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Spectroscopic measurements of streamer filaments in electric breakdown in a dielectric liquid

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Abstract. Emission spectroscopy has been utilized to provide information about the electron density and temperature in streamers and breakdown arcs in transformer oil. Recorded spectra include strongly broadened hydrogen Balmer-α lines and vibration/rotation band profiles of the C_2 molecule. The origin of the observed broadening of hydrogen lines is discussed and it is concluded that it arises mainly from collisions with charged particles, so-called dynamic Stark broadening. By assuming that the broadening is due solely to dynamic Stark broadening, electron densities between 1×10^{18} and 1×10^{19} cm^{-3} were obtained for the rear of positive streamer filaments during the later stages of propagation. For negative streamers we obtained an upper limit of 3×10^{16} cm^{-3} and for breakdown arcs electron densities up to 4×10^{18} cm^{-3}. The temperature information in the C_2 emission profiles and the intensity ratio of the hydrogen Balmer lines are discussed. Rough estimations of the temperature are presented both for positive and for negative streamers.

1. Introduction

The physics of electric breakdown in liquids is complicated and difficult to model theoretically. To improve our knowledge of this matter, experimental studies employing image converter cameras and streak cameras [1–3], together with monitoring of broad-band measurements of light emission and electrode current during the pre-breakdown phase, have been performed by others. These studies provide a substantial amount of information on the initiation, propagation and appearance of streamers preceding the breakdown.

Little is known, however, about the physical characteristics of these streamers. Generally they are regarded as thin (diameter up to tens of micrometres), weakly conducting and ionized gaseous [4–7] filaments, propagating through the liquid propelled by the electric field. The streamer propagation speed in the presented experiments conducted in transformer oil is in the range 0.1–10 km s^{-1}. Streamers propagating in a homogeneous field will eventually bridge the whole electrode gap. At that time a strong current will very rapidly begin to flow in the connecting streamer filament and a breakdown arc is established. From gas chromatographic measurements [8] it has been shown that hydrogen molecules are the most abundant stable species (80%) formed by streamer discharges in hydrocarbons, followed by low hydrocarbons such as methane, ethane and ethylene. By using spectroscopic methods, also radicals can be detected and earlier measurements [9–13] detected lines from C_2 and C_3 radicals and ions from the electrode material together with atomic and molecular hydrogen.

In this paper emission spectroscopy of the light emitted by streamers is utilized to obtain information about the physical properties of the streamer propagation process. The broadening of the atomic hydrogen lines by the Stark effect [14] is used to measure the mean electron density in streamers in transformer oil. This is the first time, to our knowledge, that this quantity has been measured for streamers in liquids.

The experimental technique is outlined in section 2 and the measurements are presented in section 3. In the analysis (section 4) the origin of the observed hydrogen line broadening is discussed. In particular, whether radial fields caused by net space charges or inhomogeneously distributed charges might have an influence is discussed. Experimental values of the mean electron density are given for the rear of the streamer filaments both for positive and for negative streamers just before breakdown and also time-resolved values for breakdown arcs are given. Our results are discussed in section 5. The possibility of obtaining a temperature from the vibration/rotation profiles of the C_2 Swan bands [15] or the intensity ratio of the hydrogen Balmer lines is also treated. A conclusion is found in section 6.

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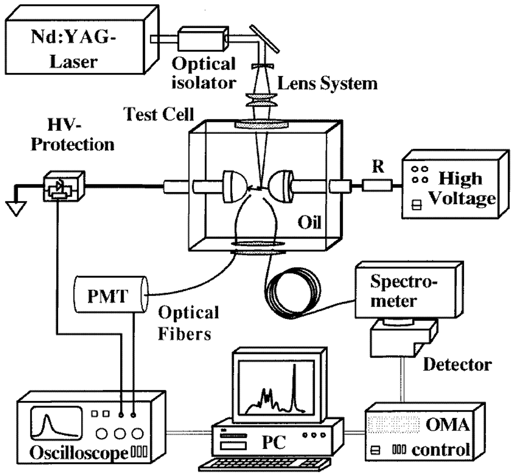

Figure 1. The experimental arrangement for spectral analysis of streamers and electric breakdown.

2. The experimental arrangement

The experiments are focused on analysing the small amount of light that is emitted from the streamer filaments during liquid electric breakdown and thereby drawing conclusions about the ongoing processes. By conducting the experiments in close to homogeneous electric fields and using a laser initiation method several advantages are obtained compared to other methods, as will be discussed later. The initiation method has been described in [16].

The experimental arrangement is shown in figure 1. An electric breakdown is initiated by a laser-produced plasma between two HV electrodes in a test cell filled with transformer oil. Three quantities from the pre-breakdown process are recorded, namely the current induced in the electrode gap, the instantaneous light intensity emitted throughout the breakdown process and a spectrally resolved measurement of a selected temporal and spatial part of the breakdown process.

The test cell is made of stainless steel and has four windows for optical access. A 65 kV power supply and hemispherical electrodes (2 cm diameter of curvature) produce a semi-homogeneous field with a voltage variation across the gap of less than 20% for a 10 mm gap. A 10 ns long laser pulse from a Quanta Ray Nd : YAG laser is focused at an arbitrary point between the electrodes. This pulse creates a plasma that serves as the spatial and temporal starting point for the streamers. The laser wavelength is 1064 nm and maximum available pulse energy is 0.6 J.

A protection circuit with a bandwidth of more than 500 MHz transmits the small pre-breakdown currents to a Tektronix 540 digital oscilloscope and automatically drains the high breakdown arc current to earth. This provides measurements of the electrode current induced by the pre-breakdown phenomena with a sensitivity down to 20 μA. The light emitted from the pre-breakdown process is collected by two (10 m and 200 m long) 0.8 mm diameter fused silica optical fibres and transmitted to the two optical detectors. The shorter optical fibre guides the light to an EMI 9558 photomultiplier tube (PMT) with a rise time of about 20 ns. The photocurrent is recorded on the oscilloscope together with the electrode current at sampling rates up to 500×10^6 samples per second each. The light collected in the longer fibre is spectrally resolved in a grating spectrograph with 125 mm focal length and with either a 300 or a 1200 l mm^{-1} grating. An intensified diode array or CCD detector acquires the spectrum. The detector is connected to a PC-mastered control unit and a gating pulse unit. The pulse unit controls an electronic shutter in the detector with a minimum exposure time of 100 ns. With a spectrometer entrance slit width of 50 μm and 25 μm wide detector elements, the resulting resolution is either 2 or 0.5 nm, depending on the grating. The instrumental broadening using different slits has been measured using a He–Ne laser. In the analysis these were used to correct for the broadening added by the limited resolution. The instrumental broadening and the corrected value from the analysis is given for each of the measurements presented. Recorded spectra are corrected for variations in spectral response in the optical system.

2.1. Characteristics of the arrangement

With the fibre arrangement light can be collected from a chosen spatial part of the breakdown process with a spatial resolution down to 1.5 mm. An advantage with this set-up is that the detection equipment need not to be in the proximity of the HV equipment and the test cell that generates strong electromagnetic noise, thus interfering pick-up of transients is minimized. At the same time a necessary delay of the optical signal is conveniently achieved before the light reaches the OMA detector. The delay in the electronics limits the maximum exposure time to the last 700 ns of the propagation time.

By conducting the experiments in electric fields that are close to homogeneous and using the laser initiation method several advantages are obtained.

(i) There are no triggering electrodes disturbing the field distribution. Instead the initiation is based upon the formation of a gas bubble (small bubbles in the insulating liquid are sometimes thought to be the initiating disturbance leading to breakdown in commercial equipment).

(ii) The streamers can be initiated from an arbitrary point in the electrode gap.

(iii) The streamer propagation is neither dependent upon nor disturbed by electrode surface effects or charge injection.

(iv) Finally, due to the low initiation voltage with this technique, the voltage can be kept close to the voltage needed for streamer propagation. This is thus a technique to approach some of the conditions in commercial high-voltage equipment.

3. Measurements

Primarily, the aim of our present experiments is to derive temperatures, electron densities and electric fields for different parts of the streamers from spectroscopic

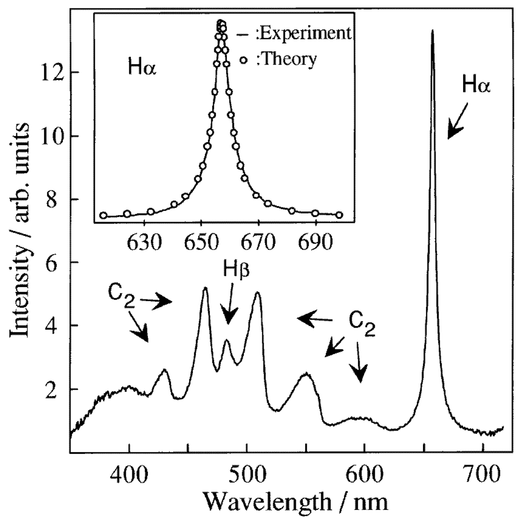

Figure 2. The spectrum from a breakdown arc. A theoretical Stark-broadened H_α line profile is fitted to the spectrum yielding the electron density $N_e = 8 \times 10^{17}$ cm^{-3}. The voltage is 40 kV and the gap distance is 4 mm.

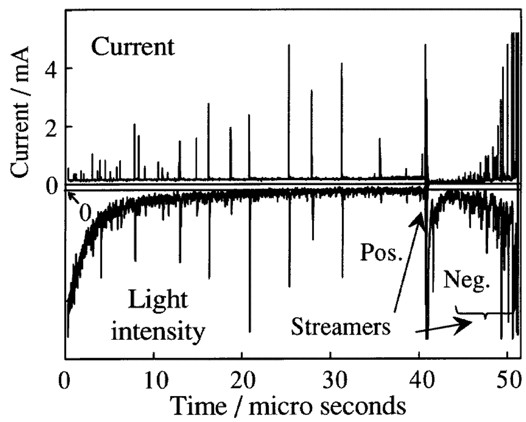

Figure 3. Current and (PMT) light recordings of laser-triggered electric breakdown. The electrode voltage is 43 kV, the gap distance is 4 mm and the laser pulse energy is 200 mJ. The baselines for both traces are marked.

measurements. The emission spectrum from a breakdown arc in transformer oil is shown in figure 2. The hydrogen Balmer lines [15, 17] H_α and H_β and the vibration/rotation band structures from the C_2 radical can be recognized and also a background continuum. This continuum mainly originates from recombination emission and broad-band spectral emission from molecules. The instrumental line width in the measurement is 2 nm.

3.1. Initiation processes

Streamers in the experiments are initiated from the laser focal point where a laser produced plasma is formed. The plasma evaporates the liquid and creates an expanding gas bubble. In this bubble, gas discharges occur which together with electrostatic forces elongate the bubble in the direction of the field [16, 18, 19]. It is believed that the discharges and the deformation of the bubble create an electric field high enough to initiate the streamers that are observed to propagate towards the electrodes. The streamer initiation process might then follow two possible schemes: streamers of both polarities are initiated independently, or a streamer of one polarity is not formed until a streamer with the opposite polarity has established contact with an electrode. Electrode current and PMT light measurements, such as the ones shown in figure 3, have been our main source of information from which to understand the laser-initiated breakdown process. The laser pulse was focused in the centre of the electrode gap and the optical fibre collected light from the central parts of the gap. In figure 3 the traces of the fast positive streamers (about 5 km s^{-1}) and the slower negative streamers (about 200 m s^{-1}) are indicated. The trace of the positive streamer itself is actually too short to be discerned in the picture, instead the backstroke of charges following the streamer contact with the electrode causes the large current and light pulse just after 40 μs.

3.2. Streamer measurements

By choosing the position of the laser plasma with respect to the positive and negative electrodes, it is possible to select whether a positive or a negative streamer should be the second and final streamer leading to breakdown. Figure 4 shows the current and PMT light measurement for (*a*) a positive streamer and (*b*) a negative streamer leading to breakdown. (Note that the current trace for the negative streamer is inverted.) The HV electrode potentials were −60 and +60 kV respectively and the electrode gap was 8 mm. The laser pulse was in both cases focused at a point 3 mm from the earth electrode. In both figures 4(*a*) and (*b*) the streamers are propagating towards the HV electrode and thus the propagation distance is approximately 5 mm, leading to average propagation speeds of 3 and 0.7 km s^{-1} for the positive and negative streamers respectively. The smoothly increasing current and light traces are characteristic of positive streamers but frequently correlated light and current pulses also occur. The negative streamer measurement shows pulsed light and current traces characteristic of this streamer type. The last 0.5 μs just before breakdown shows a more continuously increasing current and light signal. This signature is quite common with the laser initiation method for this electrode distance (8 mm). It might be possible that this is evidence of a transition to a fast negative streamer [20]. 8 mm is close to the longest electrode distance still leading to breakdown with the maximum available voltage of ±65 kV.

Figures 5(*a*) and (*b*) show spectra, averaged over approximately ten single shots each, of light-emitting events between the plasma bubble and the negative electrode and the plasma bubble and the positive electrode. The optical fibre viewed a volume stretching from 1 to 2.5 mm away from the plasma. The instrumental line width in figure 5(*a*) is 2.2 nm and in figure 5(*b*) it is 1.5 nm. PMT light and current recordings lead to the interpretation that figures 5(*a*) and (*b*) show spectra from positive and negative streamers, respectively. Both the appearances of the light and current traces and the fact, which has been ascertained in experiments, that the positions of the most luminous parts

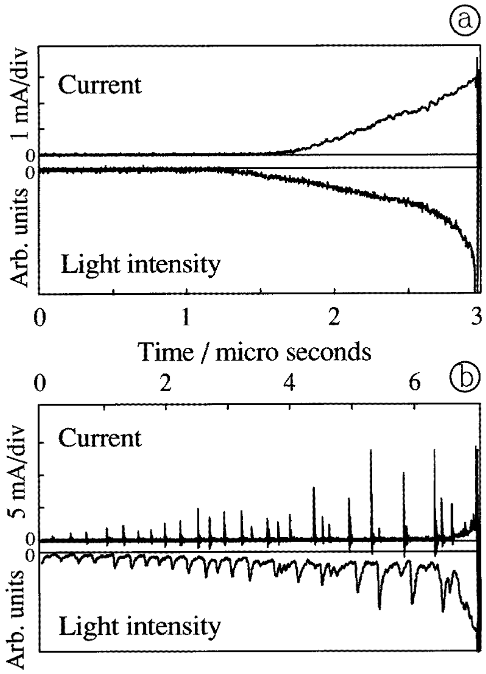

Figure 4. Current and light measurements of laser-initiated (*a*) positive streamers (U = −60 kV) and (*b*) negative streamers (U = +60 kV). The gap distance is 8 mm and the streamer propagation distance is 5 mm. The baselines are marked.

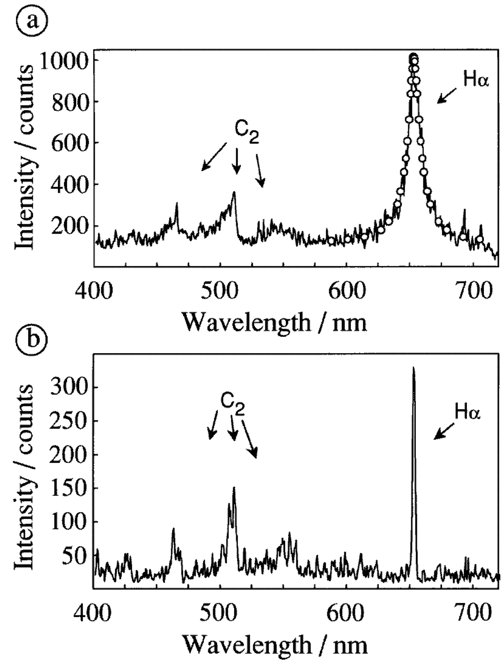

Figure 5. Spectra of laser-initiated streamers: (*a*) positive streamers, U = −65 kV and (*b*) negative streamers, U = +65 kV. The gap distance is 9 mm. A profile fit (circles) in (*a*) yields $N_e = 3 \times 10^{18}$ cm^{-3}. The upper limit in (*b*) is $N_e = 3 \times 10^{16}$ cm^{-3}. Light emission was collected 1–2.5 mm from the plasma.

in the beginning of the processes move in time from the plasma initiation point towards the electrodes, indicate this. In figures 5(*a*) and (*b*) the H_α line and the C_2 bands are recognized. Due to the lower light intensity, the noise level is high compared to the breakdown arc measurements. The light in figure 5(*a*) was recorded during the last 0.7 μs of a total of around 1.5 μs propagation time for the positive streamer. The light in figure 5(*b*) was recorded during the last 0.7 μs of around 7 μs negative streamer propagation time. The light intensity increases markedly with time so the recorded spectra are characterized more by the light emitted just before breakdown than they are by that emitted at the beginning of the period. The light is collected by the fibre from a volume stretching from 1 to 2.5 mm from the initiation point in both cases. This means that the recorded light is emitted from the rear of the streamer filament, far away from the streamer tip. Measurements up to 5 mm away from the plasma bubble show similar spectral signatures. This ascertains that the characteristic spectral profiles of the measurements in figures 5(*a*) and (*b*) are related to the streamer filaments and are not an effect of the closeness to the initiating plasma bubble.

Measurements of positive streamers generated in needle-plane geometry with step voltage were also performed. These provided spectra of high quality from the streamer filament with spectral signatures similar to that figure 5(*a*). The H_α line of such a measurement is shown in figure 6. The instrumental line width was 10 nm. The light was emitted from a volume stretching from 3 to 5 mm away from the needle electrode during 700 ns ending 50 ns before breakdown. The needle was an ordinary sewing needle without further modification. Figure 6 is the sum of 11 streamer spectra.

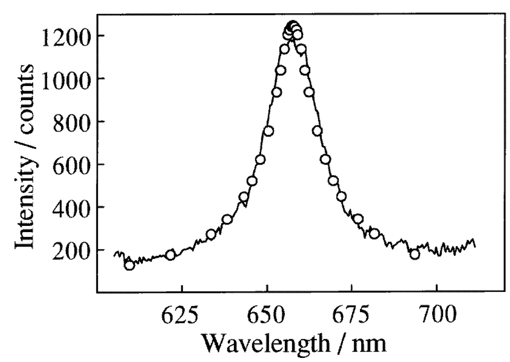

Figure 6. The H_α line of positive streamers and a profile fit (circles). The fit yields $N_e = 4 \times 10^{18}$ cm^{-3}. Needle–plane electrodes were used, with U = +60 kV and gap distance 12 mm. Light was collected 4 mm from the needle.

4. Analysis

4.1. Theory

Hydrogen is affected by the linear Stark effect and its energy levels are very sensitive to electric fields compared to those of other atoms. The presence of atomic hydrogen in a volume subjected to high macroscopic or microscopic electric fields can thus be utilized to measure the size of these fields. The Stark effect is manifested as shifts of

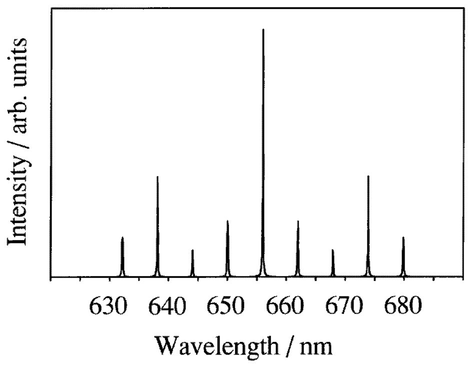

Figure 7. The different Stark-shifted components of the H_α line. Theoretical shifts and line intensities are from [22] at an electric field of 1 MV cm^{-1}.

the atomic energy levels when hydrogen is exposed to an electric field. Moreover, different sub-levels within a specific energy state are shifted by different amounts, either to higher or to lower energies. For a radiative transition between two atomic energy levels this results in a number of discrete emission lines, see figure 7, or, if broadening or a non-uniform electric field is present, a wavelength distribution, creating a line profile. Hydrogen atoms in a plasma experience strong, time-varying local electric fields created by free electrons and ions. These fields result in a strong broadening of the hydrogen atom emission lines called dynamic Stark broadening. The ensuing line profiles are strongly dependent on the electron and ion densities and to a lesser extent on the temperature in the plasma. For example, in [21] calculated line profiles from hydrogen plasmas are tabulated with the electron density and temperature as parameters. The broadening model for pure hydrogen plasmas is assumed to be applicable in the following analysis since using this model is a general technique to analyse also impure hydrogen plasmas [14, p 304].

4.2. The breakdown arc

In a breakdown arc with a large number of ions and electrons in a larger volume no high macroscopic electric fields can exist. Therefore, the predominant Stark broadening of hydrogen emission from the arc should arise from dynamic Stark broadening. Other broadening processes are discussed in the next section but should not have a noticeable influence on the broadening of the hydrogen lines. In figure 2 the inset shows a theoretical line profile fitted to the H_α line from a breakdown arc spectrum. Before optimizing the electron density parameter to obtain the right shape of the line, the temperature was calculated or estimated, a flat background level was added and the height of the curve was adjusted. The excitation temperature in breakdown arcs has been measured from the intensity ratio of the H_α and H_β lines assuming a Boltzmann temperature distribution function. Measurement on a 4 mm electrode gap at a voltage of 40 kV yielded a temperature maximum slightly above 10 000 K 300 ns after the breakdown arc had been established. Since the H_α line profile is much less sensitive to temperature variations than it is to changes in the electron density, an estimation of the temperature is sufficient if not very high accuracy is needed. For example, by doubling a fictitious electron density from 1×10^{18} to 2×10^{18} cm^{-3} the calculated line width (FWHM, full width at half maximum) of H_α increases by approximately 50%; whereas by doubling the temperature from 10 000 to 20 000 K the linewidth is increased by only 5%. The fit in figure 2 yields an electron density of 8×10^{17} cm^{-3}. The close fit could be taken as an indication that this technique for calculating the charge density is correct.

4.3. Non-Stark-effect related broadening mechanisms

When analysing spectra of positive streamers in particular, the question of the cause of the broadening of the H_α line arises. To determine the broadening mechanism we can first conclude that the emission in the presented measurements of positive streamers most probably really originates from the column rather than from a new streamer tip at the rear of the streamer tree. As was described in section 3, it was the rear parts of the streamers that were observed in the measurements in figures 5(a) and (b) and 6. Also, we found no indication in other reports that a new streamer tip growth should occur at this location in a positive streamer and, moreover, such a process seems unlikely because of the expected lower fields in this part of the streamer. Could there then be broadening processes other than the dynamic Stark broadening, resulting in similar profiles?

4.3.1. General broadening processes.

Line radiation from the hydrogen atoms is also affected by the following broadening processes [22]: (i) natural line broadening which is usually very small and is determined by the lifetimes for the energy states in the transitions, (ii) Doppler broadening which is due to the velocity distribution of the radiating atoms and is thus determined by the temperature and (iii) pressure broadening from neutral particles which arises from collisions between the radiating atoms and the surrounding atoms and molecules. The first two processes give line broadening far less than that which is observed for positive streamers. Pressure broadening and dynamic Stark broadening are related in that they are both caused by collisions with particles. However, the range over which the electric forces from charged particles affect the atoms far exceeds the effect from neutral ones and even with only 1% ionization, pressure broadening is dominated by dynamic Stark broadening. The internal streamer pressure at the tip should be very high, but, due to expansion, it decreases rapidly further back in the filament [7]. There, at the rear of the filament, the pressure should not be orders of magnitudes higher than the surrounding atmospheric pressure (inferred from [7]). Pressure broadening of hydrogen in a gas even under high pressure and temperature, for example 30 bar and 10 000 K, is no more than 1 nm in width (FWHM). Thus, since the recorded radiation from positive streamers is expected to originate from a gaseous [6, 7] streamer filament, the pressure broadening from neutral particles is also negligible.

4.3.2. Liquid broadening. Radiation from the liquid, as an alternative to radiation from the streamer gas, is not expected in any substantial amount, since there the atoms would experience very strong quenching, namely, non-radiative de-excitation. Therefore, liquid broadening shall not be considered here further as a cause of the observed broadening.

4.4. Stark broadening from electric field gradients

It seems clear from the previous section that the hydrogen broadening in the presented measurements of positive streamers mainly arises from the Stark effect. The question is then whether the electric fields causing the broadening are macroscopic or, as for breakdown arcs, generated on a local level.

To generate a substantial broadening as in figures 5(*a*) and 6, fields in the region of 1 MV cm^{-1} are necessary and, also, there has to be a certain distribution of the electric field strength since a constant electric field would only result in a discrete set of emission lines, figure 7. Moreover, the central, main component in the H_α line is to a first approximation not shifted by an electric field and so the atoms have to be subjected to an additional broadening mechanism. (The central component is affected by the quadratic Stark effect which is much weaker than the linear effect at fields around 1 MV cm^{-1}. A wavelength shift of less than 1 nm can be observed in breakdown arc measurements, but the noise in the streamer spectra makes the determination of a shift impossible.) There are two possible effects that perhaps could result in the correct field distribution. The first is that there is a sufficient amount of excess charge with a certain distribution in the streamer volume producing high electric field strengths. The second possibility is that electric fields are instead caused by different radial distributions of equal amounts of ions and electrons in the streamer. In arc and glow discharges in gases, see section 5.1, this gives rise to radial electric fields [24]. However, the field calculated for streamers using values from [24] as a rough approximation gives values far too low to produce the observed broadening.

4.4.1. Net charges as the cause of the broadening. If there is a net charge in the positive streamer filament then it should be, due to mutual repulsion of equally charged particles, distributed not in the bulk of the streamer, which is thought to be gaseous [6, 7], but rather at the liquid boundary, there forming a charged shield. Such a shield would not be infinitely thin; it would probably have a density distribution with highest density near the gas–liquid boundary, decreasing exponentially away from the liquid. As a comparison the distribution of net charges in an electrolyte near a charged interface can be studied in [25]. The width of the shield corresponds approximately to the Debye length and is then of the order of 100 nm at, for example, 5000 K and with an electron density of 10^{16} cm^{-3}. Calculations to evaluate the resulting emission line profile from hydrogen atoms assuming this type of charge distribution were performed. The contributions from the different sub-levels of the emitting hydrogen atoms, at different radial positions in the streamer, experiencing different field strengths, were integrated. Parameters for the calculations were estimated using values from the literature regarding streamer size and net charge [26] and from experiments regarding temperature, see section 5.3. To eliminate errors in the calculations due to uncertainties in the parameters, these were varied over wide ranges. The calculations showed, however, that, with the assumptions made, it is neither possible to achieve emission profiles with the width nor with the shape that has been seen in experiments.

4.5. Dynamic Stark broadening

In section 4.3 it is concluded that the observed H_α broadening is due to the Stark effect and the conclusion from section 4.4 is that macroscopic fields from space charges alone do not give rise to the correct emission profiles. In combination with extensive dynamic Stark broadening the profiles can become similar to the one in figure 5(*a*), with the influence from macroscopic fields acting as a perturbation of the original dynamic Stark broadening profile. This type of calculation of H_α broadening due both to dynamic Stark broadening and to space charge fields can also be found in [27]. That space charges have an influence on the broadening can definitely not be ruled out from the presented measurements, but it can be concluded that they have only a limited influence. The main broadening process of hydrogen radiation in the streamer filament should thus be dynamic Stark broadening and approximate values of the charge density can therefore be determined from the recorded line profiles.

4.5.1. The electron density in positive streamers. Theoretical line profiles have been fitted to streamer spectra, providing values of the mean electron density. The influence from the instrumental broadening was taken into account in the presented values. In figure 5(*a*) a theoretical profile has been fitted to measurements from laser-triggered positive streamers (circles). The fit in this example yields an electron density of 3×10^{18} cm^{-3}. Generally the measurements of positive streamers yield electron densities between 1×10^{18} and 1×10^{19} cm^{-3}. The temperature cannot be calculated from the intensity ratio of the hydrogen lines in figure 5(*a*) as was done for breakdown arcs, because the H_β line cannot be discerned. For the fitting procedure the temperature has instead been estimated to be 10 000 K, see section 5, but the influence on the result from an erroneous temperature would be, as has been mentioned, small. An H_α profile fit to measurements in point–plane geometry is shown in figure 6 (circles). The fit yields an electron density of 4×10^{18} cm^{-3}. The experimental curve has a lower and flatter peak than has the theoretical one, which is mainly due to the spectrometer entrance slit width limiting the resolution of the measurement to 10 nm. (A wide entrance slit increases the light level and thus lowers the relative noise.) The width of the entrance slit influences the line width but the line profile is not seriously disturbed and the measurement should be relevant for evaluating the electron density based upon line shape analysis. The close fit in figure 6 could be taken as an additional indication that the main hydrogen broadening process in streamers is most likely to be dynamic Stark broadening.

The electron density values obtained are indeed high and imply a high degree of ionization, see section 5.1. It should be emphasized though that the experiments provided spectra that are dominated mainly by the emission from later stages of the streamer propagation process, as described in section 3.2.

4.5.2. The electron density in negative streamers. The performed measurements of negative streamers, such as in figure 5(*b*), can only give an estimation of the upper limit of the electron density. The line width is limited by the 1.5 nm spectral resolution which is also the width of the H_α line in figure 5(*b*). The electron density can thus be concluded to be below around 3×10^{16} cm^{-3}. In the fitting procedure the temperature was set to 5000 K, see section 5.3. The difference in electron density that we obtained for positive and negative streamers just before breakdown is remarkable and may indicate a clear difference in the degree of ionization in the streamer gases.

4.5.3. The electron density in breakdown arcs. Spectral signatures of breakdown arcs at different times after streamer contact are shown in figure 8. The instrumental line width was 2 nm. The H_α line is strongly broadened shortly after the contact and narrows considerably during the later stages of the breakdown. According to the measurements in figure 8 the average electron density during the first 50 ns is 4×10^{18} cm^{-3}; after 500 ns it has decreased to 8×10^{17} cm^{-3} and after 750 ns, when the H_α line intensity is quite low, it is down to below 2×10^{17} cm^{-3}. These numbers for the breakdown arc are highly dependent on laser energy, gap distance and voltage. During the early stages of the breakdown arc the electron density might be expected to be higher than in the streamers preceding it. This is clearly the case when the connecting streamer is of negative polarity. With a connecting streamer of positive polarity the electron density seems to decrease after contact in some cases, though. However, the breakdown channel experiences rapid expansion due to heating and the following high pressure. This strongly tends to decrease the electron density. Furthermore, the limited charge available from the power supply or actually from the charged electrode capacitor, see section 2, is exhausted over a very short time period when the arc resistance drops. After that time the electron density is expected to decrease rapidly.

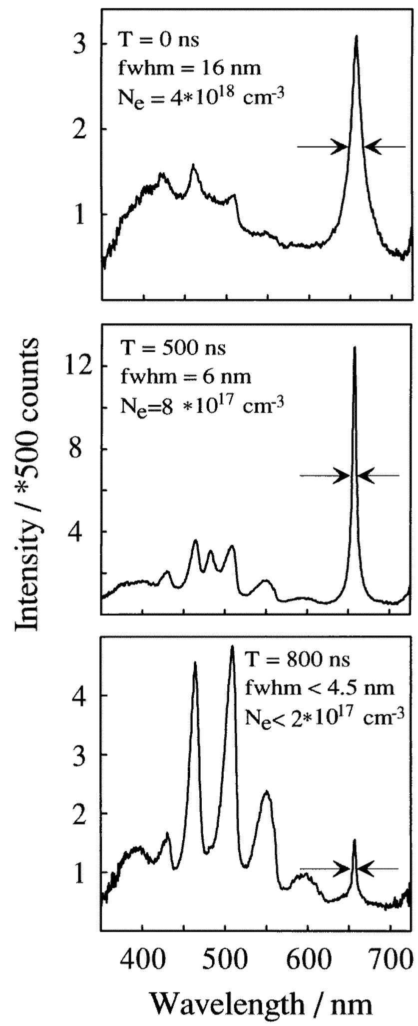

Figure 8. The spectral development of breakdown arcs in transformer oil. U = 40 kV and the gap distance is 4 mm. T is the time after the inception of breakdown, fwhm is the line width and N_e is the resulting electron density.

5. Discussion

Different broadening mechanisms have been discussed and it has been concluded that the broadening most probably primarily arises from dynamic Stark broadening. Assuming that this is true, the experiments have shown a great difference in electron density in the rear of negative and positive streamer filaments. Similar differences have been observed up to 5 mm away from the plasma bubble. The difference thus remains also further away from the plasma bubble and closer to the tip of the streamers. It may be wise to be cautious when interpreting the measurements of negative streamers, though. Even if the light is collected close to the streamer root, it is possible that the emission might arise from new streamer tip growth at this location. In that case, the negative streamer spectra are not directly comparable to those from positive streamers since they are expected to be related to the charge transport in the streamer filament feeding the tip propagation.

5.1. The degree of ionization and comparison with gas discharges

Due to the relatively high electron densities measured late in the positive streamer propagation process, the hydrogen emission should originate from a highly ionized gas. Assuming a pressure and temperature of, for example, 10 bar and 10 000 K, an electron density of 5×10^{18} cm^{-3}

and that only singly ionized species exist, the degree of ionization amounts to about a third. This high degree of ionization and also other quantities of the positive streamer filament, such as the radius, current and current density, at the relevant pressures, are similar to the quantities in arc or high-pressure glow discharges under certain conditions. The resemblance between the positive streamer gas and the arcing regime in gases has also been pointed out in [20]. The measurements result in high degrees of ionization indeed and a possible explanation for this follows.

The main conduction in gas discharges at high pressure occurs in the centre of the discharge tube. The radius of the conducting volume can be much smaller than the radius of the discharge tube and it decreases with increasing pressure and also with increasing current [24, 28]. This type of constriction of the conducting volume could be considered also for the later stages of positive streamers. By estimating the total energy delivered to a streamer filament from the external circuit and considering the different energy-consuming processes [20], the hypothesis that just before breakdown only a part of the streamer volume is strongly ionized can be made credible. The available energy estimated from the streamer current and voltage drop, for example 4 mA and 10 kV cm^{-1} at a propagation speed of 1 km s^{-1} for a single creeping streamer filament [26], is 400 μJ cm^{-1}. The energy required to ionize the whole filament volume with, for example, a streamer radius of 40 μm at the rear of the filament [7], with 10 eV ionization energy, to an electron density of 5×10^{18} cm^{-3}, amounts to 400 μJ cm^{-1}. Considering the energy needed for all the streamer processes (wherein the mechanical energy and the energy needed for decomposition are dominant [20]), it is evident that it should not be possible too achieve this degree of ionization throughout the whole volume. Note also that the streamer current in our measurements, figure 4(a), is much lower and the propagation speed is higher; thus the available energy for ionization is even lower than that for the example above.

5.2. The streamer tip

The tip of a positive streamer filament, where the actual propagation processes occur, should have physical properties and a spectral signature quite different from those of other parts of the filament. The tip of a positive streamer is believed to have a net charge of some nano-Coulombs that produces high electric fields governing the propagation of the streamer [20]. The hydrogen emission at the tip would, due to the field at the tip, which is in the region of 10 MV cm^{-1}, experience extensive Stark shifts and broadening, perhaps producing emission lines too wide to be discernible from the continuum.

The spectral signature from the negative streamer tip might be expected to be somewhat similar to that from the negative streamer filament, since both processes are believed to be gas discharges. The light intensities from the tip and from the filament have also been reported to be of similar strengths [3, 29] which may indicate a similar conductivity and charge density. This reasoning and questions about differences in temperature, see section 5.3, for example, might be investigated by means of the method described in this paper.

In future measurements we expect to be able to increase the detected light level and we will also have a system that enables us to perform measurements at an arbitrary time in the streamer propagation process. It will then be possible to obtain more detailed information about the spectral differences along the streamer filaments.

5.3. The temperature in streamers

Preliminary estimations of the molecular and electronic excitation temperatures were obtained from the presented streamer spectra. Upper and lower limits of the temperature were obtained from the relative hydrogen line intensities and the C_2 line profiles. The method by which to use the H_α and H_β intensity ratio to obtain the excitation temperature was mentioned in section 4.2. For the presented streamer measurements only an estimation of the upper limit of the temperature is possible with this method, but recent experiments promise to give more information. Upper temperature limits have been estimated to be 5000 K for the presented negative streamer measurements and around 10 000 K for the positive streamer measurements. C_2 emission profiles can be precisely calculated [30] and fitted to streamer C_2 spectra. Preliminary results with this technique clearly indicate a temperature below 5000 K for the negative streamer measurements and above 5000 K for the positive streamer measurements. At the present state this rather crude temperature determination does not allow us to distinguish between the rotational and vibrational temperatures. It can only be stated that for negative streamers the vibrational and rotational temperatures of C_2 cannot both be above 5000 K and for positive streamers they cannot both be below 5000 K. Whether local thermodynamic equilibrium (LTE) prevails or not must be considered before drawing far-reaching conclusions based on the temperature. If the majority of the molecules are excited by chemical reactions instead of by collisions, the emission can give temperatures that strongly deviate from the kinetic temperature.

6. Conclusion

We have studied the spectral signature of the light emitted late in the propagation process by streamers and especially the broadening of the H_α line. The cause of the observed broadening has been thoroughly discussed. Common gas broadening processes and the Stark shift induced by electric fields from space charges in the streamer filament have been considered together with dynamic Stark broadening. The broadening was concluded to arise most probably from dynamic Stark broadening. We have thus presented an experimental technique providing time-resolved information about the electron density in streamers and also about electric breakdowns. Also, the temperature can be obtained from the measurements. It is the authors' belief that these physical streamer parameters can be quite efficient in reducing the difficulties inherent to building a physical model of the streamer process.

The methods might come to be used for characterization of the insulating properties of dielectric liquids. The measurements may also open the possibility of deducing, for example, the conductivity in the streamers. Knowing physical parameters such as electron and ion density, their distribution and the temperature in the streamer filament gives a good foundation upon which to calculate the conductivity. We believe that the data that can be obtained with the presented technique combined with imaging measurements of streamer growth processes constitute a promising method to achieve an improved understanding of the physics of streamers.

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