Streamer Discharges Caused by High-Frequency Voltage Leading to Ignition of Hydrogen/Air Mixtures

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1 Introduction

Electric discharges can ignite flammable gas/air mixtures and must therefore be taken into account in the explosion protection of electrical apparatuses for usage in hazardous areas. Concerning the type of protection Increased Safety, energised components which are not insulated must be protected by an increased dimensioning of the creepage distances and the clearances [1]. The supply voltage is used as an assessment basis, whereby transient overvoltages are not taken into account. In electrical supply networks or in the case of converter-fed drives, however, transients which are due to switching operations with high-frequency overvoltages may occur, leading eventually to streamer discharges. Hence, the incendivity of streamer discharges needs to be considered.

In contrast to spark discharges, the ignition through streamer discharges caused by high-frequency voltage has been examined to a lesser extent. The incendivity of streamer discharges without a subsequent flashover in a rod/plane gap using different hydrogen/air mixture compositions has been analysed and demonstrated in previous work with respect to the number of cycles, the voltage amplitude, and the gap distance between rod and plane necessary for ignition [2]. The ignition process itself has not been analysed so far, although this is necessary to get an in-depth understanding of the physical and chemical processes leading to ignition.

In this work, the ignition of hydrogen/air mixtures by streamer discharges is examined experimentally. The electric field strength is calculated by a simulation of the rod/plane configuration used in the experimental set-up to compare the values of the electric field with values necessary for streamer formation at a positive and a negative rod. The results of the calculation in conjunction with an analysis of the streamer formation during one voltage cycle lead to a comprehension of the point of ignition.

2 Background

A streamer is a discharge in an electric field and often occurs as a predischarge when a conductive channel is built before the actual electric flashover. The voltage must thereby be sufficiently high to generate an electric field in which a single electron can take in enough energy in the mean free path length so as to dissociate other gas molecules or ionise gas atoms to thus generate further charge carriers. This creates an anode-oriented electron avalanche. The less mobile positive ions remain in the

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avalanche tail. Through photo-ionisation due to recombination processes, so-called secondary pre-avalanches or secondary lagging avalanches can occur outside the avalanche head. These can fuse together with the original avalanche and thus rapidly create a conductive channel [3]. Due to the interaction of the charge carriers with the electric field and with the neutral gas particles, an energy deposit effectively occurs in the gas mixture. With the aid of a rod-plane arrangement, Lienesch et al. have shown in [2] that streamer discharges can lead to the ignition of hydrogen/air mixtures. The electric field created between the rod and the plane is extremely inhomogeneous. This contributes to the avoidance of flashovers for the used voltage values. This thus enables streamer discharges to be systematically investigated.
In contrast to DC fields, in the case of a high-frequency alternating voltage, the different mobilities of the respective charge carriers must be taken into consideration. At critical frequencies, space charges due to ions which do not bridge the gap distance during a half-cycle of the supplied alternating voltage can build up. Due to the space charge, the electric field increases which, on the one hand, considerably reduces the breakdown voltage and, on the other hand, can increase the energy of a discharge [2].

3 Test set-up

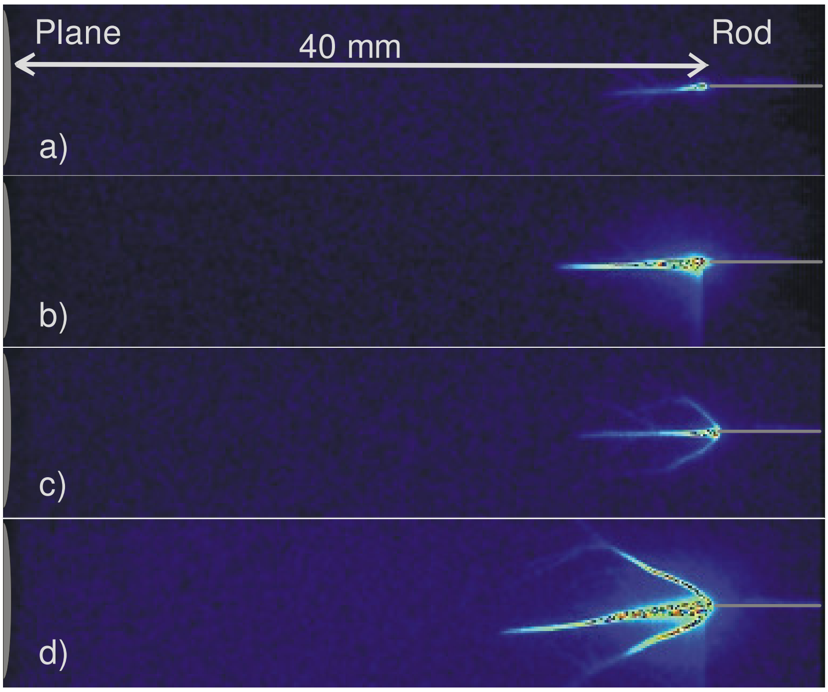

Fig. 1 Streamer discharge in air using a rod-plane configuration; a) 9 kV, 740 kHz, 25 voltage cycles, exposure time 35 µs; b) 9 kV, 740 kHz, 100 voltage cycles, exposure time 140 µs; c) 11 kV, 740 kHz, 25 voltage cycles, exposure time 35 µs; d) 11 kV, 740 kHz, 100 voltage cycles, exposure time 140 µs

All results are achieved using the same test set-up as presented in [2]. To generate high-voltage high-frequency discharges, an alternating voltage is used. The sinusoidal alternating voltage, generated by means of a frequency generator, serves as an input signal for a power amplifier. The amplified signal causes an air-cored coil to resonate and allows alternating voltage amplitudes of up to 20 kV. The voltage alternates with a frequency between 600-750 kHz - depending on the resonance frequency of the coil. The electrodes are configured in a rod/plane arrangement (gap of 40 mm), with the rod having a radius of 0.1 mm (Fig. 1). The tests take place in a plexiglass vessel. The use of quartz glass windows allows the optical observation, also in the UV range. The discharge and combustion phenomena are recorded by means of an intensified CCD camera.

4 Results and Discussion

In Fig. 1 the streamer formation in air for a different number of voltage cycles at 9 kV and 11 kV is shown. One can see that the length increases with an increasing number of voltage cycles and with an increasing maximum voltage amplitude. Furthermore, formation of three streamer channels is observed at 11 kV.

A typical time series showing the ignition of 22% hydrogen in air by streamer discharges at 9 kV, using 100 cycles, is presented in Fig. 2. In the first two images streamer discharges with a maximum length of 13 mm are visible. Between image 2 and 3, ignition has occurred. Hence, beginning with the third image, the direct emission of the subsequent combustion is visible, leading to a growing flame kernel. Based on a wide set of experiments, it can be concluded that the probability of an ignition is the highest near the tip of the rod.

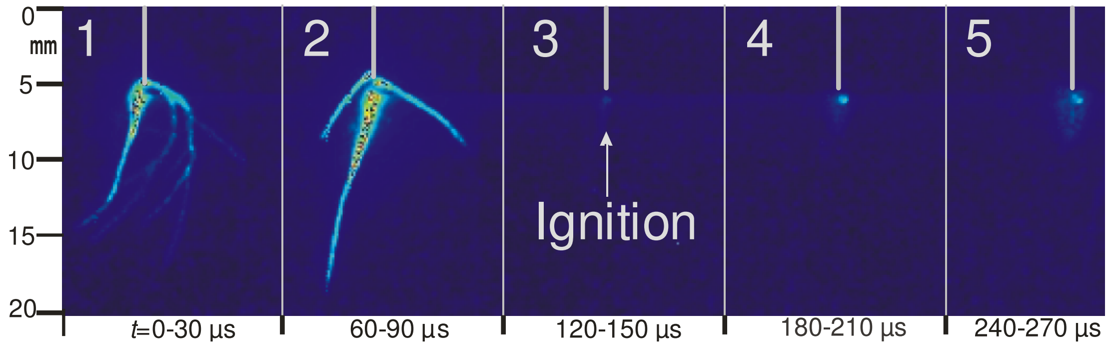

Fig. 2 Image sequence of streamer discharges and subsequent ignition of 22% hydrogen in air (9 kV, 680 kHz, exposure time 30 µs); the images 1/2 show the streamer discharge, the images 3/4/5 show the developing flame front

In the tests AC voltage is supplied to the electrodes, which leads to a maximum electric field strength at the voltage peak. To compare the values of the electric field with known values necessary for streamer formation at a positive and a negative rod, the electric field strength is calculated in an axis-symmetric simulation [4] of the rod/plane configuration used in the test set-up. For the calculation, a fixed voltage value is used, which corresponds to the value of the maximum AC voltage amplitude. First of all, the calculation in Fig. 3a shows that the electric field in the test set-up is sufficient for streamer formation. The limit for positive and negative streamer formation is due to the derived values from Cooray [3]. According to the graph, the first positive streamer can propagate up to 2 mm, whereas the first negative streamer can only propagate 0.8 mm. As a result of ions which do not bridge the gap distance during a half-cycle of the applied alternating voltage for the used frequencies, the first streamer changes the space charge which in turn changes the electric field. This can lead to higher electric fields in the gap between rod and plane. The space charge leads, due to the changed electric field strength, in case of a positive rod to further propagating streamers, whereas for a negative rod the propagation is negatively affected [5]. Furthermore, this leads to the conclusion that only during a small period of time (positive rod) an expanded streamer formation can be observed, whereas for the rest of the time only a short elongation (glow) can be expected.

Hence, the streamer formation caused by one single voltage cycle is examined experimentally using an exposure time of 0.1 µs, which is less then a tenth of the oscillation time of one cycle. Therefore, one cycle approximately in the centre of two hundred cycles has been chosen. As can be seen in Fig. 3b-d, the change of the electrical field during one single cycle influences the shape of the streamer. In fact, only during a short period of time (not exceeding a quarter of the oscillation time) - near the positive rod – it is possible to observe streamer formation with a length of a few millimeters (Fig. 3c). In the remaining time, one can see a glow directly in front of the rod (Fig. 3b), or nothing (Fig. 3d).

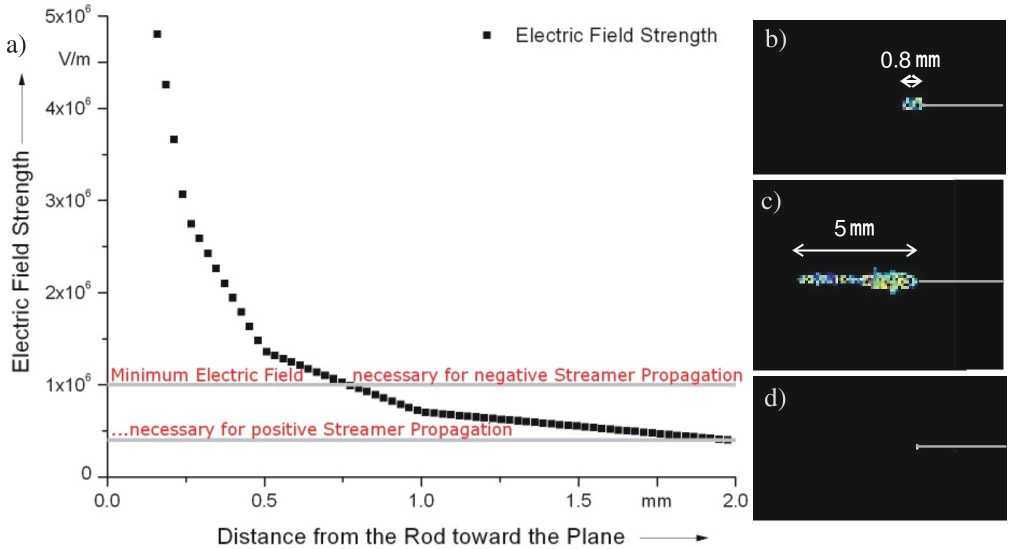

Fig. 3 a) Electric field strength between rod and plane for a fixed voltage of 9.2 kV; b) Streamer discharge in air at negative rod; c) Streamer discharge in air at positive rod; d) Nearly no visible discharge in the turning point of the AC voltage signal

Regardless of whether the rod is supplied with positive or negative voltage, the streamers propagate in both cases into the volume directly in front of the rod. A current flows in the propagating streamer channel, which heats up the volume of the streamer channel. The small volume directly in front of the rod is heated in case of a rod supplied with positive and negative voltage. As described in [6], the ignition takes place in a volume where the temperature is sufficiently high for the chemical reactions leading to ignition, which explains the point of ignition directly in front of the rod.

5 Conclusions

The ignition process caused by streamer discharges using hydrogen/air mixtures in a rod/plane geometry at high-frequency voltage is examined. The tests show that ignition takes place directly in front of the rod. The electric field strength for the test set-up is calculated. The results of the calculation in conjunction with the minimum electric field strength values, necessary for streamer formation, show that streamer formation is possible in the test set-up used. Furthermore, the calculated results are consistent with the observation in the tests that streamers do not occur during the whole voltage cycle with the same elongation. At high frequencies the space charge affects the streamer formation, which leads to a different streamer propagation, depending on the polarity. Together it explains the point of ignition. The ignition starts in a volume where, independent of the polarity, streamers occur. The streamer current and the with it accompanying energy deposit heats the volume until the temperature is sufficiently high for the chemical reactions leading to ignition.

References

[1] *Explosive atmospheres - Part 7: Equipment protection by increased safety "e"*, EN 60079-7, Beuth Verlag, Berlin 2004.

[2] F. Lienesch et al., *Ignition of Hydrogen/Air Mixtures through Electric Discharges at High Frequency AC Voltage*, Chem. Eng. Technol. 2009, 32 (1), DOI: 10.1002/ceat.200800528, in press.

[3] V. Cooray, *The Lightning Flash*, MPG Books Limited, Cornwall 2003.

[4] D. Meeker, Software FEMM 4.2, http://femm.foster-miller.net, 06.01.2009.

[5] A. Küchler, *Hochspannungstechnik*, Springer-Verlag, Berlin 2005.

[6] J. Warnatz, U. Maas, R.W. Dibble, *Combustion*, 4th Edition, Springer-Verlag, Berlin 2006.