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Matching a (sub)nanosecond pulse source to a corona plasma reactor

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Abstract. In this paper we investigate the energy transfer from the pulses of a (sub)nanosecond pulse source to the plasma in a corona-plasma reactor. This energy transfer (or ‘matching’) should be as high as possible. We studied the effect of multiple parameters on matching, such as the reactor configuration, the pulse duration and amplitude and the energy density.

The pulse reflection on the reactor interface has a significant influence on matching, and should be as low as possible to transfer the most energy into the reactor. We developed a multiple-wire inner conductor for the reactor which decreases the vacuum impedance of the reactor to decrease the pulse reflection on the reactor interface while maintaining a high electric field on the wire. The results were very encouraging and showed an energy transfer efficiency of over 90 percent. The matching results further show that there is only a small effect on the matching between different wire diameters. In addition, a long reactor and a long pulse result in the best matching due to the more intense plasma that is generated in these conditions. Finally, even without the multiple-wire reactor, we are able to achieve a very good matching (over 80 percent) between our pulse source and the reactor.

1. Introduction

Transient plasmas generated by high-voltage pulses have been widely studied and used for industrial and environmental applications for more than 100 years [1, 2]. Due to the fast electrons that are generated by these non-thermal plasmas, they are very efficient in producing highly reactive radical species and energetic photons [1, 3]. These products can consequently react with, for instance, particles in gas streams (for example, pollutants, odour and dust), contamination in water, biological tissue, and material surfaces [4, 1].

The focus of our research is the use of (sub)nanosecond pulsed power technology to generate transient plasma for air-purification applications. We know from literature that these very short pulses can be beneficial to plasma-processing applications [5, 6, 7, 8, 9]. However, when the pulse duration of the applied pulses becomes short (nanoseconds with sub-nanosecond rise time), maximising the energy transfer of the pulse source to the plasma load — generally called ‘matching’ — becomes a challenge. In this regime a corona-plasma reactor behaves as a transmission line and part of the applied high-voltage pulse will be reflected back to the pulse source. Therefore, this part of the pulse energy is lost and will not contribute to the initial plasma process. In this paper we investigate matching of a pulse source to a corona-plasma reactor in detail. In particular we want to know: what is the reactor configuration that results in the best energy transfer efficiency?

1.1. Plasma load

An energy transfer efficiency of 100 percent from the pulse source to the plasma is only possible if the plasma is a perfectly matched load (if the output impedance of pulse source is equal to the impedance of plasma and the interfacing transmission line). However, the reality is much more complex. When a voltage pulse with a long rise time is first applied to a reactor, the reactor behaves predominantly as a capacitor (and only slightly as an inductor due to the long rise time). During the charging of this capacitor by the voltage pulse, streamers can initiate. Since the streamers have a resistive character, the load of the high-voltage pulse now becomes part dissipative. However, the resistive part of the streamers is only between the high-voltage wire and the streamer head. Between the streamer head and the reactor wall only a displacement current can flow. The streamer can therefore be seen as a time-varying resistor with a time-varying capacitor in series. These first streamers are the primary streamers. When the streamers bridge the gap, they form a predominantly resistive load and reach the secondary streamer phase.

The result of this streamer development in time is that the plasma load undergoes three phases in which it is successively 1) mainly capacitive, 2) partly capacitive, slightly inductive and partly resistive and 3) mainly resistive. Therefore, the plasma load is a very dynamic and complex load. Achieving perfect matching in the primary streamer phase (partly capacitive and partly resistive) is nearly impossible. Unfortunately (from

a matching point of view), with our very short pulses we expect that the streamers will mainly exist in the primary streamer phase. Furthermore, our voltage pulse has a short rise time, whereas in the analysis above we assumed a pulse with a long rise time. With a short-rise time pulse the inductance of the reactor becomes important as well and the reactor will act as a transmission line. Therefore, reflections at the reactor interface and in the reactor become significant and the voltage in the reactor will change on short time-scales and might be very different at different positions in the reactor. Therefore, matching the pulses of our nanosecond pulse source to a corona-plasma reactor becomes very challenging.

1.2. Previous matching studies

At Eindhoven University of Technology, pulsed corona plasmas for air purification have already been studied for a long time [10, 11, 12, 13, 14, 15]. Naturally, matching the pulse source to the plasma was one of the topics that some of these studies treated. More specifically the conclusions of Yan [12] and Winands [14] on matching which are relevant for our work are listed below.

- Applied voltage: a higher voltage results in better matching. This effect was attributed to the generation of more parallel streamers at high voltages.
- Pulse duration: longer pulses match better than short pulses. For short pulses the streamers consist only of primary streamers, whereas for longer pulses secondary streamers can form as well. When a plasma consists of secondary streamers the corona-plasma reactor behaves as a resistive load and therefore the matching can become very high.
- A plasma with positive streamers can be matched better to the pulse source than a plasma with negative streamers.

These conclusions once more emphasise the challenge of matching a very short pulse to a corona-plasma reactor.

Previous studies into the energy transfer of a nanosecond pulse source to a corona-plasma reactor focused on changing a number of reactor and source parameters such as reactor length, reactor configuration, pulse amplitude, pulse polarity, pulse duration, pulse rise time, pulse source output impedance and DC bias voltage [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. The results show a number of good matching methods. Naturally, changing the output impedance of the pulse source to the plasma load works well [23], but this is not always practical. Changing the plasma load itself would often be a more flexible solution. Changing the plasma load by changing reactor parameters such as length and electrode spacing works well in some instances [26, 25]. Another practical method of providing good matching is changing the plasma load by changing the parameters of the high-voltage pulse that generates the plasma, like we already showed in the conclusions of Yan and Winands. For instance, a short rise time and a high amplitude generate a low-impedance streamer plasma, which matches better to the

source [20, 21, 26]. What all these results show above all is that matching is a complex process, which depends greatly on the used setups. Only some common conclusions can be found, like the increased matching with voltage (which increases the electric field).

One of the matching-tools that Yan en Winands used (as well as other researchers) is the use of a DC bias voltage [16, 17, 18, 19, 22, 26]. This DC voltage is superimposed on the pulsed voltage and has some significant advantages. First, a DC bias increases the electric field in the corona-plasma reactor and consequently increases the matching. Second, this DC bias can generally be added at a low cost and therefore offers a cheap method to vary the plasma behaviour and last, the DC bias offers a simple way to add energy to the plasma without the complexities of switching a high current and a high voltage. The downside to the DC-bias method is that the DC voltage has to be decoupled from the pulse voltage by a decoupling network, which can have an adverse effect on the properties of the pulse. In [27] we introduce a method to add a DC bias voltage to the pulse voltage of a nanosecond pulse source without these adverse effects. These experiments were performed with the 5-ns triaxial Blumlein source developed by Wang *et al.* [6, 28] and showed an initial matching that improved by a factor of 1.2–2.

The parameter that commonly results in higher matching is a high E/n value (where E is the applied electric field and n is the gas density) in the plasma reactor. We already mentioned that increasing E (with the pulse voltage and a superimposed DC voltage) increases matching. The gas density can be varied by pressure and temperature. For instance, previous studies showed that a higher temperature (lower n) increases the dissipated plasma energy [29, 30, 31]. Previously, we investigated the dependency of the matching and streamer propagation when the E/n value was changed by changing the pressure and the temperature. We showed that a higher E/n value (low pressure or high temperature) increases the energy consumption of the plasma and therefore leads to a better matching [32].

In this paper, we perform our experiments at room temperature and at atmospheric pressure. Therefore the only pulse parameter to vary E/n is the voltage in the reactor. Besides this matching parameter, the matching in our experiments will depend on the reactor configuration, as this configuration determines parameters like the initial transmission-line impedance and the electric field at the high-voltage wire. Due to the very short rise time of our pulses, we also have to consider pulse reflections on the reactor interface and in the reactor, because these reflections determine the voltage locally in the reactor and therefore influence the streamers.

1.3. Paper organisation

In this paper we investigate a number of corona-plasma reactor parameters to obtain a good transfer efficiency. We will use a coaxial corona-plasma reactor to obtain a large volume plasma required for effective chemical processing of gasses. The parameters we vary to study the effects on matching are: pulse voltage amplitude, voltage polarity, pulse duration, reactor inner-wire diameter, reactor inner-wire configuration, reactor

length, and energy density.

With electrical measurements we are able to measure the pulse energy and the plasma energy and with ozone measurements we measure ozone concentrations. We measure these ozone concentrations to investigate whether changes in matching also reflect in the ozone yield of the plasma. This ozone yield indicates how efficiently the plasma energy is utilised to generate reactive oxygen species (which then form the long-lifetime component ozone). The ozone yield is generally used as a monitor for plasma performance, because it indicates how efficiently energy is used to form reactive species in the plasma [33, 34, 35, 36, 37, 38, 5, 28].

In the next section we elaborate on the experimental setup and procedure to measure energies, ozone and how to determine the matching. The three subsequent sections present the matching and ozone yield results for when we vary the reactor wire diameter, the reactor length and pulse duration and the energy density respectively. These sections are followed by Section 6 which presents a multiple-wire reactor and Section 7 in which we discuss the observations on the difference between the matching between negative and positive pulses. Finally, we present the summary and conclusions of this paper.

2. Experimental setup and procedure

2.1. Nanosecond pulse source

The nanosecond pulse source we used for the experiments in this paper was recently developed at Eindhoven University of Technology. It is a single line pulse source, consisting of a pulse forming line that is charged by a microsecond pulse charger and is subsequently discharged by an oil spark gap. The full design of this system is described in [39, 40, 41, 42]. The output pulses from this nanosecond pulse source ($50\ \Omega$ output impedance) have an adjustable amplitude of 3–50 kV (positive and negative), an adjustable pulse duration of 0.5–10 ns and a rise time of less than 200 ps. Figure 1 shows some example waveforms.

With a pulse-charger controller and a DC power supply we control the pulse charger and therefore the charging of the nanosecond pulse source. The pulse repetition rate and the charge time of the IGBTs of the pulse charger are controlled by the pulse charger controller in an EMC cabinet. The output voltage of the nanosecond pulse source is controlled by changing the DC charge voltages and the gap distance of the oil spark gap in the nanosecond pulse source. In general, for all measurements we set the DC charge voltage and adjust the spark gap accordingly. The DC charge voltages that we used in the experiments of this paper were 200 V, 300 V, 400 V, 500 V and 600 V. Furthermore, we always perform experiments with both positive and negative pulse polarities. The total experimental setup is further presented in Section 2.6.

Figure 1: Example waveforms of the nanosecond pulse source (both from [42]). (a) A 8-ns pulse with different amplitudes. (b) The variation in pulse duration.

2.2. Corona-plasma reactor

The nanosecond pulse source is connected to a SA24272[‡] cable to transmit the output pulses to the load. It is a 28-m long cable which has the main purpose (besides transmitting the pulse to the load) of delaying the pulse for synchronisation with diagnostics such as fast intensified cameras.

The SA24272 cable has an impedance of $50\,\Omega$ and is therefore matched to the pulse source. As a result, no reflections of the pulse occur on the interface between the pulse source and the cable. Therefore, from an impedance point of view, the cable is an extension of the pulse source.

Figure 2 shows the corona-plasma reactor we designed and connected at the other end of the SA24272 cable. It is a wire-cylinder reactor of length l_r . In our experiments we will use three different reactor lengths: 0.25 m, 0.50 m and 1.0 m. A thin wire of diameter d_i is strung between two removable heads as the high-voltage wire electrode of the reactor. We will use four different wire diameters: 0.3 mm, 0.5 mm, 0.7 mm and 1.0 mm. The Plexiglass window at the end of the reactor enables visual inspection of the plasma and a gas inlet and a gas outlet offers the possibility to flow a gas through the reactor.

The SA24272 cable is attached to the reactor via a custom-made cable coupler. It is oil-filled and internally supported by a PTFE part for high-voltage insulation and allows the cable to be connected to the reactor with a minimum of impedance mismatch. An oil reservoir (not shown) is mounted on top of the cable coupler to ensure that the cavity inside the coupler remains oil-filled.

[‡] The SA24272 cable was manufactured by Suhner (later Huber-Suhner). It was used at Eindhoven University of Technology at the end of the 1980s and the beginning of the 1990s for low-loss signal transport [43, 44]. A technical data sheet of the SA24272 cable is included as an appendix in [43]. A comparable cable in today's market would be the LMR-1700 cable from Times Microwave.

Figure 2: The corona-plasma reactor (the length of the reactor has been shortened for display purposes). On the right side of the sketch, the SA24272 cable is connected to the a cable coupler, much like the connection of the SA24272 cable to the nanosecond pulse source. The cable coupler is oil-filled for high voltage insulation. An oil reservoir (not shown) is connected on top of the coupler. The inner conductor of the cable is connected to a stainless-steel electrode with a removable head. Between the interface of the coupler and the reactor we placed a PTFE insulator and the reactor is connected to the cable coupler. The wire electrode is strung between the removable heads of the electrode and the tightening mechanism and is tightened by pulling the tightening mechanism outwards with a nut on a threaded body. Furthermore, the reactor has a gas inlet and a gas inlet for the process gas.

Figure 3: The sensor configuration (from [45]). The sensor body at the pulse source side has only one D-dot and B-dot sensor. The two sensor bodies near the corona-plasma reactor have two D-dot and two B-dot sensors.

2.3. Energy measurements

Energy measurements are crucial for our matching investigation, because to measure this matching we need to measure the energy that is consumed by the plasma, as well as the energy that was supplied by the nanosecond pulse source. For these energy measurements we developed D-dot sensors and B-dot sensors, which are capacitively and inductively coupled sensors and are presented in [45]. With these sensors we can measure the voltage and the current of the pulses. Their positions are shown in Fig. 3.

With sensors D_5 and B_5 we could measure the energy from the pulse source, but then we would only have two channels of the 4-channel LeCroy WavePro 7300A oscilloscope left for the plasma energy measurements and we specifically integrated two sensors of each type in each of the load-side sensor bodies to decrease the influence of interference on our measurements. Likewise, with sensors D_1 , D_2 , B_1 and B_2 we could measure

Figure 4: An example energy measurement. (a) The voltage and current measured by sensors D_3 , D_4 , B_3 and B_4 . In this figure we can distinguish three pulses: the pulse that the nanosecond pulse generates and is transmitted over the SA24272 cable (incident pulse), the pulse that is reflected on the interface to the corona-plasma reactor (reflected pulse) and the pulse that is transmitted into the reactor, travels up and down the reactor and is then transmitted back into the cable (reflected pulse through reactor). (b) The waveforms that are measured after the pulse and its reflections have reflected back onto the pulse source and are reapplied to the reactor (2nd pulse). (c) The corresponding power of the waveforms of (a) and (b) (the waveforms are shifted about 230 ns for display purposes) and finally (d) shows the energies. The total applied energy to the reactor is indicated with E_{tot} , the energy that was consumed by the reactor as E_1 and the energy associated with the reapplied pulse as E_2 .

the energy that is dissipated by the plasma, but have no channels left to measure the supplied energy by the nanosecond pulse source. The solution to this problem is the use of sensors D_3 , D_4 , B_3 and B_4 . We purposely situated these sensors at a distance from the reactor such that we can measure the incoming pulse as it arrives and then measure the reflected pulse from the reactor with enough time interval between these pulses (even at the 10-ns pulse duration setting of the pulse source). In this way we can calculate the plasma energy as the incoming energy minus the reflected energy.

Figure 4 shows an example of an energy measurement, starting with the measured voltage and current with sensors D₃–D₄ and B₃–B₄ respectively in Fig. 4a. By using this sensor position we can first see the complete 5-ns incident pulse from the pulse source passing (notice that this would still be the case for a 10-ns pulse). Figures 4c and 4d show the corresponding power and energy calculated from these waveforms.

The power and energy are calculated from the D-dot and B-dot sensors with:

$$\text{Power}(t) = I_{B_{3-4}}(t)V_{D_{3-4}}(t). \quad (1)$$

$$\text{Energy}(t) = \int_0^t \text{Power}(\tau) d\tau. \quad (2)$$

We see that we can measure the total applied energy to the reactor E_{tot} by taking only the contribution of the first incident pulse.

When the pulse passes the sensor position it encounters the reactor and will partly reflect back to the pulse source and partly transmit into the reactor. The vacuum impedance of the gas-filled reactor Z_r is given by

$$Z_r = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} \ln \frac{d_o}{d_i}, \quad (3)$$

where μ_0 and ϵ_0 are the permeability and permittivity of vacuum respectively, d_o is the 50-mm inner diameter of the outer conductor of the reactor and d_i is the diameter of the wire electrode of the reactor. Here we assume that the reactor is a perfect coaxial structure. This reactor impedance will be higher than the cable impedance, so the reflected pulse will be positive. This is the reflected pulse as indicated in Fig. 4a.

The part of the pulse that is transmitted into the reactor propagates up and down the reactor, generating plasma, and transmits back into the SA24272 cable. This is the third, attenuated peak in Fig. 4a. It is severely attenuated and dispersed by the plasma. Part of the pulse inside the reactor will also reflect back into the reactor instead of transmitting into the SA24272 cable, but this part diminishes over time. A more detailed analysis of the reflected and transmitted waveforms inside the reactor and the cable follows Section 2.5.

If we look at Fig. 4d then we see that the reflected pulse causes as a sharp decrease in energy of the first pulse because the energy of the reflected pulse moves in the opposite direction of the incident pulse. This opposite direction is also apparent from the current in Fig. 4a. The attenuated pulse from the reactor decreases the pulse energy even more. After this time the energy is stable. The energy that is measured at this point is the energy that is ‘left’ in the reactor and is therefore the energy that was dissipated by the plasma. This energy is indicated by E_1 .

Figure 4b shows the reflected pulse after it has travelled down the SA24272 cable, reflected on the nanosecond pulse source and travelled back to the sensor position. This pulse is indicated in Fig. 4c and 4d as the second pulse. By this time it is severely attenuated and dispersed, but is still able to generate plasma if its amplitude is high enough. Figure. 4c shows that there is still significant power associated with this second pulse and Fig. 4d confirms that it still (re-)ignites the plasma. We already saw in [46]

that the reapplication of the reflected pulses from our nanosecond pulse source can reignite a plasma up to as much as the tenth reflection. However, in that experiment we only dissipated a very small amount of energy in each reflection. Here, with the larger reactor, the plasma dissipates a large amount of energy and therefore we only have to take the second pulse (the first reflection) into account. The third pulse will have a very low amplitude and dissipates a negligible amount of energy in the reactor.

The energy associated with the second pulse (that of Fig. 4b) is indicated in Fig. 4d as E_2 . Both E_1 and E_2 will be used in all the matching calculations.

We can now perform all the energy measurements with just one sensor body. This allows for the use of two D-dot sensors and B-dot sensors for all measurements. This would not have been possible with sensors D_1 , D_2 , B_1 and B_2 .

2.4. Matching definitions

To perform matching experiments we need to know how much energy was dissipated by the plasma with respect to the total applied energy. Therefore, we introduce two matching parameters: the initial matching η_i which only uses the energy of the first applied pulse and η_{tot} which also includes the energy of the first reflected pulse. They are calculated as

$$\eta_i = \frac{E_1}{E_{\text{tot}}}, \quad (4)$$

$$\eta_{\text{tot}} = \frac{E_1 + E_2}{E_{\text{tot}}}. \quad (5)$$

These matching definitions will be used in the sections on matching experiments.

2.5. Reactor impedance

In Fig. 4a we could clearly see that part of the incident pulse is reflected when it reaches the corona-plasma reactor. The amplitude of this reflected pulse is determined by the reflection coefficient of the reactor interface, which is time dependent due to the plasma. When plasma is generated in the reactor the impedance of the reactor Z_r changes. First, the plasma has the effect that the inner conductor diameter d_i in Eq. 3 increases artificially since a cloud of highly ionised plasma is generated around it. Second, the plasma consumes energy and will therefore get a more resistive character. Both of these effects result in a lower reactor impedance. Therefore, the reactor impedance (and by association the reflection coefficient) is time dependent. The reflection coefficient and transmission coefficient are then calculated as

$$R(t) = \frac{Z_r(t) - Z_{\text{cable}}}{Z_r(t) + Z_{\text{cable}}}, \quad (6)$$

$$T(t) = \frac{2Z_r(t)}{Z_r(t) + Z_{\text{cable}}}. \quad (7)$$

Figure 5: (a) The measured incident (V_i) and reflected pulse (V_r) from which the transmitted pulse (V_t) is calculated. (b) The calculated time-dependent reflection and transmission coefficients from the waveform of (a). (c) The calculated reactor impedance from the reflection coefficient of (b).

We can calculate $R(t)$ from measured waveforms such as Fig. 4a by dividing the reflected pulse by the incident pulse as

$$R(t) = \frac{V_r(t)}{V_i(t)}, \quad (8)$$

where $V_i(t)$ and $V_r(t)$ are the incident and reflected pulse respectively (here we neglected the attenuation of the pulse over the 1.7 m of SA24272 cable that separates the D-dot and B-dot sensor body from the reactor). With $R(t)$ we can now calculate $Z_r(t)$ as

$$Z_r(t) = \frac{-[1 + R(t)]Z_c}{R(t) - 1}. \quad (9)$$

We can then calculate the transmitted pulse into the reactor $V_t(t)$ as

$$V_t(t) = V_i(t)T(t). \quad (10)$$

Figure 5 shows an example of a reactor impedance measurement. In Fig. 5a we see the measured incident and reflected pulse and the calculated transmitted pulse. The results show that when $T(t)$ is larger than 1 — which it will always be when the reactor

Figure 6: The total experimental setup. A 0–800-V DC power supply controls the charge voltage of the pulse forming line of the nanosecond pulse source and the pulse charger controller engages the driver circuits of the pulse charger modules via optic fibres. The measurements with the D-dot and B-dot sensors were described in detail in [45]. A bottle of synthetic air comprises the gas supply (through a mass flow meter) for the reactor. In the gas outlet of the reactor a 30-mm path cell is used for the UV-spectrometer measurements to measure ozone concentrations.

impedance is higher than the cable impedance — the transmitted pulse amplitude is higher than the amplitude of the incident pulse. Therefore, when the matching is bad (large $R(t)$) the pulse amplitude at the beginning of the reactor is very high. However, this voltage will drop quickly when energy is dissipated in the reactor, because the associated impedance is large.

Figure 5b shows $R(t)$ and $T(t)$ for the example of Fig. 5a. Likewise, Fig. 5c shows the corresponding calculated impedance of the reactor. On the flanks of the applied pulse (before t_1 and after t_2) the coefficients are not valid. Therefore, in the remainder of this paper the reactor impedance will only be shown for the time period t_1 – t_2 . The impedance in the example drops with time, which is expected due to the plasma.

With a wire diameter of 0.5 mm and a reactor inner diameter of 50 mm the vacuum impedance of the reactor, Eq. (3) gives an impedance of around 276Ω for the reactor. Fig. 5c confirms this value as the initial impedance of the reactor.

2.6. Ozone measurements

To verify whether the matching of the pulse source has an influence on the plasma chemistry we measured ozone concentrations in the exhaust of the reactor simultaneously with all energy measurements. This allows us to calculate an ozone yield. With the addition of the ozone measurements, Fig. 6 shows the total experimental setup for the measurements of this paper.

We use synthetic air with less than 3 ppm H_2O content as the process gas in our reactor to obtain a controlled and reproducible environment in all our experiments. A mass flow meter (mfm) controls the gas flow into the reactor. In the exhaust of the reactor we placed a 30-mm optical path cell for UV absorption measurements. Optic fibres connect the path cell to a UV source and an Ocean Optics HR2000 spectrometer.

We measured the plasma-off and plasma-on spectra in the Hartley-band (230–290 nm) to obtain the ozone concentration. To minimise errors we used the absorption at 20 different wavelengths from 250–270 nm. The complete procedure is described in [14, p. 55–56].

With the measured ozone concentration C_{O_3} (in ppm) and the energies E_1 and E_2 we can define the ozone yield of the plasma G_{O_3} (in $\text{g}\cdot\text{kWh}^{-1}$) as

$$\begin{aligned} G_{O_3} &= \frac{\frac{C_{O_3}}{10^6} \times \frac{1}{V_m} \times 48 [\text{g} \cdot (\text{mole } O_3)^{-1}]}{\frac{1}{F} \times 60 f_{\text{rr}} (E_1 + E_2)} \\ &= \frac{C_{O_3} F \times 48 \times 3.6}{V_m f_{\text{rr}} (E_1 + E_2) \times 60}, \end{aligned} \quad (11)$$

where V_m is the molar volume ($24.5 \text{ L}\cdot\text{mole}^{-1}$ at room temperature), f_{rr} is the repetition rate of the pulse source and F is the gas flow (in $\text{L}\cdot\text{min}^{-1}$). The expression can be further reduced if we introduce the energy density ε (in $\text{J}\cdot\text{L}^{-1}$) as

$$\varepsilon = \frac{f_{\text{rr}} (E_1 + E_2) \times 60}{F}. \quad (12)$$

The ozone yield then becomes

$$G_{O_3} = \frac{C_{O_3} \times 48 \times 3.6}{V_m \varepsilon}. \quad (13)$$

3. Matching results and discussion: wire diameter

In this section and Section 4, 5 and 6 we experimentally investigate the matching of the pulses from the nanosecond pulse source to the corona-plasma reactor for different reactor parameters and experimental settings.

The first reactor parameter we investigate is the diameter of the wire electrode d_i in the reactor. If we look at Eq. 3 we see that if we want to get the impedance of the reactor as close as possible to the impedance of the SA24272 cable, d_i should be as large as possible. For a perfect $50\text{-}\Omega$ impedance d_i should be 21.7 mm . However, if we look at the electric field at the wire electrode it follows that d_i should be as small as possible to obtain the highest electric field:

$$E_{\text{max}} = \frac{2V_0}{d_i \ln \frac{d_o}{d_i}}, \quad (14)$$

where V_0 is the amplitude of the applied voltage pulse. If the electric field at the wire is high, E/n is higher and the plasma will consequently dissipate more energy, which increases the matching.

Therefore a trade-off exists. To get the pulse from the nanosecond pulse source to propagate into the reactor d_i has to be large to lower Z_r , but then almost no plasma will develop because E_{max} is too low. Likewise, if we have a small d_i , E_{max} can be high,

Figure 7: Energy measurements showing the total pulse energy (E_{tot}), the energy dissipated in first pulse (E_1) and the energy dissipated in the first pulse reflection 230 ns later (E_2) for different applied voltage settings and different wire diameters for (a) positive voltages and (b) negative voltages. Experimental settings: $f_{\text{rr}} = 100$ Hz, $\Delta t = 5$ ns, $l_r = 1.0$ m and $F = 5.0$ L·min $^{-1}$.

but the incoming pulse is transmitted poorly into the reactor because of the high Z_r that a small d_i ensures. Both a low Z_r (large d_i) and a high E_{max} (small d_i) will increase matching, so d_i has to be chosen such that the matching has an optimum.

3.1. Energy measurements

3.1.1. Experimental setup and method In our experiments we use four values of d_i to investigate which results in the best matching: 0.3 mm, 0.5 mm, 0.7 mm and 1.0 mm. For these experiments we use a reactor length l_r of 1 m, a flow of synthetic air through the reactor F of 5.0 L·min $^{-1}$, a pulse duration Δt of 5 ns and a pulse repetition rate f_{rr} of 100 Hz. We then measure the energies E_{tot} , E_1 and E_2 for five spark-gap settings of the pulse source. Due to the jitter on the spark-gap switching, the output voltage will vary from pulse to pulse for each spark-gap setting and therefore we are able to measure energies in the range of 5–40 kV for the five spark-gap settings [41]. The standard deviation on the energy measurements for E_{tot} , E_1 and E_2 is around 3%, 10–15% and 20–30% respectively. This standard deviation is the result of the noise on the individual D-dot and B-dot measurements and translate into an error on individual energy measurements. Furthermore, a streamer plasma is a stochastic process, which results in a natural standard deviation on plasma energy measurements. This explains why the standard deviation on the plasma energies E_1 and E_2 are larger than the standard deviation on the applied energy E_{tot} . By taking 250 measurements for each spark-gap setting we are able to make use of voltage binning: we divide the voltage range in steps of several kV and for each of these bins we display the mean value of the measurements (voltage and energy) in this bin. The results of the wire-diameter measurement is then shown in Fig. 7.

Figure 8: The matching of the pulses to the corona-plasma reactor calculated with the data from Fig. 7 for (a) positive voltages and (b) negative voltages. The matching is calculated with E_1 (solid line) and with $E_1 + E_2$ (dashed line) respectively.

3.1.2. Results The results of Fig. 7 show that there is no large difference in plasma dissipation between the different wire diameters. To clarify this we have to look at the matching parameters.

With the matching definitions of Eq. 4 and 5 we can generate Fig. 8. Obviously, η_{tot} is higher than η_i , but what is also interesting is that the matching increases with the applied voltage. This is in accordance with for instance [47, 24, 48, 26, 25] and can be explained by the fact that at higher voltages a more intense plasma is generated, which increases the energy consumption of the plasma, but also decreases the impedance of the reactor. Both these phenomena result in a better matching. Therefore, the conclusion of Yan [12] and Winands [14] that a higher voltage results in better matching also applies to our reactor and furthermore confirm that a high E/n value increases matching.

When we compare the different wire diameters the result is that there is no significant difference in matching between the different diameters. Only $d_i = 0.3$ mm seems to underperform for both polarities. A striking difference between the matching results of both pulse polarities is that negative pulses match better on average than positive pulses. This is the opposite of what most researchers find and also runs contrary to the conclusion of Winands, who found that positive pulses match better. We explain this result in more detail in Section 7.

The wire resulting in good overall similar matching for both polarities is the 0.5-mm wire. It will be this wire that we will use in the remainder of the experiments.

Figures 9 and 10 show an additional display of the measurements. First, Fig. 9 shows the normalised voltage for five different voltage amplitudes V_p when the 0.5-mm wire was used. It shows that the amplitude of the reflected pulse (refer to Fig. 4a for the terminology) decreases in time when a higher voltage is applied. The reason for this effect is that during the application of the incident pulse on the reactor, plasma is generated. This decreases the reactor impedance while the pulse is being applied.

Figure 9: Normalised output voltage as a function of the pulse voltage. Experimental settings: $f_{\text{rr}} = 100 \text{ Hz}$, $\Delta t = 5 \text{ ns}$, $d_i = 0.5 \text{ mm}$, $l_r = 1.0 \text{ m}$ and $F = 5.0 \text{ L} \cdot \text{min}^{-1}$.

Figure 10: Normalised output voltage as a function of wire diameter. Experimental settings: $f_{\text{rr}} = 100 \text{ Hz}$, $\Delta t = 5 \text{ ns}$, $V_{\text{pulse}} = 33 \text{ kV}$, $l_r = 1.0 \text{ m}$ and $F = 5.0 \text{ L} \cdot \text{min}^{-1}$.

Figure 11: Reactor impedance as a function of the pulse voltage calculated with the waveforms of Fig. 9.

Figure 12: Reactor impedance as a function of wire diameter calculated with the waveforms of Fig. 10.

This results in a lower value of the reflection coefficient and therefore in a larger part of the pulse being transmitted into the reactor and a lower part of the pulse being reflected back towards the pulse source. Figure 11 confirms that the reactor impedance indeed decreases when the applied voltage increases and when time passes. We already mentioned earlier that this is one of the reasons a higher applied voltage increases matching (besides the higher E/n in the reactor). Another observation from Fig. 9 is that the reflected pulse through the reactor has a lower amplitude and that it is longer for a higher applied voltage. The reason for this effect is that more energy is consumed by the plasma at higher voltages, which increases the attenuation and dispersion of the pulse in the reactor.

Second, Fig. 10 shows the normalised voltage for the 33-kV measurements of the different wire diameters. Earlier we stated that a larger d_i would result in a lower reflection coefficient and this is demonstrated in Fig. 10 by the slightly lower amplitude of the reflected pulse for $d_i = 1.0\text{ mm}$. This amplitude increases as d_i decreases. On the other hand, the 0.3-mm wire was able to consume more energy in the plasma, which results in a slightly lower and longer reflected pulse trough the reactor. The amplitude of the reflected pulse through the reactor increases with d_i , indicating that a plasma with larger wire diameter is unable to consume as much of the energy that is transmitted into the reactor.

Figure 12 confirms the lower reactor impedance for thicker wires. The initial values of the reactor impedances correspond well with the theoretical values calculated with Eq. 3; for $d_i = 0.3\text{ mm}$, 0.5 mm , 0.7 mm and 1.0 mm the calculated impedances are $307\text{ }\Omega$, $276\text{ }\Omega$, $256\text{ }\Omega$ and $235\text{ }\Omega$ respectively.

Figures 10 and 12 confirm all the assumptions we made about the effect of d_i . However, in practice, the difference in matching between the different wires is very small.

Figure 13: Ozone concentrations which were measured simultaneously with the energy measurements of Fig. 7 for (a) positive voltages and (b) negative voltages.

Figure 14: The ozone yield calculated from the results of the energy measurements of Fig. 7 and the ozone measurements of Fig. 13 for (a) positive voltages and (b) negative voltages.

3.2. Ozone measurements

We measured ozone concentrations generated by the plasma simultaneously with the energy measurements. Figure 13 shows the results for each setting. Aside from the lower ozone concentrations for the 0.3-mm wire, all results are very similar.

The ozone measurements have a very low time resolution (several spectra per second) as compared to the energy measurements. Therefore we can only show average values of the ozone yield. Figure 14 shows the ozone yields. The yields were calculated with Eq. 11. The results show that the ozone yields when different wire diameters were used vary very little and that the only conclusion that can be drawn is that the plasma generated with positive pulses perform slightly better than the plasmas generated with negative pulses. This last observation is not consistent with the results of Winands who found that a negative pulse results in a higher ozone production [14]. Another

inconsistency with other studies is that the ozone yield appears to increase slightly with the applied voltage in our measurements.

A final observation from the ozone yield results is that the yields are high for a corona plasma. This shows that very short pulses are efficient for ozone production. Other studies with corona plasma reactors report efficiencies in the range of 15–100 g·kWh⁻¹ [33, 34, 37, 38], with the exception of Wang *et al.* who report a very high yield of over 200 g·kWh⁻¹ [28]. We will use the ozone-yield results in the remainder of this paper as a comparison between different reactor configurations.

4. Matching results and discussion: reactor length

With the inner-wire diameter of the reactor chosen as 0.5 mm, we now turn our attention to the length of the reactor. It was already shown in by Namihira *et al.* and Matsumoto *et al.* in [49] and [25] respectively that the matching of a nanosecond pulse source to a reactor improves as the reactor becomes longer. However, in that study, a 7-ns FWHM (Full Width Half Max) pulse with a rise- and fall time of around 3 ns was used. In our experiments we can use pulses of 0.5 ns to 10 ns duration and therefore a longer reactor might not always result in the best matching. Also, our pulses have a rise- and fall time that are an order of magnitude shorter than the pulses from the triaxial Blumlein line pulse source used in [49] and [25].

The length l_p over which a pulse with duration Δt is present in the reactor (in air) is given by

$$l_p = c\Delta t, \quad (15)$$

where c is the speed of light in vacuum. Therefore, a 1-ns pulse is only 0.3 m ‘long’ in air, which is shorter than our longest reactor. The propagation of such a pulse through a long reactor is a complex phenomenon and is presented in detail in [50, Chapter 7].

For the experiments in this section we used all combinations of three different pulse durations (1, 5 and 9 ns) and three different reactor lengths (0.25, 0.50 and 1.0 m). Furthermore, each experiment was again performed at five different DC charge voltages and for both positive and negative pulse polarities at a repetition rate of 100 Hz and with a gas flow rate of 5 L·min⁻¹.

4.1. Energy measurements

Figure 15 shows the results of the energy measurements. An overall observation is that the matching significantly decreases when the reactor length decreases. The reason for this decrease is that the pulse is present in the reactor for a shorter time in a short reactor and consequently is unable to dissipate the same amount of energy as in longer reactor. This effect is observed for all three pulse durations. This indicates that there is no optimal reactor length for each pulse duration in the range of reactor lengths we investigated. Moreover, it means that our results are in agreement with the results with the lower-rise-rate pulse that were achieved in [49] and [25].

Figure 15: The matching of the pulses to the corona-plasma reactor (using E_1 and E_2) for different reactor lengths and pulse durations for (a) positive voltages and (b) negative voltages. Experimental settings: $f_{rr} = 100$ Hz, $d_i = 0.5$ mm and $F = 5.0$ L·min⁻¹.

A second observation is that longer pulses appear to match better to the reactor. This effect is independent of the reactor length. However, the effect is stronger for longer reactor lengths and also appears to be somewhat stronger for positive pulse voltages. This is an indication that very short pulses are unable to generate plasma effectively; they are too short at these voltages. If we would be able to go to much higher voltages shorter pulses might also be able to match well, but we are limited by arc discharges that occur at the end of the reactor at high voltages. The arc discharges occur at the end of the reactor because at this position the pulse reflects and because the pulses have such a short rise time the voltage at the end of the reactor will almost double in amplitude.

The effect that longer pulses match better to the reactor was already observed by Winands [14]. He attributed this effect to the very resistive nature of secondary streamers, which are present for a longer time for longer pulses. In [50] we saw that we mainly have primary streamers in our reactor for most conditions. Therefore, there is no significant contribution of secondary streamers in our matching results. In our case, the streamers dissipate the energy while propagating through the reactor. For longer pulses, the streamers propagate for a longer time and reach further into the reactor, thereby dissipating more energy than when short pulses are used.

If we look at the 5-ns matching results, we see that negative pulses again match slightly better than positive pulses. However, for the 9-ns pulses the positive pulses appear to match better. The length of the reactor has no great effect on the difference between negative and positive pulses. We address this observation in more detail in Section 7.

Figure 16: The ozone yield calculated from ozone measurements which were performed simultaneously with the energy measurements for Fig. 15 for (a) positive voltages and (b) negative voltages.

4.2. Ozone measurements

If we look at the results of the ozone measurements in Fig. 16 we see no significant difference in ozone yield between different reactor lengths. Now the differences in the results, if any, seem to be more the result of pulse duration. For positive pulse voltages the 1-ns pulses perform less well than the longer 5-ns and 9-ns pulses. This difference is less pronounced at negative pulse voltages.

In the experiments with a variable plasma-reactor length we obtained the best matching in the longest reactor and there was no significant difference in ozone yield between the different reactor lengths. Therefore, we will use the 1-m reactor in all future plasma experiments.

5. Matching results and discussion: energy density

In a practical implementation of a transient plasma application there are two important application aspects: yield and throughput. So far we have only focussed on yield. However, gas throughput is also an important issue because it determines how much gas flow can be treated by the plasma in a given amount of time. Therefore, in this section we look at the energy density ε (in $\text{J}\cdot\text{L}^{-1}$) of the plasma, which is given by Eq. 12.

From this equation we see that there are two parameters to change the energy density independently (while keeping the output voltage of the pulse source constant):

- change the repetition rate while keeping the gas flow rate constant;
- change the gas flow rate while keeping the repetition rate constant;

We changed the repetition rate in the range 10–100 Hz while keeping the flow constant at $1 \text{ L}\cdot\text{min}^{-1}$ and in a second experiment we changed the flow in the range 0.5–

Figure 17: Matching as a function of the energy density. The energy density was varied by varying the repetition rate of the pulse source and the gas flow rate through the reactor for both positive and negative 30-kV 5-ns pulse voltages.

Figure 18: The ozone yield calculated from ozone measurements which were performed simultaneously with the measurements of Fig. 17.

6 L·min⁻¹ at a repetition rate of 50 Hz. The pulse voltage was 30 kV (both polarities) and had a pulse duration of 5 ns. The measurements resulted in an energy density from 10 to 250 J·L⁻¹, which is in the range that is often used in plasma-processing applications [18, 36, 38, 51, 1, 31, 52, 53, 54]. Figures 17 and 18 show the matching results and ozone-yield results of these experiments respectively.

The results show that matching is independent of the energy density up to 250 J·L⁻¹. Moreover, the method by which we change the energy density results in around the same matching. The other observation is that the negative pulses again match slightly better and that the positive pulses again obtain a slightly higher ozone yield. A general observation is that the ozone yield decreases with the energy density.

The decrease in ozone yield at high energy density was also reported in [28, 36, 34, 38, 51, 8]. This process is the result of an increase in the concentration of NO_x and an increase in the gas temperature with energy density. Both of these effects promote the reaction of ozone with NO_x and consequently reduce the ozone concentration [34, 35, 36].

The results of this section indicate that increasing the energy density comes at a cost in the ozone yield, but that even at high energy densities the performance of

Figure 19: The four configurations used in the multiple-wire experiments. From the left to the right the inner conductor is made up of 1, 4, 6 and 8 wires respectively. For the multiple-wire configurations, the 0.3-mm thick wires are placed in a circle with a 15-mm diameter.

the plasma is still quite good. Another important result is that the matching is quite constant over the whole energy density range.

6. Matching results and discussion: multiple-wire inner conductor

In the first part of Section 3 we explained that using a small wire diameter in the reactor would increase matching because a plasma ignites sooner on the wire because of the higher electric field — calculated with Eq. 14 — that is associated with a small wire diameter (as opposed to a large wire diameter). However, a smaller wire diameter would also increase the reflection coefficient — calculated with Eq. ?? — and therefore more energy is reflected at the reactor interface, which decreases matching. This analysis was confirmed by the experiments of that section.

The best way to transmit the largest part of the incoming pulse into the reactor is by increasing the wire diameter substantially. However, to still be able to ignite a plasma, the electric field at the wire has to be high enough, which is a condition that is not satisfied with a solid conductor. Therefore, we propose a multiple-wire inner conductor of the reactor.

We mount these wires on the circumference of the removable heads of the reactor (refer to Fig. 2). Therefore, the radial spacing between the wires is 15 mm. To investigate the effect of such an inner conductor we tested four configurations with a different number of wires N_w . We used $N_w = 1, 4, 6$ and 8 . The diameter of the wires is 0.3 mm. Figure 19 shows the four configurations.

With the multiple-wire conductor the electric field close to the wires will be high, but not as high as with a single-wire conductor. However, the electric field is high enough for plasma to be able to ignite on the wires. Further removed from the wire the electric field will drop off quickly, but because the inner conductor is closer to the grounded electrode in the multiple-wire configuration, the average electric field in the gap is higher for this configuration as compared to the single-wire setup. This might significantly affect the propagation of the streamers and therefore the matching. A downside of the multiple-wire configuration is that the plasma volume might be smaller because there

Figure 20: The plasma generated by the different multiple-wire inner conductors. The photographs were taken with a Canon 7D with a 300-mm lens at f/9 and with an exposure time of 10s. Note that the left-most photo was taken off-axis to visualise the plasma of the 1-wire configuration (the symbols beneath the photos depict the camera position with respect to the reactor).

is no plasma inside the 15-mm diameter circle of the multiple-wire electrode.

Figure 20 shows the plasma that is generated by the different wire configurations. Note that the first image was not taken with the lens axis parallel to the reactor axis, but slightly askew to be able to see the plasma. The other images were taken with the lens axis parallel to the reactor axis to visualise the pattern of the plasma.

It is clear that the plasma with the multiple-wire configurations is not as homogeneous as with the single-wire conductor. This is expected because the plasma will ignite only on the wire-positions and therefore not the entire volume is filled with plasma.

It is very difficult to tighten each wire to the same extent in the multiple-wire configuration. Inevitably, the wire tension will not be identical for each wire, causing some wires to be slightly closer to the reactor wall. This is especially true for the 6-wire and 8-wire configurations. This is evident in the pictures as the uneven intensity of the plasma for different wires; for the 4-wire configuration the plasma is even in intensity, but with the 6-wire inner conductor some of the wires generate less plasma. For the 8-wire configuration it is even worse. The explanation for the increase in plasma unevenness when the amount of wires increases is likely that the wire-tension differences in the wires increases because more wires are used and the process to tighten them becomes more difficult.

Figure 21 shows the matching results of the experiments with the multiple-wire inner conductors for a 5-ns pulse. The results show that matching of over 90 percent is possible for the 4-wire configuration and that all multiple-wire configurations outperform the 1-wire conductor. One of the reasons the 4-wire configuration works better than the 6-wire and 8-wire configurations is likely the same reason the plasma is uneven in Fig. 20: the effect of uneven tension in all the wires. This uneven tension results in less homogenous plasma for the 6-wire and 8-wire configurations. It is possible that the matching for these configurations would be similar to the 4-wire configuration if the

Figure 21: The matching of the pulses to the corona-plasma reactor for different numbers of wires comprising the inner conductor for (a) positive voltages and (b) negative voltages. Experimental settings: $\Delta t = 5$ ns, $f_{rr} = 100$ Hz, $l_r = 1.0$ m and $F = 5.0$ L·min⁻¹.

Figure 22: The same figure as Fig. 10, but now with the multiple-wire results added. The reflected pulses are now much lower in amplitude, indicating better matching.

plasma could be made to be more homogenous. The second possible reason is that as N increases, the resemblance of the inner conductor to a solid conductor increases. There will likely be a value for N where the matching is optimal.

We added the results of the multiple-wire experiments to the waveforms in Fig. 10 to see the effect on the reflection coefficient when a multiple-wire conductor is used. Figure 22 shows the results. It is obvious from the reflected pulse that the multiple-wire configurations result in a much lower reactor impedance. This is the primary reason for the better matching results. Figure 23 shows the reactor impedances corresponding to the waveforms of Fig. 22. Here it is again obvious that using a multiple-wire reactor results in a much lower reactor impedance.

Figure 24 shows the ozone yields for the multiple-wire experiments. These results indicate that the ozone yield is very similar for all configurations. Therefore, the better matching of the multiple-wire configuration, combined with the similar ozone yields, suggests that the total yield of a reactor with a multiple-wire inner conductor is

Figure 23: The calculated reactor impedances for the waveforms of Fig. 22. Again we see the better matching of the multiple-wire configurations.

Figure 24: The ozone yield calculated from ozone measurements which were performed simultaneously with the energy measurements for Fig. 21 for (a) positive voltages and (b) negative voltages.

higher than with the conventional 1-wire solution that is generally employed in coaxial plasma reactors. Furthermore, the non-homogeneous plasma that we observed in Fig. 20 apparently has no detrimental effect on the ozone generation.

In conclusion, the multiple-wire reactor that we developed in this section shows improved matching over the generally used 1-wire reactor. It will be left for future work to perform several interesting experiments with the multiple-wire reactor:

- optimise the number of wires in the reactor (with equally tight wires);
- optimise the diameter of the circle in which the wires are placed;

7. Discussion: positive vs. negative streamers

In the previous sections we found that negative pulses sometimes resulted in a better matching than positive pulses. This is surprising because other studies show that positive pulses match significantly better to a plasma reactor [48, 26]. Furthermore,

Figure 25: The difference in reactor impedance for the negative and positive results of the 0.5-mm wire plasma experiments of Section 3. The reactor impedance for the negative pulses is slightly lower.

Figure 26: The energy measurements for negative and positive pulses for the 0.5-mm wire plasma experiments of Section 3. The consumed plasma energy for the negative pulses is slightly higher.

negative streamers generally initiate at a higher voltage than positive streamers, making our observations even more peculiar [55, 48, 26]. The reason that positive voltages result in more streamer activity and consequently in a better energy utilisation by the plasma is one of the reasons that most studies only focus on positive streamer discharges.

If we want to discover what the mechanism is for the improved matching for negative pulses with our system as compared to other studies we have to focus on the very significant difference between our high-voltage pulses and the pulses others used: our pulses have a very short rise time and are applied after transmission over a long cable. Therefore pulse reflections on the cable coupler and the associated reactor impedance become a significant aspect of the matching process.

In Figs. 25 and 26 we compare the 0.5-mm wire positive and negative results of Fig. 8 at different voltage amplitudes. The impedance of the reactor energised with negative pulses is lower than when we used positive pulses. Since this lower impedance is closer to the 50-Ω output impedance of the SA24272 cable, negative pulses have better matching, which can also be seen in the energy measurements of Fig. 26. This indicates

that the pulse reflection is less for negative pulses, which is an effect that can only occur when a more dissipative plasma is generated or when the wire diameter increases (see the results of Section 3).

To explain the negative vs. positive matching results we assume that there has to be a time-dependent effect that originates from the difference between the inception of positive and negative streamer inception.

7.1. Inception cloud

There are two (not mutually exclusive) possible phenomena that would explain the matching results from the streamer inception mechanisms. The first is the inception cloud.

Lately it has been observed, in air and in nitrogen, that when a fast voltage pulse is applied to a sharp electrode, a fast ionisation front is generated around this electrode. This ionisation front propagates towards the counter electrode and is called the inception cloud [56, 57, 58, 59, 60]. The inception cloud forms a highly ionised region around the high-voltage electrode. The associated high conductivity virtually increases the electrode size and therefore the applied potential on the electrode is transported to the edge of the inception cloud. When the electric field on the edge of this virtual electrode becomes equal to the critical field strength E_{crit} the ionisation cloud destabilises and breaks up into streamers.

If we apply the concept of the inception cloud to our wire-cylinder reactor then we find the radial electric field $E(r)$ at the edge of the inception cloud as

$$E(r) = \frac{V_p}{r \ln \frac{d_o}{2r}}, \quad (16)$$

where V_p is the applied voltage pulse amplitude, d_o is the outer diameter of the corona-plasma reactor and we assume that the complete voltage potential is transported to the edge of the inception cloud. If we then set the electric field to E_{crit} we find

$$d_{\text{max}} \ln \frac{d_o}{d_{\text{max}}} = \frac{2V_p}{E_{\text{crit}}}, \quad (17)$$

where d_{max} is the maximum inception cloud diameter.

Therefore, the maximum diameter of the inception cloud is dependent on the voltage and the pressure (through E_{crit}), which was also found in [56, 60, 57]. Other observations were that the inception cloud in air is larger than in nitrogen [61, 60], that even in large gaps in air at atmospheric pressure inception clouds are present [62, 63], that a high rise-rate results in a more stable inception cloud and that a high repetition rate results in a smaller inception cloud [64]. However, the most important property of the inception cloud for our investigation is that a negative inception cloud can achieve a diameter that is very close to d_{max} , whereas a positive inception cloud breaks up sooner than that and therefore achieves a smaller diameter [59, 65]. This effect was attributed to the stabilising effect of electron drift on the propagation of negative ionisation fronts.

We have no reason to expect that the results in literature on the inception cloud that were all found for point-plate geometries will not apply for our wire-cylinder geometry. The other difference between our investigation and the other studies is our very high rise-rate of around $50\text{--}100\text{ kV}\cdot\text{ns}^{-1}$, which is at least an order of magnitude higher than in the other studies. However, if we can apply the previous findings on the inception cloud to our investigation then we can assume that the inception cloud around the wire is larger when we use negative pulses to energise our reactor. This virtually increases the diameter of the wire as compared to when we use positive pulses and therefore the impedance of the reactor will decrease. Consequently, the matching increases.

If we use Eq. 17 for a 20-kV pulse and E_{crit} as $30\text{ kV}\cdot\text{cm}^{-1}$ then we find a maximum inception cloud diameter of 6.6 mm, which is large enough to significantly decrease the impedance of the reactor. However, if we use the same equation for a 30-kV pulse, we find that there is no solution for $E_{\text{crit}} = 30\text{ kV}\cdot\text{cm}^{-1}$. In reality, the inception cloud will have a final conductivity and therefore not the entire voltage potential is transported to the edge of the inception cloud and we estimate that d_{max} will be in the range of 3–7 mm for an applied voltage of 20–35 kV. Optical measurements are necessary to show whether we have such an inception cloud around our electrode.

7.2. Initial streamer velocity

The second reason for the improved matching of the negative pulses could originate from the initial streamer propagation velocity. Almost all studies on positive and negative streamer propagation show that streamers generated by positive pulses propagate faster than those generated by negative pulses [66, 67, 68, 69, 70, 48, 71, 72]. However, due to the support of electron drift, negative streamers should propagate faster for a similar electron distribution and field enhancement at the tip of the streamer [73]. That this is not the case in experiments and simulations is because the positive streamers have a more concentrated and smaller head and therefore have a higher field enhancement [65]. Most interestingly however, is that the simulations of Luque *et al.* show that it takes some time for the negative streamer head to become diluted by electron drift, and for the positive streamer head to become concentrated [65]. Therefore, after the inception of the streamers, negative streamers will propagate faster. Since the tails of the streamers are highly ionised and therefore highly conductive, this phenomenon can also virtually increase the wire diameter in the reactor, again leading to increased matching. Therefore, if negative streamers propagate faster than positive streamers in the initial stages of the plasma development, the matching for negative streamers will be better.

7.3. Total matching effects

The difference in matching between negative and positive polarity was significant for 5-ns pulses, but for 9-ns pulses the difference was very small and in favour of the positive pulses. In this case, it seems likely that for longer pulses the more traditional matching

effects become important. For a longer pulse the streamers can propagate further, even reaching the grounded electrode. Therefore, more energy can be consumed by the plasma. This effect can become more important than the initial streamer phases, such as the inception cloud and the initial streamer velocity.

8. Summary and conclusions

In this paper we investigated the energy transfer of the pulses from the nanosecond pulses to the plasma in the reactor. This energy transfer, or ‘matching’, should be as high as possible, because the rest of the energy is lost in the system and does not contribute to the plasma-processing application. We studied the effect of multiple parameters on matching, such as the reactor configuration, the pulse duration and the energy density.

The main conclusions are listed below.

- The reflection of the pulse on the cable coupler significantly influences matching. To minimise the reflection at the cable coupler (thereby increasing the energy transfer to the reactor) the inner-wire diameter of the reactor should be as large as possible. However, for a large-diameter wire, the electric field in the reactor will be lower and less plasma will develop, which decreases the energy dissipation. From experiments with different wire diameters we found an optimum in these two contradicting effects around a wire diameter of 0.5 mm, even though the differences in matching between the wire diameters were very small. A surprising effect was that the negative pulses matched better than the positive pulses. A possible origin of this effect is the size of the inception cloud (which can become larger for negative polarities) and the initial streamer velocity (which can become higher for negative streamers).
- We developed a multiple-wire inner conductor for the reactor which decreases the vacuum impedance of the reactor, thereby decreasing the pulse reflection in the reactor interface while maintaining a high electric field on the wire. The results were very encouraging and showed matching of over 90 percent.
- Matching experiments with different reactor lengths (0.25 m, 0.5 m and 1 m) and different pulse durations (1 ns, 5 ns and 9 ns) showed that the longest reactor and the longest pulses result in the best matching. The explanation for this effect was that for a longer reactor and a longer pulse, the streamer plasma has more time to develop and to dissipate the energy from the applied pulses.
- For all experiments, higher applied voltages resulted in better matching. This was also observed by other researchers. However, where their plasma had a secondary streamer phase, we have only primary streamers. Nevertheless, the result that a higher voltage results in a more intense plasma is the same and our pulses are so short that a significant current can flow even in the primary streamer phase.
- Finally, even without the multiple-wire reactor, we are able to achieve a very good matching (over 80 percent) between our pulse source and the reactor, which shows that even a plasma with just a primary streamer phase can be matched to a pulse source if certain conditions are met (short rise time, high voltage, optimal reactor

configuration, etc.).

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