Development of plasma pulses in He jet ignited with sinusoidal AC voltage in the kHz frequency range

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The development of plasma pulses was investigated in a 500 µm quartz tube and in the He jet emerging into the ambient air. At voltages in the range of 5.5-7.5 kV only one pulse during a positive half-period of applied voltages was observed while at higher voltages up to 6-7 pulses appeared each half-period. The voltage where several pulses started to occur depended on the flow rate and position of the grounded electrode. The development of the first pulse and subsequent pulses during the same half-cycle was essentially different. The sharp rise of optical emission characterizing the front of the ionization wave occurred initially near the high-voltage electrode. The ionization wave moved towards the orifice of the tube and further to the end of the He jet in the ambient air. The development of ionization wave coincided with the sharp rise of the current which obtained maximum after the wave reached the end of the jet. For subsequent pulses of the same half-period, the emission occurred initially at the tube orifice and the ionization wave moved simultaneously in two directions: towards the high-voltage electrode and the end of the jet in the ambient air.

1. Introduction

The plasma jets ignited by AC or pulsed voltages with kHz frequencies consists from discrete plasma pulses with duration considerably shorter than the half-period of the plasma. The behaviour and development of the pulses during one period of applied voltage depends on a number of parameters: voltage amplitude [1], frequency [2], gas flow rate [3] and electrode configuration [4].

Several pulses have been reported to occur during one period in a DBD-like jet [5] and inside a capillary [6]. The repetition of pulses depends on the experimental parameters, e.g. applied voltage, flow rate and electrode configuration. In a single electrode configuration jet with an additional plane electrode outside the tube, it was shown that the mode of operation of the jet depends mainly on the applied voltage amplitude and three modes were identified: chaotic, bullet and continuous mode [7].

This study was aimed on characterising a single electrode kHz plasma jet in a 500 µm tube and outside in the He plasma jet by recording the current-voltage characteristics and optical emission with a photomultiplier tube (PMT).

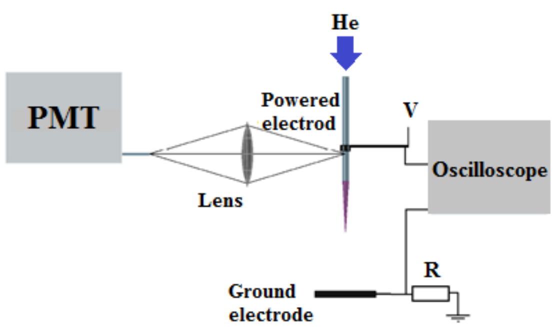

Figure 1. Experimental set-up.

In the first part of the work the transition voltages from single pulse to multi pulse mode was determined. In the second part of the work, the evolution of the ionization wave was investigated by recording the shape of the current pulse and correlating it with the development of light emission along the tube.

2. Experimental and results

2.1. Experimental set-up

The configuration of experimental setup used for the investigation of plasma jet is shown in figure 1. It is similar to that of our previous study [8] with the addition of a grounded electrode downstream from the high voltage electrode. Quartz tube with inner diameter of 500 µm and wall thickness of 10 µm was used in the experiments. High voltage electrode surrounding the quartz tube was fixed at 10 mm from the tube orifice and a second, grounded plate electrode was positioned at 1 cm or 2 cm downstream from the tube orifice. The discharge was ignited with a 6 kHz frequency sinusoidal voltage with amplitude varying from 6- 20 kV.

The applied voltage and the temporal current and optical emission were all recorded with a Tektronix TDS-540B oscilloscope. The voltage was measured with a capacitive voltage divider, and 1:10 Tektronix P6139A probe. Current was determined from the voltage drop on a resistor *R* (1.3 kΩ). Optical emission from the plasma was collected with an optical lens system (focal length of 60mm, magnification of 1:1) with the spatial resolution of 1mm and projected onto an optical fibre coupled with a PMT 1P28A (200nm< λ <600nm) similarly as in a previous experiment [9].

Two different types of measurements were carried out with the setup. The number of current

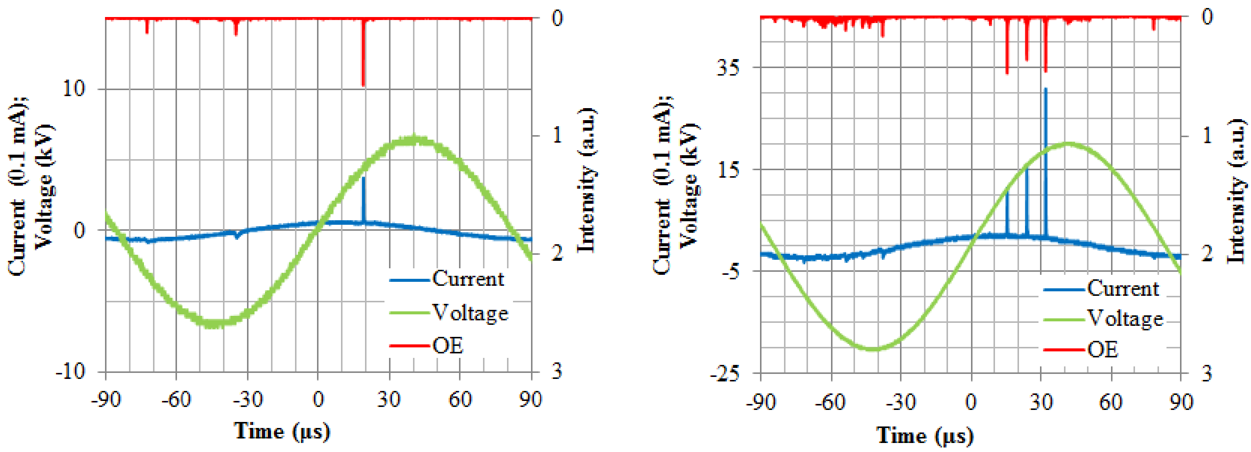

Figure 2. Applied voltage waveform, observed current and optical emission pulses for a 500 µm tube at He flow rate of 100 sccm at (a) 7 kV and (b) 20.5 kV voltage amplitude. The inter-electrode distance was 3 cm. Optical emission was registered 5 mm downstream of the high-voltage electrode.

pulses during one half-period of applied voltage was determined from the recordings of one period of applied voltage. During these measurements, optical emission was collected 5 mm downstream from the powered electrode. The development of a certain plasma plume was determined by recording the voltage, current and light emission during single current pulses. The trigger levels were set to obtain the current signal in certain amplitude range. The light emission was obtained along the axis of the tube and He jet in steps of 1 mm to follow the development of plasma front.

The plasma bullet velocity was calculated from the time delay difference of radiation in different positions along the tube axis and outside in the He jet during the positive half-period.

2.2. Effect of applied voltage

Figure 2 depicts the current and optical emission pulses registered during one period of the applied voltage at a He flow rate of 100 sccm and applied

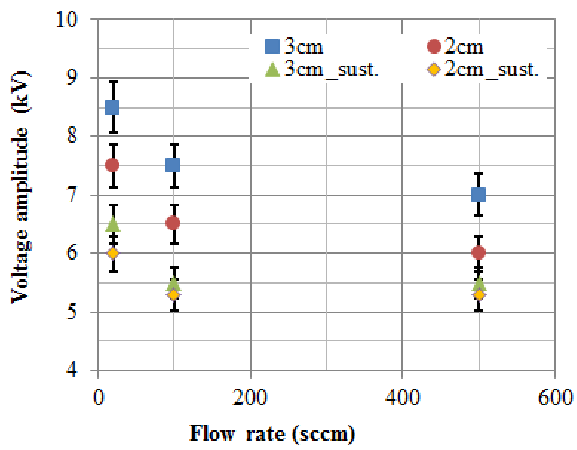

Figure 3. The minimum applied voltage amplitude at which at least 2 pulses were detected and the sustaining voltage during the positive half-cycle as a function of He gas flow rate for electrode separation of 2 and 3 cm.

voltage amplitude of 7 kV (a) and 20.5 kV (b). The number of pulses produced during one half-period depended mainly on the applied voltage. At 7 kV there was only one pulse detectable during the positive half-period of the applied voltage (fig. 1a). At 7.5 kV second pulse started to appear and with

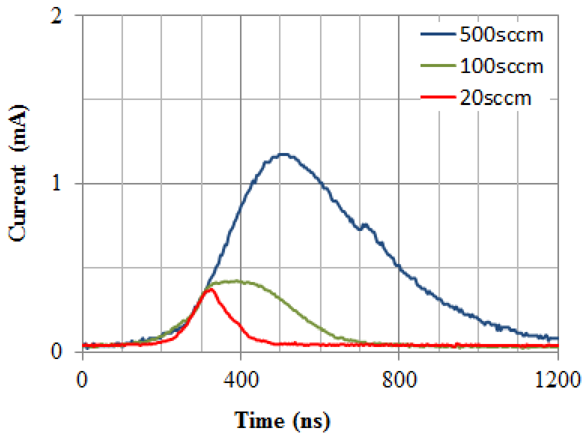

Figure 4. The shape of the current pulse in single pulse mode during the positive half-period for 20, 100 and 500 sccm.

increasing voltage there was growing number of half-periods where two pulses occurred. The number of pulses occurring during one half-period increased with voltage. At 20 kV up to 6 pulses during the positive half-period and 5 pulses during the negative half-period could be counted (fig. 1b). As a note, it was not possible to observe only one pulse for negative voltage polarity.

In figure 3 the minimum voltage at which two pulses occurred on every positive half-cycle is shown. It further illustrates that two pulses appeared at lower voltage with the electrode distance of 2 cm than in case of 3 cm. The effect of higher flow rate was the decrease of the voltage at which two pulses

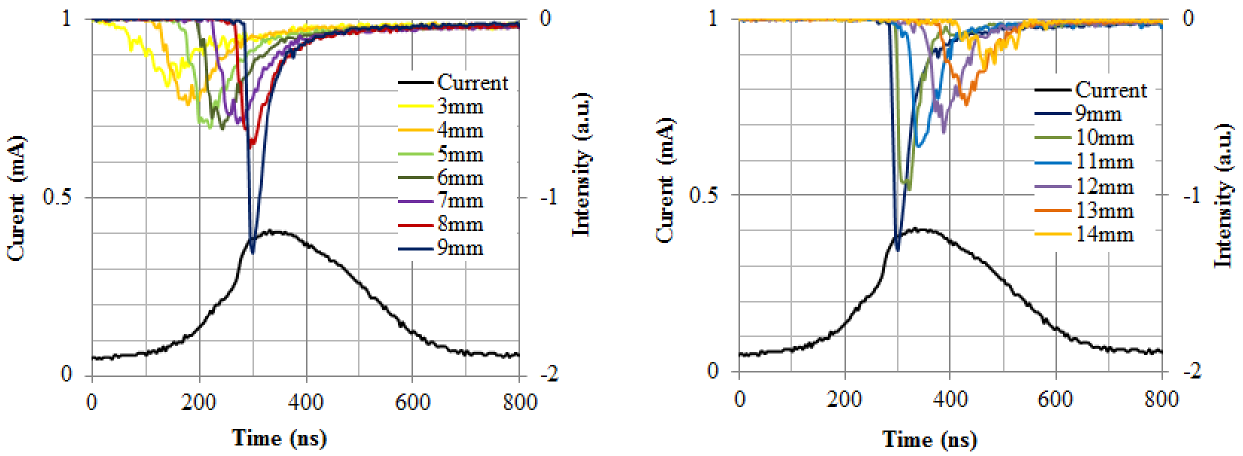

Figure 5. Current registered during single plasma pulse and optical emission recorded at different axial positions inside the microtube and outside in the He gas jet: 3- 9 mm (left) and 9- 14 mm (right). The applied voltage amplitude was 7 kV, He flow rate was 100 sccm and inter-electrode separation was 3 cm.

appeared. In addition, the minimum voltage where the plasma could be sustained is shown on figure 2 to demonstrate the narrow voltage region where only one pulse per half cycle was observed.

2.3. The propagation of the plasma plume

The shape of the first current pulses during positive half-period is shown in figure 4 for three flow rates (20, 100 and 500 sccm). These pulses were registered at 7 kV where only single pulse occurred. It was confirmed that at higher voltages where several pulses occurred during one half-period, the propagation of first pulses was essentially the same. The shape of the first current pulse at each half-cycle (both positive and negative) had good reproducibility. The full width at half maximum was in range of 100- 500 ns depending on the flow rate. At the beginning of the current pulse, there was a slow but increasing growth of current and most of the current rise occurred between 200-300 ns. This initial increase of the current was similar to all flow rates. With increasing flow rate, the currents continued to rise for longer time which resulted in higher maximum values and longer pulse duration. After reaching the maximum value, the current started to slowly decrease. Similar behaviour of the current pulse was detected when grounded electrode was at the distance of 2 cm. This suggests that the grounded electrode did not influence the development of ionization wave at these conditions.

The shape of the current pulse at 100 sccm flow rate and 7kV voltage together with the optical emission pulses registered at various positions downstream from the powered electrode (0 mm) for the single-pulse regime for positions 3- 9 mm (left) and 9- 14 mm (right) is shown in figure 5.

For the first pulse of one positive half-period, it was possible to follow the development of the ionization wave (optical emission) along the length of the tube and a few millimetres outside. In the first 1- 2 mm downstream from the powered electrode, the light signal was noisy and the front of the emission pulse was ill-defined. In addition, during the first few millimetres the emission pulse had a long onset of about 300 ns before a steep rise in optical emission. The point of the steep rise is taken as the start of the plasma plume. At 3-4 mm from the electrode the emission pulse obtained a clear front with a sharp well-defined onset. Further away from the electrode there was an increasing delay of the appearance of this wave front while its rise became steeper. Regardless of the flow rate, the maximum intensity of the emission increased along the tube until reaching the tube opening. Outside from the tube, the emission started to decrease whereas the distance where the emission diminished increased together with the flow rate. The current on the other hand started to decrease after the emission was diminished.

At applied voltage where multiple pulses occurred during one half-period, the formation and propagation of subsequent pulses was seen to be different. The emission first appeared at the tube orifice and the ionization front then propagated downstream in the He jet and upstream towards the powered electrode.

2.4. Plasma propagation velocity

The sharp front and position dependent delay of optical emission allowed the measurement of the velocity of wave. The propagation distance of the plasma plume as a function of time during the positive half-cycle are plotted on figure 6 (first pulse of a half-period) and figure 7 (subsequent pulses).

For the first pulses of a half-period, the highest velocity was achieved at the tube orifice. Outside from the tube, the velocity of the wave decreased together with the emission intensity. The propagation of the plasma front was clearly visible starting from 3 mm downstream of the powered

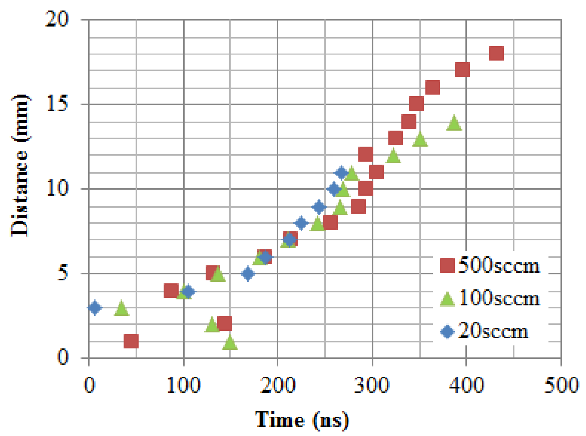

Figure 6. Propagation of plasma plume in the single pulse mode (7 kV) during the positive half-period for different He flow rates as a function of time. Electrode separation was 3 cm.

electrode. The velocity of ionization wave inside the tube (positions 4- 8mm) is 30, 28 and 24 km/s for 20, 100 and 500 sccm respectively. At the tube outlet a peak velocity of over 100 km/s was observed for flow rates of 100 and 500 sccm. As the plasma propagated into the ambient air it slowed down to 30 km/s in the He gas jet for the higher He flow rates while at 20 sccm the flow rate was too low to produce a visible plasma jet outside the tube.

The velocities of the ionization waves for subsequent pulses of same half-period were higher than for the first pulses: 160 km/s in the He gas jet and 120 km/s inside the quartz tube.

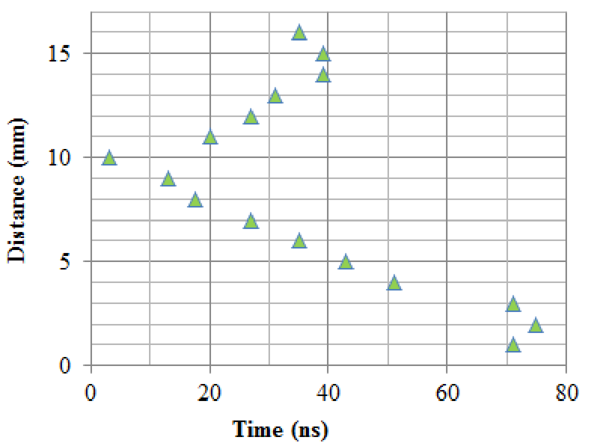

Figure 7. The subsequent plasma plume evolution in multi-pulse mode (20.5 kV) during the positive half-period He flow rate of 100sccm as a function of time. Electrode separation was 3 cm.

3. Conclusions

The number of plasma pulses occurring during one half-period of applied sinusoidal voltage depended on the voltage amplitude. At low applied voltage only one pulse was observed during positive half-period while at higher voltages up to 6 pulses were detected in one half-period.

The propagation of the plasma plume was correlated with the pulse current by recording optical emission along the tube axis. The first pulse during one half-cycle started near the high-voltage electrode and moved continuously towards the tube orifice and further to the ambient air. Subsequent pulses started at the tube orifice and moved at two directions.

The velocity of the propagating plasma was deduced from the difference in the time delay between the current pulse onset and the emission onset at varying axial positions. For the first (single) pulses, the velocity inside the tube decreased slightly with flow rate and ranged from 24- 30 km/s, while outside of the tube the velocity was 30 km/s. Velocity of subsequent pulses during same half-period was as high as 120 km/s inside the quartz tube and directed towards the powered electrode while outside in the He jet the velocity was 160 km/s.

4. References

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