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# Temperature and density effects on the properties of a long positive streamer in air

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**Abstract.** The 1.5D simulation is used to study the positive-streamer properties in air in a 20 cm sphere–plane gap versus gas temperature and density. It is shown that an increase in temperature up to 900 K at atmospheric pressure and a decrease in density by a factor of three at room temperature strongly affect the average electric field required for bridging the gap and the charge transferred through the streamer to the cathode; the temperature effect is much more pronounced than is the density effect. The calculated results qualitatively conform to available experimental data. The density effect is associated with a decrease in the rates of three-body processes such as three-body electron attachment to $O_2$ or conversion of $O_2^+$ ions into $O_4^+$ ions. The temperature effect is due to the decomposition of positive cluster ions which decreases the rate of dissociative electron–ion recombination. Electron attachment and detachment processes become important only when the electron density greatly decreases (by a factor of ten and more).

## 1. Introduction

A study of the effects of temperature and density on the properties of a long streamer in air, apart from its practical significance, provides insight into the mechanism of the streamer-to-leader transition. In a non-uniform field the leader stage of a discharge is important for the breakdown of the long air gaps including the thundercloud–ground gaps 10 km in length bridged by lightning. The mechanism of the transition from a cold weakly conductive streamer to the hot highly conductive leader is still under discussion. It is clear that the plasma channel is finally heated to temperatures high enough for thermo-ionization. A basic problem is to understand why the streamer plasma does not disappear for a period of time which is much greater than the typical period of electron attachment and recombination in the ambient air.

Today it is generally accepted that the main mechanism responsible for increasing the conductivity of streamers and starting the formation of a leader in air consists of thermal electron detachment from negative ions (Gallimberti 1979, Raizer 1991, Bondiou and Gallimberti 1994). According to this hypothesis the electron detachment compensates for the losses of electron attachment and the streamer channel is conductive for a period of 1–10 $\mu$s, provided that the gas temperature within the channel is raised above a critical value of 1000–2000 K. Then, owing to the current flow, the temperature increases further and becomes enough for vibration–translation energy exchange (V–T) processes of generation of bulk energy, which is stored in vibrational levels of molecules. Gas heating is also accelerated owing to the increase in reduced electric field $E/N$ caused by the decrease in neutral molecule density $N$ (see, for example, Marode *et al* (1979)). These processes finally lead to thermo-ionization.

There has been no direct experimental or theoretical verification of the hypothesis proposed by Gallimberti. It is important to identify the density effect and the specific temperature effect, both of which contribute to the total temperature effect on the streamer properties at constant gas pressure. The specific temperature effect can be due to the temperature-dependence of the rates of collisional processes, such as electron detachment; the density effect can result from a difference in the density-dependences of the rates for two-body and three-body processes.

Allen and Ghaffar (1995) measured the variation of the electric field required for propagation of positive streamers in air and propagation velocities as functions of ambient temperature in the range 294 K $< T <$ 421 K. For the uniform-field 18 cm gap, they observed a pronounced temperature effect at constant pressure: the propagation field decreased by a factor of 1.6. The results obtained were compared with other measurements (Phelps and Griffiths 1976) of the propagation field in which the density has been changed by variation of pressure at constant temperature. However, it was difficult to identify the direct temperature effect because of the discrepancy (of up to 20%) between the available data obtained under standard conditions.

Aleksandrov *et al* (1984) studied the temperature effect on the properties of positive streamers propagating through a 46.5 cm air gap in a non-uniform electric field. In the range 290 K $< T <$ 900 K they measured the averaged field required for bridging the discharge gap and recorded oscillographically the charge transferred through the channel to the cathode. The data obtained testified that the streamer plasma conductivity increases with temperature by about a factor of 100. These observations were interpreted in terms of fast thermal electron detachment according to the hypothesis proposed by Gallimberti. Aleksandrov *et al* also performed a similar investigation in which the density was changed by variation of pressure at room temperature and obtained that the effect of density on the average field is less pronounced than is the total temperature effect (Bazelyan and Razhanskii 1988). Unfortunately, the measured oscillograms of the charge transferred under room temperature conditions have not yet been published.

In the present paper, we simulate the positive-streamer properties as a function of density and temperature under the conditions of the experiment by Aleksandrov *et al* (1984). Since the main purpose of this work is to reveal the general discharge mechanism rather than to obtain exact values, a 1.5D model with a fixed channel radius is used. Section 2 presents a brief description of the experimental technique and the main results by Aleksandrov *et al* (1984) including the unpublished data on the density effect on the streamer properties. In section 3 the model used is considered; the results of our calculation and their comparison with the experimental data are given in section 4. The mechanisms of the density and temperature effects on long-streamer properties are also discussed in this section.

## 2. The apparatus and experimental results

The apparatus used to study the streamer properties has been reported previously (Aleksandrov *et al* 1984); therefore, only a brief description follows. The measurements were performed in a 46.5 cm rod–plane air gap. A positive voltage up to 250 kV with a 0.5/400 $\mu$s impulse shape was applied to the rod electrode with a hemispherical tip of radius 0.5 cm. The electrode system was contained in a transparent quartz cylindrical chamber of radius 10 cm in which air was heated up to 900 K at constant pressure. It was also possible to study the room-temperature discharge characteristics versus gas density by accommodating a similar electrode system within a hermetically sealed chamber and varying the gas pressure at constant temperature in it.

The distinguishing feature of the apparatus used in the present experiment was a cathode containing a few small-sized measuring sections. Owing to the small area of a section, the current detector connected to it responded only to a streamer reaching the section and was insensitive to the displacement current induced by nearby streamers and the streamers propagating over the quartz surface of the chamber. This provided a way of measuring the voltage required for bridging the gap by a single streamer propagating in air and the conduction current flowing through it after bridging. The section sizes were adopted in order to minimize the probability of simultaneous contact of a few streamers with a section. When the section diameter was in the range 0.1–1 cm, it was more common to observe the opposite case: bridging of the discharge gap was not accompanied by the arrival of a streamer at the section. To cover a wide range of currents (up to three orders of magnitude) the electric charge transferred through the streamer branch to the cathode section was measured. The sensitivity threshold for the integration circuit did not exceed $10^{-11}$ C with the time constant for the circuits of stray leakage which exceeded 500 $\mu$s at maximum temperature.

A wide statistical dispersion in the measured values of transferred charge $Q$ was observed (under standard conditions, from $2\times10^{-11}$ to $1.3\times10^{-9}$ C with $5\times10^{-10}$ C average). This can be attributed to a dispersion in the streamer length; there were streamers starting from the anode and those starting from the tip of the leader during its propagation to the cathode. It is clear that the latter streamers could be a few times shorter than the former. In addition, the branching affected the streamer diameter and path length.

However, the effects of density and temperature on the oscillograms of the transferred charge were clearly recognized due to the increase in charge by a factor of 100. Figure 1 shows the typical oscillograms of charge $Q(t)$: ($a$) measured under standard conditions and at gas density reduced three times ($b$) with a decrease in gas pressure at gas temperature $T = 290$ K and ($c$) with gas heating up to 900 K at atmospheric pressure. Curves correspond to similar values of $E/N$. As could be expected, the gas heating increases drastically the amplitude and the rise time of the current flowing through the streamer channel. Although less pronounced, similar behaviour is observed when the gas density decreases at constant temperature. These observations can be understood as a deceleration of the streamer plasma decay with decreasing density and increasing temperature.

Figure 2 shows the average electric field required for bridging the gap by an initial streamer flash which was measured at constant temperature or pressure as a function of the relative air density

$$\delta = \frac{p}{1012}\,\frac{290}{T}$$

where $p$ is the pressure in millibars and $T$ is the temperature in kelvins (Aleksandrov *et al* 1984, Bazelyan and Razhanskii 1988). The data of Phelps and Griffiths (1976) obtained at constant temperature are also shown in figure 1. The measured field decreases with the decrease in $\delta$; this field falls more if the density is changed by variation of temperature at constant pressure. Like the oscillograms of the transferred charge, the effects of density and temperature on the average threshold field can be explained in terms of an increase in the conductivity of

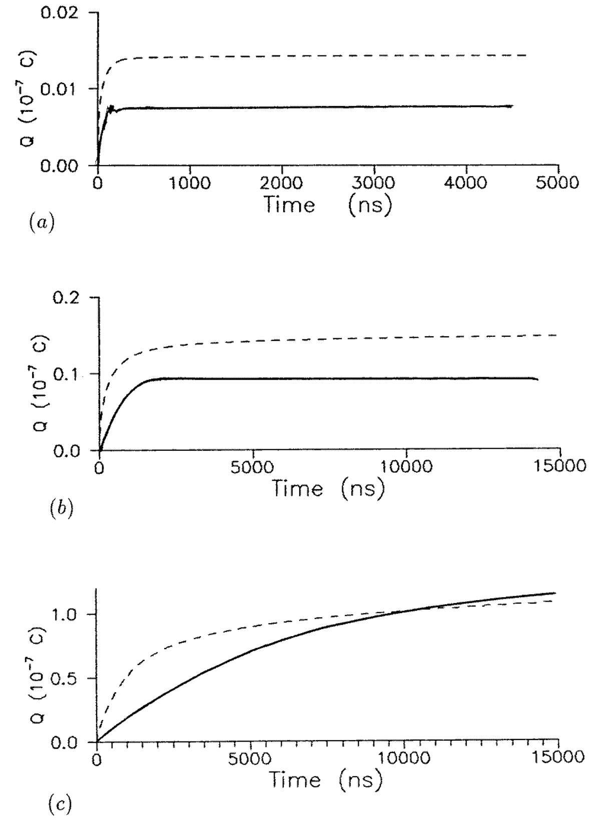


**Figure 1.** Oscillograms of transferred charge: (*a*) under standard conditions and at a gas density reduced by about a factor of three; (*b*) with a decrease in gas pressure at room temperature; and (*c*) with an increase in gas temperature under atmospheric pressure. Full curves are the measurements and broken curves are the theoretical calculations.

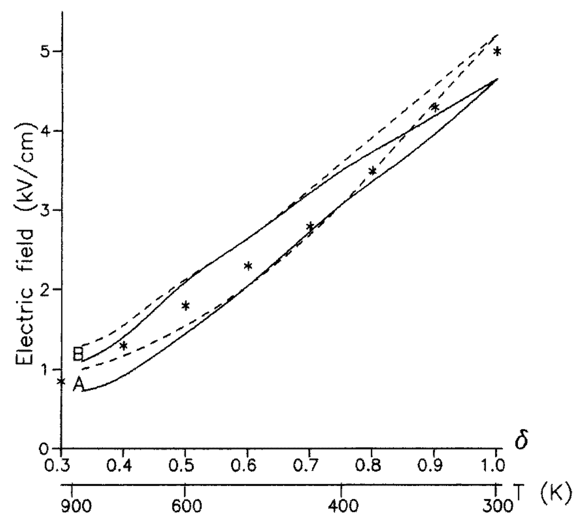


**Figure 2.** The averaged electric field required for bridging the gap as a function of the relative air density: curve A, at constant pressure; and curve B, at constant temperature. Full curves are the measurements of Aleksandrov *et al* (1984) of the 50% bridging field and broken curves are the theoretical calculations. Points are the measurements of Phelps and Griffiths (1976).

the streamer channel because this implies an increase in the field and the ionization rate in the streamer tip and therefore favours bridging the gap.

## 3. The simulation model

The 1.5D (axisymmetrical) simulation model and numerical method used in the present calculation are essentially the same as those used by the authors (Bazelyan and Bazelyan 1993, 1994, Aleksandrov *et al* 1995, Aleksandrov and Bazelyan 1996). Therefore, only a brief description follows. A cathode-directed streamer was considered in the 1.5D model; that is, the radius of the streamer channel was assumed to be fixed. The basic dynamical equations for the streamer propagation are the continuity equations for electrons, ions and active particles; Poisson's equation for the electric field; and the balance equations for the vibrational energy of $N_2$ molecules and for the translational energy of neutral species. These equations were solved numerically. The finite-difference method with the adapted mesh was used; the mesh was stretched in the axial coordinate near the anode and in the streamer head, and was uniform in other regions. The electric field was determined from the condition that the streamer space charge is distributed over the cylindrical channel surface. To determine the change in charge for each mesh, the current through the mesh boundaries was calculated.

The charge–particle kinetic model for high-temperature air had been developed before to study a variety of problems including microwave breakdown (Dyatko *et al* 1987), the glow phase of a spark gap (Rodriguez *et al* 1991), corona discharge (Mnatsakanyan *et al* 1986), shock-tube plasmas (Park 1989), ionized supersonic flows in a transversal magnetic field (Aleksandrov *et al* 1991) and spectral line intensities for plasma diagnostics (Taylor and Ali 1988). However, the streamer plasma differs in many respects from the media of the above-mentioned examples. Therefore our kinetic model is based on the assumptions used before for the simulation of long-streamer propagation in air at room temperature (Bazelyan and Bazelyan 1993, 1994, Aleksandrov *et al* 1995, Aleksandrov and Bazelyan 1996). The model includes 20 components and 120 collisional processes which are important in the $N_2$–$O_2$ mixture in short time intervals ($10^{-6}$ s) with temperature-dependent rate coefficients found experimentally or calculated from the Boltzmann equation for electrons. To simulate streamer propagation through the high-temperature air we considered the effect of a high temperature on the electron energy distribution, on the rates of electron attachment/detachment processes; and on the rates of electron–ion and ion–ion recombination.

The direct effect of high temperatures on the electron energy distribution is negligible at moderate electric fields ($E/N > 10^{-17}$ V cm$^2$) when the mean electron energy is much greater than the gas temperature. Gas heating is also accompanied by an increase in density of the vibrationally excited $N_2$ molecules which heat up electrons and disturb the electron energy distribution through superelastic vibrational collisions. To account for this effect we solved the equation for the vibrational temperature $T_v$ and used the rates of the electron-impact reactions obtained from the Boltzmann equation as a function of $E/N$ and $T_v$ (Aleksandrov and Bazelyan 1996).

Negative ions are formed in ambient air through several electron attachment reactions, the most important ones being the dissociative attachment to $O_2$

$$e + O_2 \rightarrow O^- + O \tag{1}$$

and the three-body attachment

$$e + 2O_2 \rightarrow O_2^- + O_2. \tag{2}$$

The cross section of process (1) is temperature-dependent because of vibrational excitation of the $O_2$ molecule (Massey 1976, Smirnov 1982). Taking the cross sections from experiment and calculating the electron energy distribution from the Boltzmann equation, we obtained the rates for process (1) as a function of the gas temperature which was assumed to be equal to the vibrational temperature of the $O_2$ molecules (Aleksandrov *et al* 1991). The same approach was used to calculate the rate of dissociative electron attachment to the $O_2(a\ ^1\Delta_g)$ molecule using cross section found experimentally (Massey 1976). The temperature-dependence of the rate of process (2) is more complicated. In the calculation of this quantity we took into account the processes of electron attachment to the vibrationally excited $O_2$ molecules (Aleksandrov and Konchakov 1984, Aleksandrov 1993) and to the $O_2(a\ ^1\Delta_g)$ molecules (Aleksandrov 1993). We also considered the temperature-dependence of the quenching rate for the unstable $O_2^-$ ion (Aleksandrov 1986) which is an intermediate product in process (2).

Collisional electron detachment also proceeds via several mechanisms. Detachment of the outermost electron from a negative ion can be enabled by the chemical energy (for example, an associative detachment, the inverse of process (1)), or by the transfer of internal or translational energy of the colliding particles. Little is known about the rates of these processes in high-temperature air (Massey 1976, Smirnov 1982, Christophorou 1987). The rates of reactions without energy thresholds are usually only slightly dependent on $T$, whereas reactions with too high an energy threshold can be neglected. We assumed that the rate is temperature-dependent only in the process

$$O_2^- + O_2 \rightarrow e + 2O_2 \tag{3}$$

with the 0.44 eV threshold. This rate was calculated as a function of $E/N$ and $T$ using a semi-empirical approach (Aleksandrov 1986).

Simulations of the long-streamer propagation at $T = 300$ K (Aleksandrov *et al* 1995, Aleksandrov and Bazelyan 1996) indicated a predominance of positive cluster ions ($O_4^+$ and $N_4^+$) in a streamer-channel plasma. At high temperatures these ions can be decomposed through the reactions

$$O_4^+ + M \rightarrow O_2^+ + O_2 + M \tag{4}$$

$$N_4^+ + M \rightarrow N_2^+ + N_2 + M \tag{5}$$

resulting in a deceleration in the plasma decay because the rate of electron–ion recombination for cluster ions is many times higher than is that for simple ions (Eletskii and Smirnov 1982, Mitchell 1990). To take into account this effect we used the temperature-dependent rates for processes (4) and (5) (Kossyi *et al* 1992) and for the reverse processes (Bohringer *et al* 1983, Guthrie *et al* 1991). In addition, the rate of dissociative electron–ion recombination can depend on the temperature because of the vibrational excitation of the molecular ions. However, an estimation based on the available experimental data for the recombination rates (Mitchell 1990) shows that this effect can be neglected at $T < 1000$ K. Three-body ion–ion recombination

$$A^+ + B^- + M \rightarrow \text{products}$$

was also assumed to be temperature-dependent with the rate proportional to $T^{-3/2}$ (Smirnov 1982).

## 4. Simulation results

### 4.1. The average field and oscillogram of the transferred charge

We simulated the propagation of a positive streamer in the 20 cm sphere–plane gap from a spherical anode of 1 cm radius. Here the streamer bridging the gap is intermediate in length between those observed in the experiment by Aleksandrov *et al* (1984). In most cases the radius of the streamer channel was assumed to be 0.03 cm. Under standard conditions this model yields a value of the average field corresponding to bridging of the gap which differs from the value measured by Aleksandrov *et al* by no more than 10% (5.2 instead of 4.65 kV cm$^{-1}$ in the experiment). The simulation was performed for a rectangular voltage impulse of amplitude 104 kV under standard conditions; at reduced gas density the voltage was changed to retain constant the ratio $E/N$.

Figure 2 shows the calculated average field in the bridging gap as a function of relative air density $\delta$; the temperature or the pressure are fixed. Figure 1 presents the simulated oscillogram of the transferred charge under the conditions of the measurement by Aleksandrov *et al* (1984). Evidently, the calculation qualitatively conforms to the observations by Aleksandrov *et al* (1984) and by Phelps and Griffiths (1976). This shows the potential of the method used. The main discrepancy between the calculated and measured values can be ascribed to a roughness of the 1.5D model and to complexity of the considered phenomenon.

### 4.2. The properties of a streamer plasma

It is of interest to consider the mechanisms of electron loss and generation in the streamer channel at different densities and temperatures. Figure 3 shows the temporal evolution of the frequency $\nu$ for each specific process in the streamer plasma at a distance of 5.1 cm from the anode; the frequency is normalized with respect to the total frequency $\nu_\Sigma$ of electron loss/generation processes. The rate of dissociative electron–ion recombination strongly depends on the positive ion composition, which changes during the streamer evolution. In air under standard conditions, the species of positive ions dominating in the streamer channel change with time in the following way (Aleksandrov *et al* 1995, Aleksandrov and Bazelyan 1996):

$$N_2^+ \rightarrow N_4^+ \rightarrow O_2^+ \rightarrow O_4^+.$$

The $O_4^+$ ion dominates at time $t > 10$ ns when electron–ion recombination becomes important. In the following discussion it will be shown that it is important to identify contributions from cluster and simple ions to the total recombination; therefore, figure 3 shows these processes separately. For convenience, the electron density $n_e$ is also presented in figure 3. Figures 4 and 5 show the temporal density evolution of the dominant charge particles at the same cross section of the channel; the arrow marks the instant at which the streamer bridges the gap. The axial profile of $n_e$ at that instant is shown in figure 6.

It is generally believed that the loss of electrons in the streamer channel in air under standard conditions is dominated by three-body electron attachment to $O_2$ molecules (process (2)) (see, for instance, Gallimberti (1979)). Figures 3 and 4 show that, under these conditions, the electron density initially decreases by a factor of ten through the dissociative recombination with $O_4^+$ ions

$$e + O_4^+ \rightarrow 2O_2. \tag{6}$$

Process (2) becomes important only about 100 ns later when the density of positive ions falls by a factor of ten, as shown in figure 5. Electron detachment from negative ions can be neglected because of its low rate at room temperature and because of the low density of negative ions, as shown in figure 4. When the streamer head approaches the cathode (250 ns after inception) the electron density in the 'old' domains of the streamer decreases by a factor of 100. Figure 6 shows that the axial profile of $n_e$ becomes nearly uniform after the gap has been bridged. We have $n_e \simeq 2 \times 10^{12}$ cm$^{-3}$ everywhere but near the electrodes; that is, in air under standard conditions the streamer becomes weakly conductive before bridging the gap. Thus, our calculation shows that process (6) rather than (2) dominates during the first and more important phase of the plasma decay when the discharge energy supply changes drastically.

A decrease in the gas density at constant temperature decelerates three-body reactions. This slows down the plasma decay through electron attachment (process (2)) and, which is more important, changes the positive-ion composition in the channel plasma, as shown in figure 5; the cluster ion ($O_4^+$) density decreases and the simple ion ($O_2^+$) one increases because of the deceleration of the three-body conversion processes such as

$$O_2^+ + O_2 + M \rightarrow O_4^+ + M. \tag{7}$$

The rate of dissociative electron–ion recombination for cluster ions is ten times that for simple ions (Eletskii and Smirnov 1982, Mitchell 1990). Therefore, the apparent rate of electron–ion recombination also decreases with decreasing gas density.

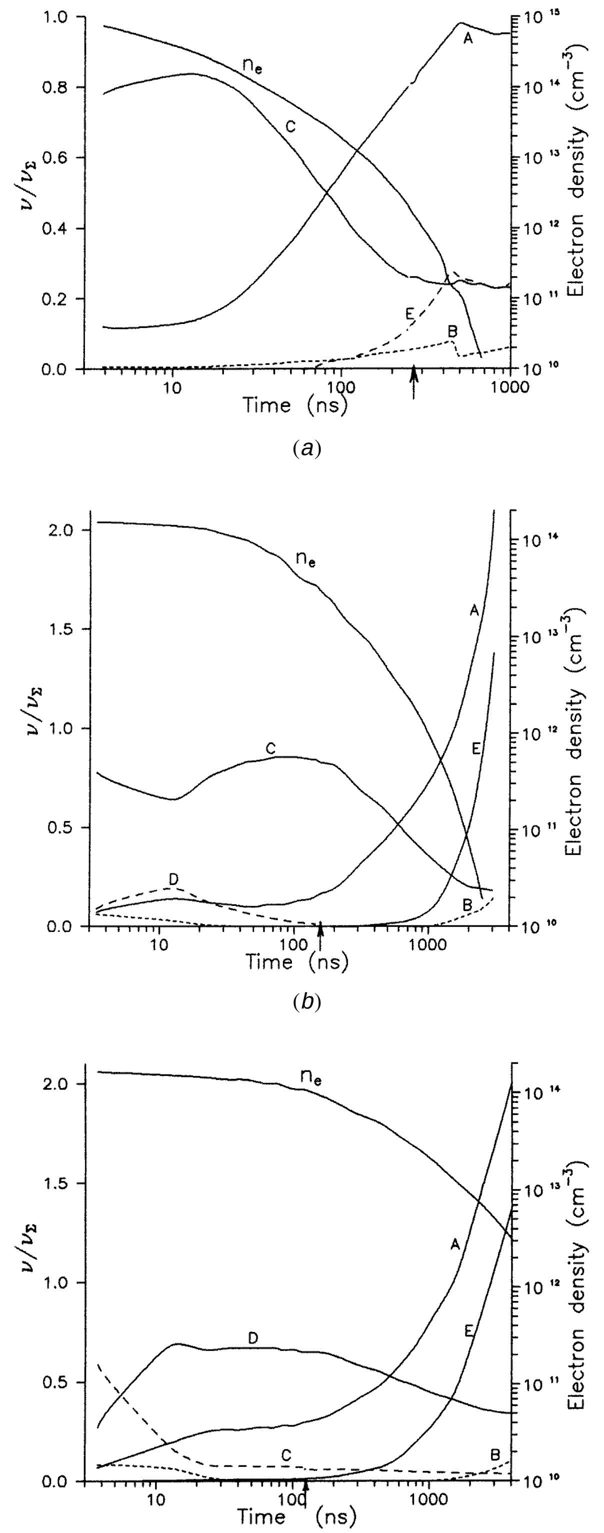


**Figure 3.** The temporal evolution of $n_e$ and of the frequency of each electron loss/generation process normalized with respect to the total electron loss/generation frequency in the streamer channel:(*a*), (*b*) and (*c*) correspond to the same initial conditions as those in figure 1. The processes are: curve A, three-body attachment to $O_2$; curve B, dissociative attachment to $O_2$; curve C, recombination with cluster ions; curve D, recombination with simple ions; and curve E, electron detachment from $O_2^-$.

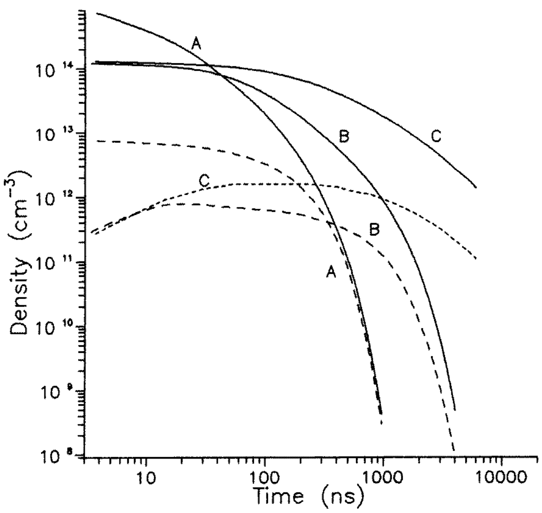


**Figure 4.** The temporal evolution of electron density (full curves) and the density of $O_2^-$ ions (broken curves) in the streamer channel: curves A, under standard conditions and at gas density reduced by about a factor of three; curves B, with a decrease in gas pressure at room temperature; and curves C, with an increase in gas temperature at atmospheric pressure.

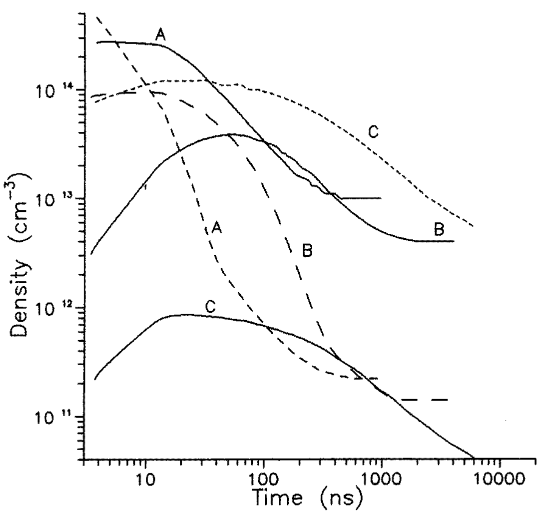


**Figure 5.** The temporal evolution of the density of $O_4^+$ (full curves) and $O_2^+$ (broken curves). the curves correspond to the same conditions as in figure 4.

The deceleration of the plasma decay in the low-density air increases the conductivity of the streamer channel and as a consequence the electric field in the streamer head. Then, the streamer accelerates and approaches the cathode in a time which is less than that under standard conditions by a factor of 1.5. As a result, the streamer conductivity decreases only by a factor of three during its propagation. Figure 6 shows that, after bridging, the axial profile of $n_e$ becomes nearly uniform with the average value of $2 \times 10^{13}$ cm$^{-3}$ which is greater than that under standard conditions by a factor of ten. Electron attachment becomes important only for a time $t > 500$ ns when the electron

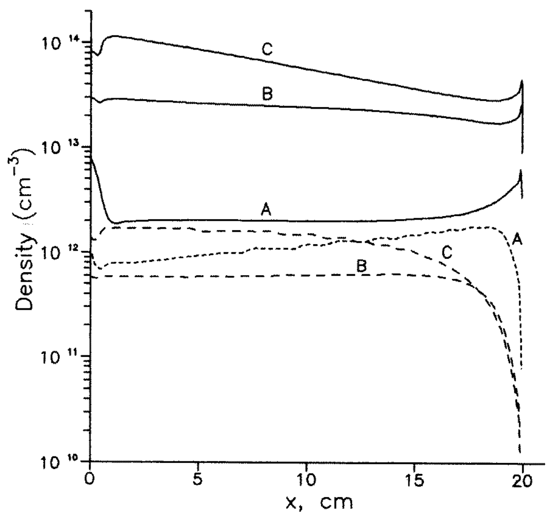


**Figure 6.** Axial profiles of electron density (full curves) and the density of $O_2^-$ (broken curves) at the instant at which the streamer bridges the gap. The curves correspond to the same conditions as in figure 4.

density falls by a factor of 100, as shown in figure 3. Electron detachment from negative ions becomes essential later ($t > 1$ $\mu$s) when the streamer conductivity is too low to be important.

Gas heating up to 900 K results in the total decomposition of cluster ions (see figure 5) through processes like (4) and (5) because of the low dissociation energy of these ions (0.5 eV for $O_4^+$). Therefore, in high-temperature air at atmospheric pressure both electron–ion recombination and three-body electron attachment to molecules slow down; the first process decelerates owing to the change in the positive-ion composition and the second one because of a decrease in the gas density. As a result, the streamer approaching the cathode remains highly conductive. At that instant ($t \sim 130$ ns) we have $n_e \simeq 10^{14}$ cm$^{-3}$, as shown in figure 6. Figure 3 shows that electron attachment becomes important for $t > 0.5$ $\mu$s only. Although the rate of electron detachment increases drastically with increasing $T$, this process becomes essential only for $t > 1$ $\mu$s when a sufficiently high number of negative ions is generated. However, the following evolution of the streamer plasma is less important because of the low conductivity of the channel.

### 4.3. Discussion

It is of interest to study how the results of numerical simulation depend on the *a priori* given radius of the streamer channel. Our calculation for a streamer radius increased by a factor of three (0.1 cm) shows that the dominant electron loss/generation processes in the channel remain intact.

As is evident from the foregoing, the effect of temperature on the properties of the streamer plasma mainly results from slowing down electron–ion recombination induced by decomposition of positive cluster ions. In fact, the rate of electron detachment strongly increases

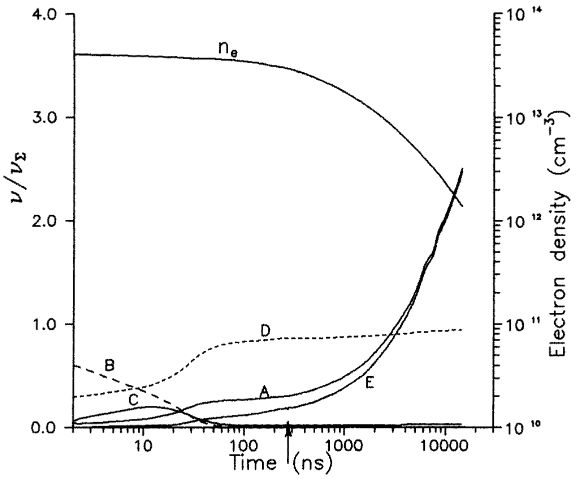


**Figure 7.** The temporal evolution of $n_e$ and the normalized frequency of each electron loss/generation process in the streamer channel at $T$ = 1500 K under atmospheric pressure. The notation is the same as in figure 3.

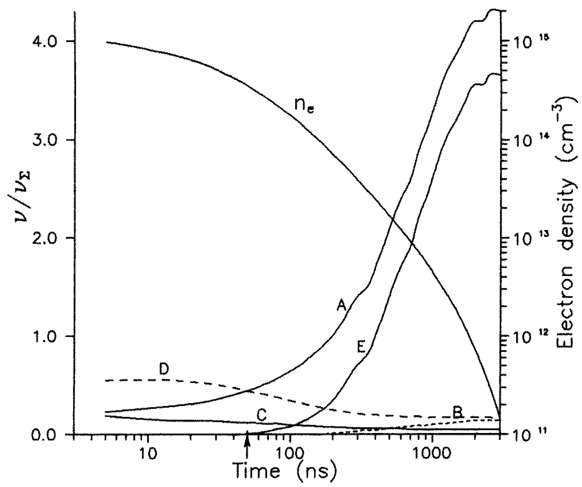


**Figure 8.** The temporal evolution of $n_e$ and the normalized frequency of each electron loss/generation process in the streamer channel at $T$ = 900 K with the gas density corresponding to standard conditions. The notation is the same as in figure 3.

with $T$. However, this process is important only if a sufficient density of negative ions is formed. In addition, the maximum effect of electron detachment should only compensate for electron loss through attachment. In high-temperature air at atmospheric pressure the slow generation of negative ions $O_2^-$ causes electron detachment to become important only later in the discharge, as shown in figures 4 and 6. To clarify directly the part played by electron detachment in high-temperature air we performed a simulation of the streamer properties for $T = 900$ K in which this process was not taken into account. Our calculation shows that neglect of electron detachment affects only the asymptotical value of $Q$ by halving it. However, the main manifestations of the temperature effect on the streamer properties, such as the strong increase in the plasma conductivity and deceleration of the plasma decay, remain as before.

It is apparent that electron detachment becomes more important for high $T$. Figure 7 shows the results of our simulation at $T = 1500$ K and atmospheric pressure. In this case electron detachment almost compensates for electron loss through electron attachment at $t > 1$ $\mu$s; thereafter, $n_e$ decreases with time only through recombination, falling by a factor of ten for a time of 10 $\mu$s. As before, deceleration of the plasma decay in the streamer channel is mainly attributed to decomposition of positive cluster ions.

The considered effects are important for the mechanism of the streamer-to-leader transition which can occur under a variety of conditions. The realization of this transition at constant pressure is more typical for the leader development from the corona stem. Here the leader can appear after a relatively long pause (about 10 $\mu$s) during which the pressure has had a chance to become uniform after gas heating (Gallimberti 1979). On the other hand, it is possible that the constant density condition is more typical for the streamer-to-leader transition when the streamers start from the leader tip. Figure 8 shows the results of our simulation at $T = 900$ K and with a gas density corresponding to standard conditions. In this case the effect of electron attachment/detachment processes on the electron loss in the streamer channel is much more pronounced. It should be noted that this is observed only in the wake of decomposition of positive cluster ions; otherwise electron–ion recombination dominates the loss of electrons.

In our simulation the dominant negative ion in the streamer channel was $O_2^-$. The negative-ion composition in ambient air strongly depends on humidity and minor impurities. However, the energy for electron detachment from $O_2^-$ (0.44 eV) is less than that for detachment from other negative ions of atmospheric interest (Gallimberti 1979, Massey 1976, Smirnov 1982). Therefore, one can expect that the effect of electron detachment on the streamer properties in ambient air is less than that in the $N_2$–$O_2$ mixture. In addition, ions of the $H_3O^+(H_2O)_n$ and $O_2^+(H_2O)_m$ types become important in humid air. As in the case of $O_4^+$, at high temperatures the water cluster ions are decomposed to produce simple ions ($H_3O^+, O_2^+$) and the apparent rate of dissociative electron–ion recombination falls. Therefore, our qualitative predictions about the slight importance of electron detachment and the key role of positive cluster ions are expected to be applicable also to streamers in ambient air.

We studied only positive streamers. Propagation fields for negative streamers are known to be several times higher than are those for positive streamers. Even though we did not consider the negative streamers, it is to be expected that the influences of temperature and density on the properties of a streamer will depend only slightly on its polarity.

## 5. Conclusions

(i) Our simulation of the long-streamer properties in air shows that a moderate increase in the gas temperature (up to 1000 K) at constant gas pressure results in a decrease in the average electric field required for bridging the gap by up to a factor of five. In this case the conduction current through the streamer after bridging and its rise time also increase; therefore, the charge transferred to the cathode varies from about $10^{-9}$ C at $T = 300$ K to about $10^{-7}$ C at $T = 900$ K if the applied voltage is changed to maintain a constant reduced field $E/N$ before streamer inception. If the same decrease in air density is achieved by variation of pressure at room temperature, the transferred charge is about $10^{-8}$ C and the average field is approximately 40% higher than that at $T = 900$ K and atmospheric pressure. The results of our simulation qualitatively conform to the available experimental results.

(ii) At $T < 900$ K and atmospheric pressure electron–ion recombination generally dominates the loss of electrons in the streamer channel. Electron attachment becomes important only when the streamer conductivity decreases by more than a factor of ten. Electron detachment is essential only during the final phase of the plasma decay.

(iii) The observed effect of density on the streamer properties is associated with a decrease in the rates of three-body processes such as three-body electron attachment to $O_2$ or conversion of $O_2^+$ ions into $O_4^+$ ions.

(iv) At constant pressure the observed effect of temperature on the streamer properties is a result of the decomposition of positive cluster ions, which decreases the rate of electron–ion recombination. The final phase of plasma decay is also affected by a change in the rate of three-body electron attachment and partially in that of electron detachment. At constant density the effect of temperature is a less pronounced one.

(v) Electron detachment, which partially compensates for electron loss through electron attachment, can be more important at higher temperature ($> 1500$ K) and/or during fast gas heating when the gas density rather than the gas pressure is constant with time. However, this is attained only in the wake of decomposition of positive cluster ions; otherwise electron–ion recombination dominates the loss of electrons. Even when electron detachment completely compensates for electron attachment, this is of no significance because of the low density of negative ions formed.

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