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AC/DC/Pulsed-Power Modulator for Corona-Plasma Generation

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***Abstract*—Gas-cleaning techniques using nonthermal plasma are slowly introduced into industry nowadays. In this paper, we present a novel power modulator for the efficient generation of large-volume corona plasma. No expensive high-voltage components are required. Switching is done at an intermediate voltage level of 1 kV with standard thyristors. Detailed investigations on the modulator and a wire-plate corona reactor will be presented. In a systematic way, modulator parameters have been varied. Furthermore, reactor parameters, such as the number of electrodes and the electrode-plate distance, have been varied systematically. The yield of O radicals was determined from the measured ozone concentrations at the exhaust of the reactor.**

***Index Terms*—O radicals, ozone yields, power modulator, streamer corona plasma.**

I. Introduction

GAS-CLEANING techniques using nonthermal plasma are slowly introduced into industry nowadays [1], [2]. The first industrial corona-plasma system was reported by ENEL for the simultaneous removal of dust, SO2, NOx, and heavy metals from exhaust gases [3]. Unfortunately, the lack of cost-effective corona-plasma generation and processing techniques discouraged industries. Nevertheless, three industrial corona-plasma demonstration systems with up to 40–120 kW in average power were recently reported in Japan, Korea, and China [4]–[6]. These systems are based on magnetic compression techniques with pulse duration of 200–500 ns. The main drawbacks of these reported systems are their relatively low-energy conversion efficiency. In 2006, we demonstrated a large-scale (with average power of 20 kW) nanosecond pulsed corona system for odor abatement [7]. The electrical efficiency (mains to reactor) was $> 90\%$, and efficient odor removal efficiencies were obtained (7 J/L for a 1000-m^3/h air flow). Such gas cleaning applications are mainly initiated by the radicals that are produced by the corona plasma, such as O and OH. In [8], we reported that the yields of O radicals produced by corona plasma in air can be very high (in the range of 3–7 mol/kWh).

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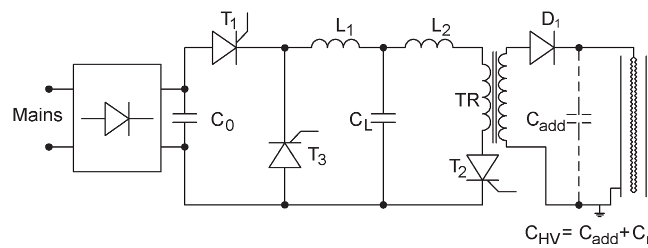

Fig. 1. AC/dc/pulsed-power modulator.

However, to be competitive, the high costs of the pulsed-power technology are still a major hurdle. Only two options are available for heavy-duty pulse compression at nanosecond timescales: 1) spark-gap switch technology in combination with transmission-line transformers [9] or 2) magnetic pulse compression techniques [10]. Both technologies rely on complicated and expensive high-voltage (HV) components. In this paper, we present a novel modulator for the efficient generation of large-volume corona plasma. No expensive HV components are required. Switching is done at an intermediate voltage level of 1 kV with standard thyristors. At the HV level, only a diode and a pulse transformer are needed. The estimated costs of this modulator are about 5 kEuro/kW, whereas the costs for state-of-the-art pulsed-power technology range from 20 to 30 kEuro/kW.

II. Experimental Setup

A. Power Modulator

A schematic overview of the ac/dc/pulsed-power modulator is shown in Fig. 1 [11].

A two-step process is used to generate the HV pulses. First, C_L is resonantly charged to $V_{\mathrm{Cl}+} \approx 1$ kV via the storage capacitor C_0, thyristor T_1, and inductor L_1. Because of charge conservation and $C_0 \gg C_L$, voltage doubling on C_L is achieved. In the second step (by switching T_2), C_L is resonantly discharged (to $-V_{\mathrm{Cl}-}$) via transformer TR to the corona reactor (with capacitance C_r) and additional capacitors C_{add} connected in parallel with the reactor. C_{HV} is the total HV capacitance (being $C_{\mathrm{add}} + C_r$). The reactor voltage rises to a maximum peak voltage $V_P \approx nV_{\mathrm{Cl}+}$, as in Fig. 2 ($n$ is the winding ratio of TR) within time $T \approx \pi^*(L_2 C_L/2)^{0.5}$($L_2$ is the leakage inductance of TR and is as small as possible, $C_L \approx n^2 C_{\mathrm{HV}}$).

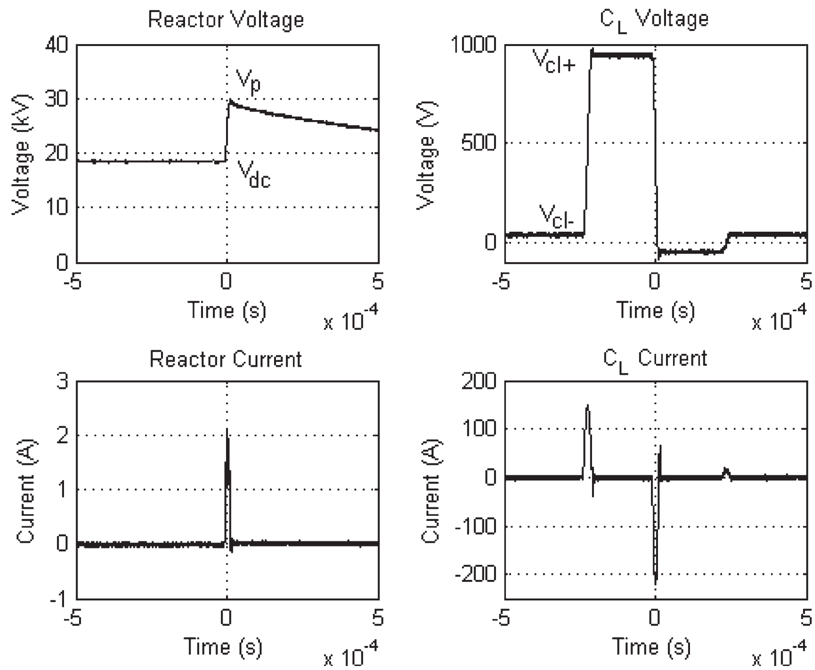

Fig. 2. Typical voltage and current waveforms.

When the voltage on the reactor reaches the plasma inception voltage, streamer formation is initiated, and corona plasma is created. First, the plasma is very intense and has streamers. After a short time period, when no streamers can propagate, a glowlike plasma remains. The plasma dissipates the energy which has been transferred to the total HV capacitance C_{HV}, and the reactor voltage drops exponentially (the plasma can be seen as a "resistance") to a voltage level V_{DC}, where the plasma quenches or a new pulse cycle commences. The following equations are used to calculate the energy E_{CL} delivered by C_L, the energy E_P dissipated by the plasma during the charging of the HV capacitance, and the total energy E_t dissipated by the plasma during pulse operation

$$E_{\mathrm{CL}} = \frac{1}{2} C_L \left(V_{C_L+}^2 - V_{C_L-}^2 \right) \tag{1}$$

$$E_P = \int_0^{t(V=V_P)} VI dt - \frac{1}{2} C_r \left(V_P^2 - V_{\mathrm{DC}}^2 \right) \tag{2}$$

$$E_t = \int_0^{t(V=V_P)} VI dt + \frac{1}{2} (C_{\mathrm{HV}} - C_r) \left(V_P^2 - V_{\mathrm{DC}}^2 \right) \tag{3}$$

where V and I are the reactor voltage and current, respectively.

In order to work safely, two features are installed in the system. D_1 protects the pulse transformer and the low-voltage side from energy flowing back into the power modulator.

In order to stabilize the average output, thyristor T_3 is switched to change the polarity on C_L as its voltage is slightly negative after the pulse discharges [9].

B. Electrical Test Conditions

The experimental setup to study ac/dc/pulsed corona generation is shown in Fig. 3. A parallel plate reactor (1 × 1 m) with a sawtooth-shaped electrode was used (electrode-plate distance of 5.5 cm). The capacitance $C_r = 0.25$ nF. Several parameters were varied to study the effect on the system:

1) C_L: 3 or 6 μF;
2) C_r: one, two, and four reactor channels in parallel;
3) C_{add}: 0, 0.5, 1, 1.5, 2, 4, 8, or 12 nF;
4) pulse repetition rate: 100–800 pps.

C. Chemical Model

To evaluate the chemical activity in the reactor, the ozone concentrations in the reactor exhaust were measured using UV absorption in the Hartley band (230–290 nm). From these measurements, the yields of O radicals can by calculated by means of a detailed kinetic model. This method is described in detail by *Peyrous* [12] and *van Heesch et al.* [8]. For this model, 71 chemical reactions, involving 17 species, were used. The initial O^* radical concentration (unknown parameter) produced by the plasma is required as an input parameter for the model. The calculation starts with a "best guess" for this value and iterates to a final value.

Another input parameter for the model is the initial concentration of water in the air, which is calculated from the relative humidity RH (in percent) by the following:

$$c_{\mathrm{H2O}} = RH \cdot Av \cdot \frac{3.1243 \cdot 10^{-6} \cdot T^3 + 8.1847 \cdot 10^{-5} \cdot T^2}{M_{\mathrm{H2O}} \cdot 10^6} + RH \cdot Av \cdot \frac{3.2321 \cdot 10^{-3} \cdot T + 0.05018}{M_{\mathrm{H2O}} \cdot 10^6} \tag{4}$$

where the concentration c_{H2O} is in molecules per cubic centimeter, T is in degrees Celsius, Av is the number of Avogadro, and M_{H2O} is the molar mass of water.

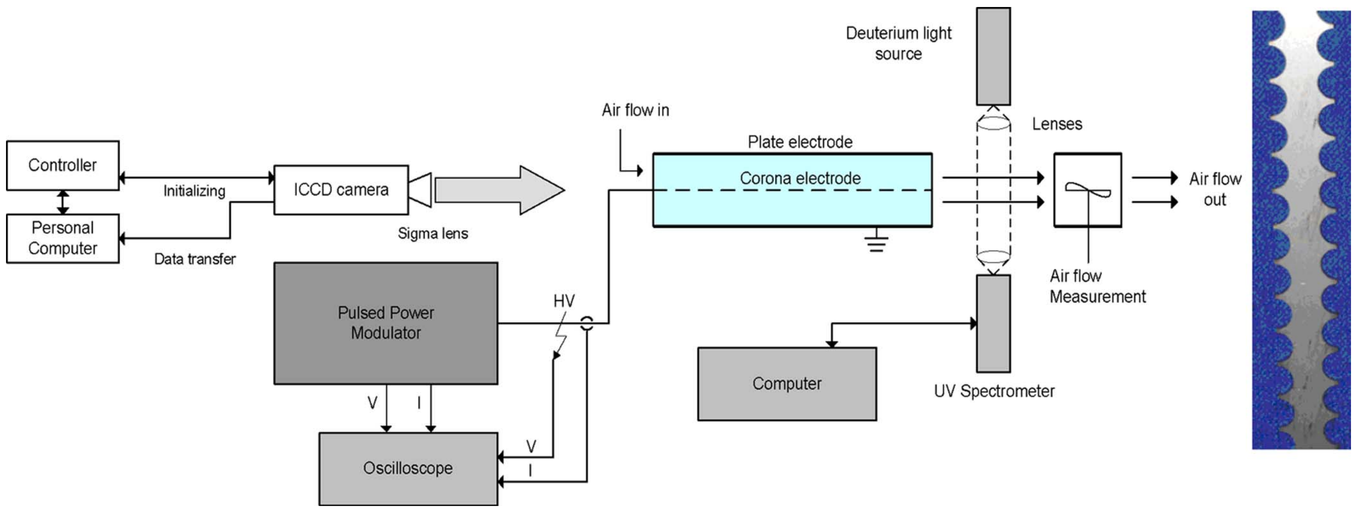

Fig. 3. Experimental setup and picture of an electrode.

Another input parameter is the ratio between the concentrations of O, N, OH, and H radicals as produced by the electrical discharge. The following ratio is used:

$$O:N:OH:H = 1:0.06:0.6\cdot 10^{-3}\cdot RH:0.6\cdot 10^{-3}\cdot RH.$$

The output of the kinetic model is the ozone concentration in the reactor ($c_{\mathrm{O3,str}}$). The O^* radical concentration entered into the model is iteratively varied, until the calculated ozone concentration is in good agreement (<0.01%) with the ozone concentration as measured in the exhaust of the reactor ($c_{\mathrm{O3,exh}}$). In order to compare the measured and calculated values, the following was used:

$$c_{\mathrm{O3,exh}} = \frac{c_{\mathrm{O3,str}} \cdot V_{\mathrm{str}} \cdot f}{F} \tag{5}$$

where $c_{\mathrm{O3,exh}}$ is the measured concentration ozone (moles per cubic meter) in the exhaust, $c_{\mathrm{O3,str}}$ is the calculated concentration ozone $(\mathrm{mole}/(\mathrm{m}^3 \cdot \mathrm{pulse}))$ in the reactor, V_{str} is volume of the plasma streamers (cubic meters), f is the pulse repetition rate (pulse per second), and F is the airflow in the exhaust (cubic meters per second). All these properties were monitored. However, the remaining unknown parameter is the plasma volume. By means of fast imaging (i.e., ICCD camera), this volume was determined.

The measured and calculated concentrations are in moles per cubic meter, and the input parameters are in moles per cubic centimeter, while the ozone and O radical yields (shown in Figs. 9 and 10) are in grams per kilowatthour and moles per kilowatthour, respectively. For us, it is important to know the chemical yield compared to the energy put into the system.

In order to calculate the ozone yield from moles per cubic meter to grams per kilowatthour, the following calculation has been done. The ozone concentration (moles per cubic meter) is multiplied by its molar mass (grams per mole) and the flow rate (cubic meters per hour) and is divided by the applied power (kilowatts).

In order to calculate the O radical yield from $\mathrm{mole}/(\mathrm{m}^3 \cdot \mathrm{pulse})$ to moles per kilowatthour, the following calculation has been done. The O radical yield $(\mathrm{mole}/(\mathrm{m}^3 \cdot \mathrm{pulse}))$ is multiplied by the plasma volume V_{str} (cubic meters) and divided by the energy per pulse (joules per pulse). This results in the O radical yield in moles per joule. Finally, this is multiplied by $3.6 \cdot 10^6$ in order to get the correct unit of moles per kilowatthour.

III. Results and Discussion

With $C_L = 3\ \mu$F, the experiments could be performed without problems. However, with $C_L = 6\ \mu$F, breakdowns were observed frequently. Most likely, because of the higher energy in the same reactor volume, the voltage rises. Because of this higher voltage, breakdowns occur on the connections. Another possibility is the charging time of the reactor. Because of the higher capacitance, charging takes longer. With the energy, pushing this can also lead to breakdowns when there is no sufficient space.

The most important parameter that was varied is the total HV capacitance C_{HV} ($C_r \sim 0.25$ nF/channel and the extra capacitance C_{add} added in parallel to the reactor). The effect of the pulse repetition rate was limited. For the future demonstration model, a pulse repetition rate of 2 kHz is required, where our modulator is limited to 800 Hz. Therefore, for our measurements, the values are the mean values with a repetition rate between 500 and 800 Hz.

In Fig. 4, the reactor voltage is shown as a function of the total HV capacitance C_{HV}. It can be clearly seen that the voltage is negatively affected by C_{HV}. A low value for C_{HV} results in a high V_P and a low V_{DC}. A higher capacitance means that the reactor is charged and discharged more slowly; the voltage is not able to overshoot the plasma inception voltage as far as with a low C_{HV} value, which results in a lower peak voltage. The slow discharge results in a higher dc level. The number of reactor channels has a significant effect on the V_P and V_{DC} levels. V_P is slightly lower when more channels are connected in parallel ($V_{P\,1\,\mathrm{reactor\,channel}}, \ldots, V_{P\,4\,\mathrm{reactor\,channels}}$ in Fig. 4). The reason for this is most likely that, because of the higher capacitance, the charging stage takes longer, and as soon as the plasma is ignited, more energy can be dissipated in the charging cycle. For the dc level, the effect is more clearly

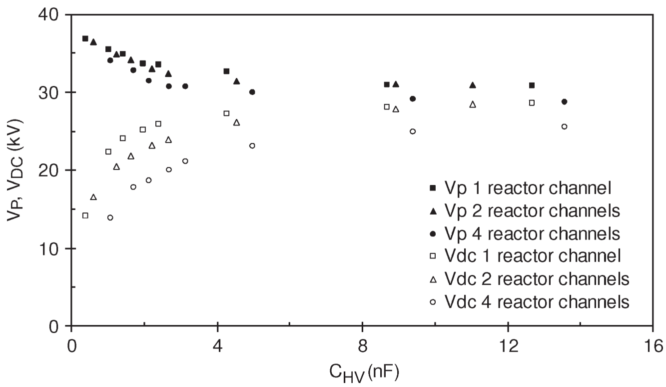

Fig. 4. Effect of the total HV capacitance on the peak and dc level of the applied voltage, at a pulse repetition rate of 800 pps.

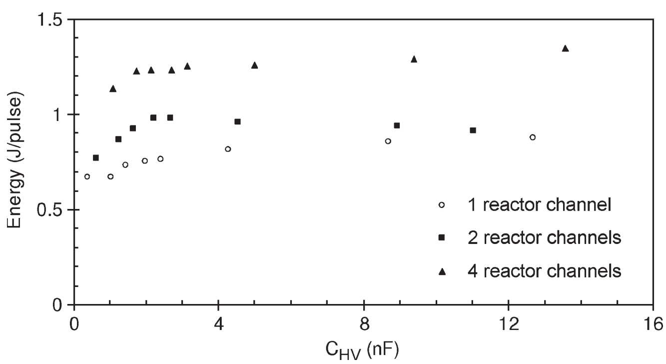

Fig. 5. Energy per pulse versus total HV capacitance for one, two, and four reactor channels (550–800 pps).

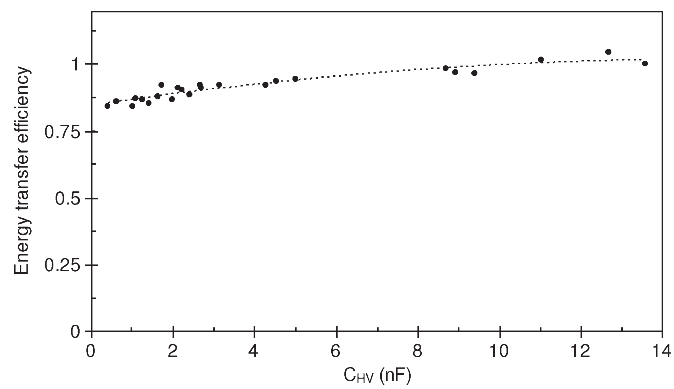

Fig. 6. Energy transfer efficiency versus total HV capacitance (550–800 pps).

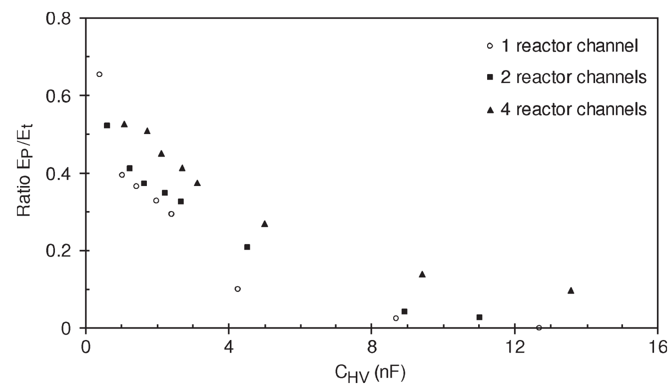

Fig. 7. Energy ratio E_P/E_t versus total HV capacitance for one, two, and four reactor channels (800 pps).

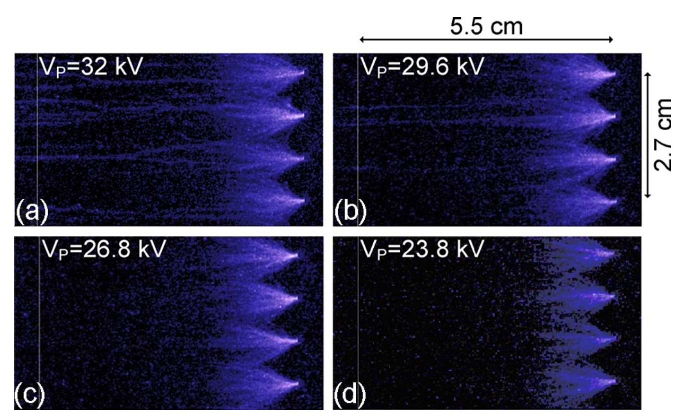

Fig. 8. Effect of peak voltage on streamer appearance. (a) Reactor voltage: $V_P = 31.9\,\text{kV}$, $V_{\text{DC}} = 20.3\,\text{kV}$. (b) Reactor voltage: $V_P = 29.6\,\text{kV}$, $V_{\text{DC}} = 20.2$ kV. (c) Reactor voltage: $V_P = 26.8$ kV, $V_{\text{DC}} = 19.9$ kV. (d) Reactor voltage: $V_P = 23.8\,\text{kV}$, $V_{\text{DC}} = 19.5\,\text{kV}$.

visible ($V_{\text{DC 1 reactor channel}}, \ldots, V_{\text{DC 4 reactor channels}}$ in Fig. 4). This can be explained by the fact that more channels imply more plasma, and as a result, a lower resistance. The reactor discharges faster.

Fig. 5 shows the effect of the total HV capacitance C_{HV} on the energy per pulse. It can be seen that more energy is dissipated by the plasma when C_{HV} is increased. When C_{HV} increases, V_{DC} increases as well (Fig. 4). A higher voltage results in a lower plasma resistance. More current can flow through the plasma, which results in increased energy dissipation. In Fig. 5, it can also be observed that the number of reactor channels has a strong effect on the energy per pulse. This finding again shows that the amount of energy that the plasma can dissipate depends on the available reactor volume.

The energy transfer efficiency (E_t/E_{CL}) improves for increasing C_{HV} (see Fig. 6) and does not depend on the number of parallel channels. The overall efficiency is high: around $92\% \pm 6\%$.

As will be shown later, an important parameter for the chemical efficiency of the plasma is the ratio between the energy dissipated by the plasma during the charging of the reactor E_P (therefore, during the rising slope of the reactor voltage) and the total energy dissipated by the plasma E_t. The energy ratio (E_P/E_t) is negatively affected by C_{HV} (see Fig. 7). A higher C_{HV} implies that less energy is dissipated during the charging of the reactor. The number of reactor channels connected in parallel has a positive effect on the energy ratio.

In order to study the spatial development of the plasma and to estimate the plasma volume, several photographs were taken under different conditions (see Fig. 8). The plasma depends on applied voltage and, thus, on the electric field in the reactor gap. If the applied voltage is high (i.e., $V_P = 31.9$ kV and $V_{\text{DC}} = 20.3$ kV), streamers cross the complete gap [Fig. 8(a)]. However, if the applied voltage is low (i.e., $V_P = 23.8$ kV and $V_{\text{DC}} = 19.5$ kV), corona is only visible near the vicinity of the electrode [Fig. 8(d)]. Apparently, for this lower voltage, the electric field is lower than the critical field strength of 5–8 kV/cm which is required for streamers to propagate [13]. From the photographs with crossing streamers, the average streamer width was determined to be 737 μm, and the plasma volume was estimated to be between 0.5 and 2.0 $\text{dm}^3/\text{channel}$.

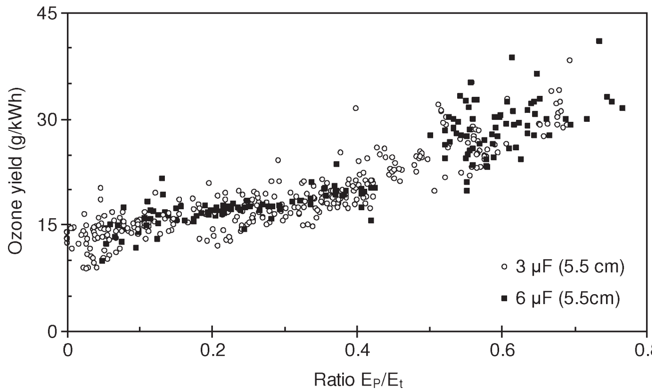

Fig. 9. Ozone yield versus energy ratio E_P/E_t for $C_L = 3\text{–}6\ \mu$F.

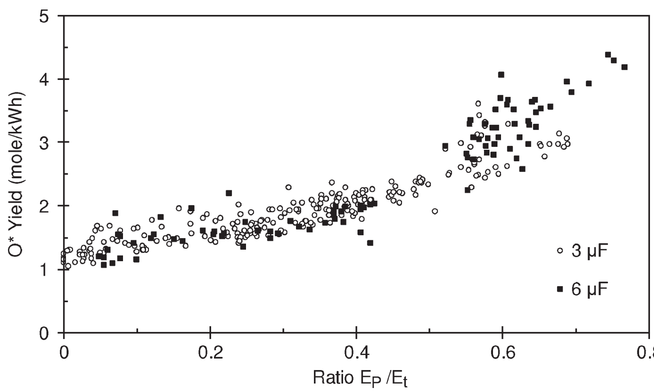

Fig. 10. O radical yield versus energy ratio E_P/E_t for $C_L = 3\text{–}6\ \mu$F.

A sensitivity check showed that the maximum difference in O* yield as a result of this estimate was small, only 12%.

Results regarding ozone yields are shown in Fig. 9. The maximum energy density during the experiments is 13 J/L. For these low energy densities, the ozone concentration depends linearly on the energy density, and the self-destruction of ozone is not significant in this regime. No significant difference can be observed between measurements with $C_L = 3$ and 6 μF. The ozone yield depends on the energy ratio E_P/E_t. The higher this ratio, the higher the ozone yield. This implies that the ozone is created more efficiently when the energy is dissipated during the charging stage of the reactor. A high energy ratio E_P/E_t can be obtained when $C_{\rm HV}$ is low. The plasma is most efficient for a high peak voltage V_P and a low $V_{\rm DC}$ level, i.e., like pulsed corona plasma. Typical yields of 35 g/kWh are very good when considering that the conditions are not ideal: relative humidity of 40%, not pure oxygen.

The O* yield also depends on the ratio E_P/E_t and is controllable between 1 and 4 mole/kWh (see Fig. 10). The higher the ratio E_P/E_t, the higher the O* yield. This implies that oxygen radicals are created more efficiently when the energy is dissipated during the charging stage of the reactor. In order to achieve high yields, $C_{\rm HV}$ needs to be low. This corresponds to a high V_P and a low $V_{\rm DC}$ (inclined toward nanosecond pulsed corona plasmas). With nanosecond-pulsed corona, typical values of 3–7 mole/kWh can be obtained, whereas the yields > 4 mole/kWh require voltage pulsewidths of < 50 ns. For the more common pulsewidths of > 100 ns, radical yields are comparable with the yields reported here for an ac/dc/pulsed-based system.

The question which is raised here is what are the dependent and independent parameters? The HV capacitance $C_{\rm HV}$ seems to be an independent parameter because this parameter can be controlled manually. Other parameters that can be controlled by hand are the low voltage capacitance C_L and the reactor capacitance C_r. C_r can be controlled by changing the wire-plate distance and the number of channels and the electrode shape. In this paper, only the number of channels was changed. The peak and dc voltages (also the voltage shape) are dependent parameters. The peak voltage is dependent on all the three independent parameters. C_L and $C_{\rm HV}$ are responsible, together with L_2, for the charging time of the reactor. A long charging time implies a lower peak voltage. However, a short charging time results in a high peak voltage which is capable to overshoot the plasma inception voltage. More reactor channels (i.e., a higher C_r) imply also a lower V_P because of the possibility of dissipating more energy during the charging stage. $V_{\rm DC}$ depends on two parameters, i.e., $C_{\rm HV}$ and the number of reactor channels. A higher $C_{\rm HV}$ results in a higher dc voltage (slower discharge), while more reactor channels result in a lower dc voltage (faster discharge). The energy dissipated is also a dependent parameter which depends on all the independent parameters aforementioned. A high $C_{\rm HV}$ implies a slow charge and discharge of the HV side which results in a low energy dissipation. More reactor channels result in more energy dissipated by the plasma.

In order to find the relation between the dependent and independent parameters and with the overshoot of the plasma inception voltage for this setup, more investigation is necessary.

IV. Conclusion

1) AC/DC/pulsed corona plasma is a good alternative for nanosecond-pulsed corona plasmas.
2) For all parameters, an energy transfer efficiency of more than 90% could be obtained.
3) With optical measurements, the average streamer width was found to be $\sim 740\ \mu$m. With this streamer width, an estimate for the plasma volume was made.
4) The obtained yields of O radicals (typically 1–4 mole/kWh) are excellent. The highest yields are obtained for high energy ratios E_P/E_t (the ratio between the energy dissipated by the plasma during the charging of the HV capacitance and the total dissipated energy). This experimental condition can be obtained when $C_{\rm HV}$ is chosen low.

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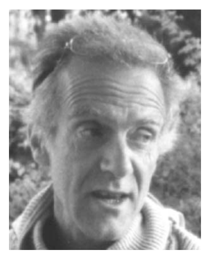
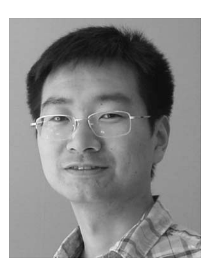
G. J. J. Winands was born in Kerkrade, The Netherlands, in 1978. He received the M.Sc. degree in applied physics from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 2002, where he also received the Ph.D. degree from the Faculty of Electrical Engineering in 2007.

Currently, he works on industrial pulsed corona systems for air treatment with HMVT, Ede, The Netherlands. His activities focus on the interaction between power modulators and plasma generation/chemical processing and are related to repetitive plasma generation for industrial-scale gas-cleaning applications.



E. J. M. van Heesch was born in Utrecht, The Netherlands, in 1951. He received the M.S. degree in physics from the Eindhoven University of Technology, Eindhoven, The Netherlands, and the Ph.D. degree in plasma physics and fusion-related research from the University of Utrecht, Utrecht, The Netherlands, in 1975 and 1982, respectively.

Since 1986, he has been an Assistant Professor with the Electrical Power Systems Group, Electrical Engineering Department, Eindhoven University of Technology, where he is leading the pulsed-power research. He was previously involved in shock-tube gas dynamics (Eindhoven, 1975) and in fusion technology (Jutphaas, The Netherlands, 1975–1984, Suchumi former USSR, 1978, and Saskatoon, Canada, 1984–1986). Among his designs are various plasma diagnostics, a toroidal fusion experiment, substation high-voltage measuring systems, and systems for pulsed-power processing. He organizes many projects with industry and national and European Union research agencies. His research is the basis for teaching and coaching university students and Ph.D. candidates. He is a Coinventor of several patents. He has coauthored more than 100 publications.



Zhen Liu was born in Xiang Cheng, China, in 1978. He received the B.Sc. degree from Xi’an Jiaotong University, Xi’an, China, in 2000, the M.Sc. degree from Tsinghua University, Beijing, China, in 2003, and the Ph.D. degree from the Electrical Power Systems (EPS) Group, Electrical Engineering Department, Technische Universiteit Eindhoven (TU/e), Eindhoven, The Netherlands, in 2008.

Currently, he is with the EPS Group, Electrical Engineering Department, TU/e, as a Postdoc Researcher. His research interest includes pulsed-power generation and plasma and its applications.