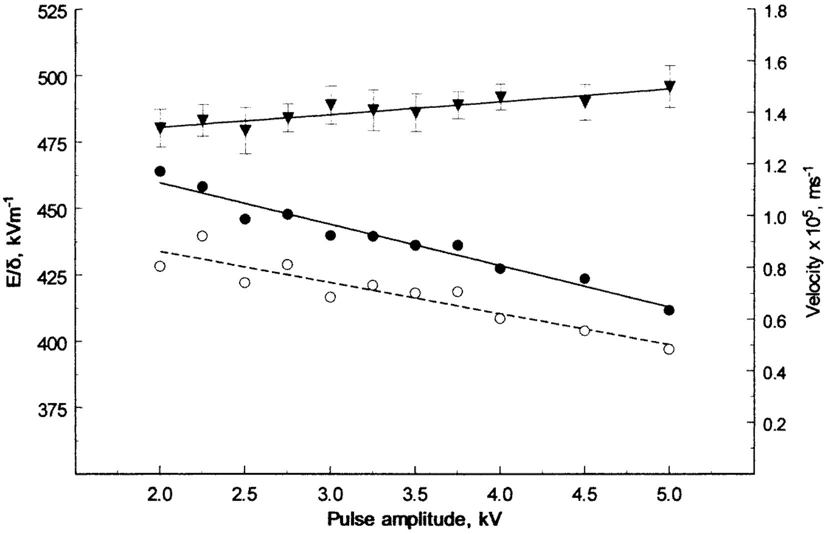


Figure 5. Threshold and stability fields and velocity as a function of the pulse amplitude, 135 ns pulse duration, average $h = 9.8$ g m^{-3}: - - -○- - -, E_{th}; —●—, E_{st}; —▼—, v_{st}.

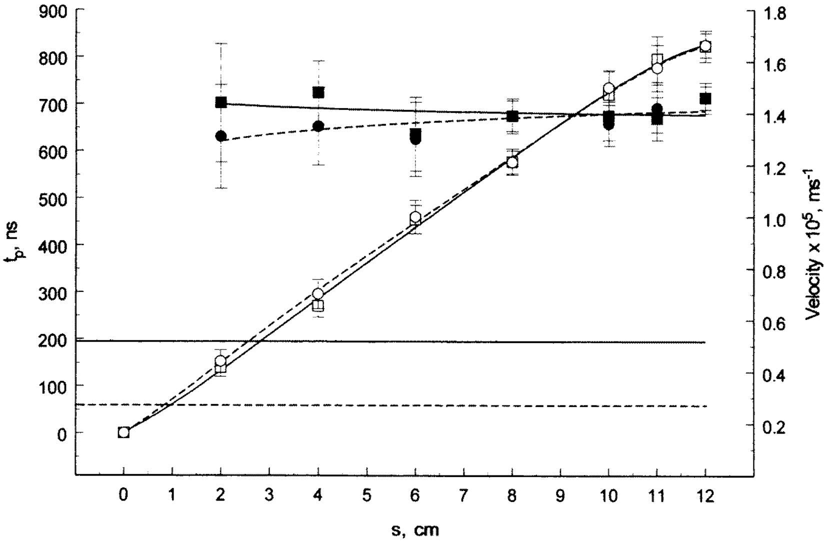


Figure 6. Time to distance curves and corresponding velocities as a function of the traverse distance, stability conditions as in figures 3 and 4, with the pulse duration as parameter; the vertical bars represent 2σ: —□—, 270 ns, t_p; —■—, 270 ns, v_{st}; - - -○- - -, 135 ns, t_p; - - -●- - -, 135 ns, v_{st}.

points derived from the experiments as summarized in figures 3 and 4, are displayed in figure 6. Each point is the average value of 20 measurements and the vertical bars represent 2σ. The straight line (parallel to the x-axis) depicts the time for which streamers are travelling whilst the pulse voltage is still applied at the point. This time is significantly larger for a pulse with 270 ns than 135 ns duration.

At the stability fields E_{st} the propagation velocity is almost constant, invariant with the distance of traverse and the pulse duration (figure 6) and varies only slowly with the pulse amplitude (figure 5) despite the fact that these parameters exert a strong influence on the electric field required for streamer propagation (figures 3, 4 and 5).

Time to distance curves under electric field values greater than the stability field, termed ‘overfield’ are shown in figure 7, with derived velocities, shown in figure 8. For relatively low ‘overfields’ the velocity decreases with increasing traverse distance, whereas for higher fields it remains approximately constant. This is shown also in figure 9(*a*), where the velocities of figure 8 are replotted as a function of electric field for various traverse distances. The horizontal line in figure 7 represents the time elapsed between the inception of the steamers and the end of the pulse. Hence, the distance traversed while the voltage still exists at the point can be derived for each applied electric field level; under high overfield, streamers may reach the cathode while the pulse voltage is still applied (figure 7, curve E).

The effect of the electric field and pulse amplitude on the propagation velocity is also demonstrated in figure 9(*b*). The velocity increases with both parameters and the rate of increase with electric field is faster for longer streamer traverse (figures 7 and 9(*a*)). In addition, a tendency for

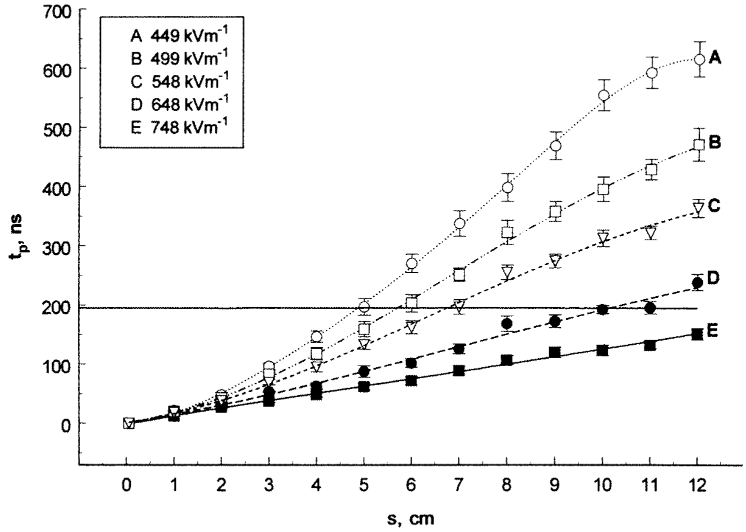


Figure 7. Time to distance curves with the electric field as parameter, 270 ns/4 kV pulse voltage, $h = 11.3$ g m^{-3}; the vertical bars represent 2σ.

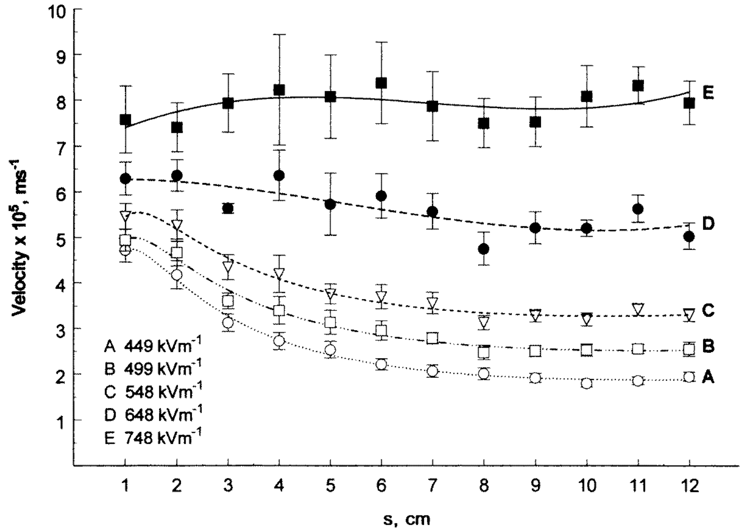


Figure 8. Propagation velocity as a function of the traverse distance with electric field as parameter, 270 ns/4 kV pulse voltage, $h = 11.3$ g m^{-3}; the vertical bars represent 2σ.

higher velocity with increasing pulse duration has been observed; this effect was stronger when streamers were traversing the first few centimetres of the gap.

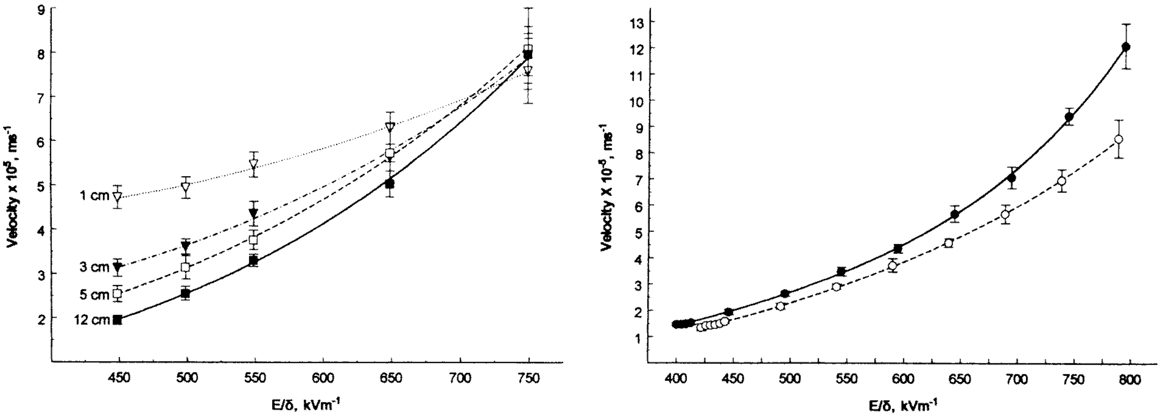
4. Discussion

Figures 3 and 4 show that for a particular pulse voltage of 4 kV, the field required for stable propagation increases with the streamer traverse distance, for both 135 ns and 270 ns voltage pulses at the point, but tending to asymptotes at a traverse of 12 cm. Figure 5, for the 135 ns voltage pulse, shows that the asymptotic fields decrease with increasing pulse voltage. The line drawn through the points of E_{st} of figure 5, has the equation

$$E_{st}(p, t) = (491 - 16u)\delta \text{ (kV m}^{-1}) \qquad (1)$$

where u is the voltage pulse amplitude in kV. The limit value of $E_{st} = 491$ kV m^{-1}, when notionally $u = 0$, is taken to represent a field which a streamer, originating with the minimum possible energy, requires in order to propagate stably, under standard pressure and temperature defined by IEC [6] and at the conditions of average humidity (9.8 g m^{-3}) at which the experiments were carried out.

If it is assumed that a given velocity is characteristic of a given resultant electric field in the streamer tip region, then propagation to the shorter distances requires smaller applied fields, since a significant field in that region is due to the voltage pulse. It is shown by the horizontal lines in figure 6 that the voltage pulse exists, during traverse, for periods covering the propagation times to short distances, especially for the longer pulse duration. The same effect is shown by the results of figure 3 which indicate that for a given applied electric field a streamer may ‘die’ after having crossed part of the gap, even up to 8–10 cm (figure 3(*b*)), denoting that while the aiding field due to the pulse has ceased, the remaining resultant electric field in the streamer tip is not sufficient to



(*a*) (*b*)

Figure 9. Propagation velocity as a function of the electric field with the traverse distance (*a*) (270 ns/4 kV pulse voltage) and the pulse amplitude (*b*) (135 ns pulse duration, 12 cm traverse distance: - - -○- - -, $u = 3$ kV; —●—, $u = 5$ kV) as parameter; the vertical bars represent 2σ.

sustain the propagation for the full traverse of the uniform field gap.

This point may be expressed in another way. The Gallimberti model [7] of streamer advance is based on the energy balance equation

$$W_l = W_g + \Delta W_{\mathrm{pot}} \qquad (2)$$

where W_l is the energy loss due to ionization in each formative avalanche, W_g is the energy gained from the electric field by the advance of the charge head and ΔW_{pot} is the change in potential energy resulting from the creation of each new streamer head. In the present case, a third term W_p on the right-hand side of equation (2) must be added where necessary to account for the added energy from the field due to the voltage pulse at the point

$$W_l = W_g + \Delta W_{\mathrm{pot}} + W_p. \qquad (3)$$

At stability fields E_{st} the influence of W_p decreases with decreasing pulse duration and amplitude and as the streamer progresses across the gap. Thus, a larger contribution to W_g from the applied field is required to balance equation (3). This argument implies that the difference between the energy used for ionization and the change in potential energy remains approximately constant at all times during transit, for the experimental conditions described. It is supported by the evidence of the approximately constant velocity, shown by experiment (figure 6), as a function of distance of traverse, in spite of the increase of the applied field required for stable propagation to increasing distances and with decreasing pulse duration.

It will be noted from figure 5 that streamer velocities, measured over 12 cm at the stability fields appropriate to increasing values of pulse amplitude, change only slowly with the latter, suggesting that the difference between W_l and ΔW_{pot} also changes slowly.

The above analysis suggests that the stable propagation of a streamer is characterized by a stability field called the 'intrinsic' propagation field E_{in} with which a characteristic velocity 'v_{in}' can be associated. The variation of the applied electric field required for this stable propagation results from the variation of the pulse voltage used at the point.

To determine these characteristic streamer properties, the data of figure 5 were used. Accordingly, the straight lines best fitting the experimental values, as displayed in figure 5, are given by equation (1) for E_{st} and by the following equation for v_{st}

$$v_{\mathrm{st}}(p, t, h) = \left(1.25 + \frac{5u}{100}\right) \times 10^5 \ (\mathrm{m\ s^{-1}}) \qquad (4)$$

where u is related to E_{st} through equation (1).

Equations (1) and (4) refer to standard pressure and temperature but for an average value of absolute humidity of 9.8 g $\mathrm{m^{-3}}$. Assuming a linear increase of the order of 1% per g $\mathrm{m^{-3}}$ of absolute humidity h for E_{st} [3], equation (1) becomes

$$E_{\mathrm{st}}(p, t, h) = (497 - 16u)K\delta \ (\mathrm{kV\ m^{-1}}) \qquad (5)$$

where $K = 1 + (h - 11)/100$ for the standard IEC [6] humidity value of 11 g $\mathrm{m^{-3}}$. In equation (4) no adjustment for humidity can be made since the effect of humidity on the streamer velocity under applied fields for stable propagation is unknown.

The limit value of $E_{\mathrm{in}} = 497$ kV $\mathrm{m^{-1}}$ (equation (5)) is taken to represent the upper limit of possible stability fields under standard atmospheric conditions. This value may be compared with the figure of 500 kV $\mathrm{m^{-1}}$, used as a working value for atmospheric corrections by the IEC [6]. Similarly, for the same stability field, the value of $v_{\mathrm{in}} = 1.25 \times 10^5$ m $\mathrm{s^{-1}}$ (equation (4)) is taken to represent a notional maximum propagation velocity.

The study of streamer velocity in fields above the stability field gives further insight into the propagation process. The experimental points of velocity against electric field, shown in figure 10, fit readily with the general empirical relation

$$v_{\mathrm{str}} = v_{\mathrm{st}} \left(\frac{E}{E_{\mathrm{st}}}\right)^3 \ (\mathrm{m\ s^{-1}}) \qquad (6)$$

where v_{str} is the streamer velocity at any reduced field E/δ.

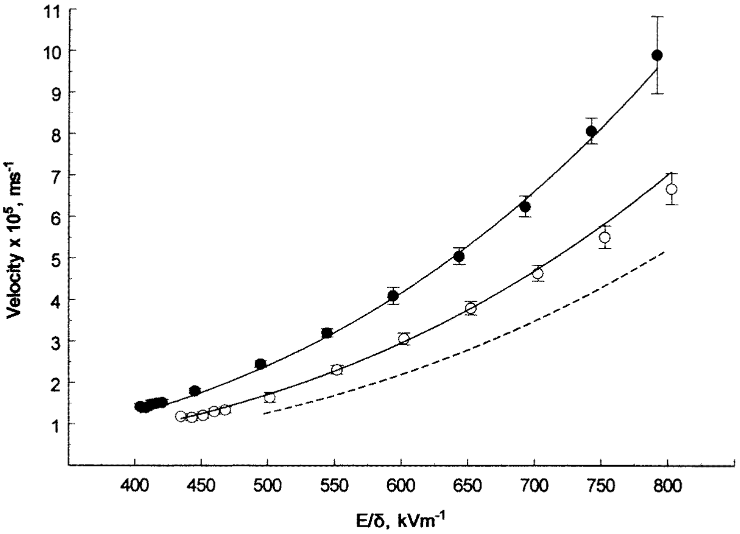


Figure 10. Computed curves compared with experimental values of propagation velocity measured over 12 cm traverse as a function of the electric field, 135 ns pulse duration; the vertical bars represent 2σ: ○, $u = 2$ kV, $h = 10.4$ g m^{-3}; ●, $u = 4$ kV, $h = 8.4$ gm^{-3}; ——, fit with equation (7); – – –, v_{str}, equation (7) for $u = 0$, $\delta = 1$ and $h = 11$ g m^{-3}.

Combining equations (4), (5) and (6), the velocity of streamers under any atmospheric condition and for any applied electric field and pulse amplitude is described by the following equation

$$v_{str}(p,t,h) = \left(1.25 + \frac{5u}{100}\right)\left(\frac{E(p,t)}{(497 - 16u)K\delta}\right) \times 10^5 \text{ (m s}^{-1}\text{)}. \qquad (7)$$

Computed curves, according to equation (7), have been drawn alongside experimental points in figure 10 (full curves). The agreement is very close; equation (7) correctly predicts the dependence of the streamer velocity on the voltage pulse amplitude, electric field in the range from 400 up to 800 kV m^{-1} and atmospheric conditions.

The result of equation (7) for $u = 0$, $\delta = 1$ and $h = 11$ g m^{-3} is also shown in figure 10 (broken curve). This curve represents the upper limit of the streamer propagation velocity, at minimum energy at the origin, for any value of the applied electric field under standard atmospheric conditions.

Finally, we consider the possible effects of streamer branching upon these experimental results. Figure 6 shows that at the stability field, that is in the lowest range studied here, streamer velocity is invariant with traverse distance. Figure 8 shows that at the highest overfields studied, the same is true. Since branching increases with distance, it would be expected that any resulting space charge effects, over any part of the range, would affect, for example, velocities or the asymptotes of figure 4. This is not so and it is concluded that branching has negligible effect and that the properties observed are characteristic of the ‘single streamer’.

5. Conclusions

To sustain the stable advancement of a single streamer in air, an electric field must be applied which depends on the energy supplied for initiation of the streamer. This stable propagation is characterized by an ‘intrinsic’ propagation field and a constant associated velocity, which are related to a constant difference between the energy required for ionization and the change in potential energy at all times during transit.

For applied fields greater than the minimum required for a stable propagation, streamer velocity is a power function of the electric field. An empirical equation accurately predicts that the velocity at any applied field is related to the ‘intrinsic’ propagation field and its associated characteristic velocity. Over the range of fields explored in the present experiments, the properties observed can be taken to be characteristic of single streamers, since branching has a negligible effect.

Acknowledgment

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