# AC/DC Power Modulation for Corona Plasma Generation

A.J.M. Pemen[1], T.H.P. Ariaans[1] LIU Zhen[1], E.J.M. van Heesch[1], G.J.J. Winands[2], YAN Keping[3]
(1 Eindhoven University of Technology (TU/e), Eindhoven 5600 MB, The Netherlands. E-mail: a.j.m.pemen@tue.nl
2 HMVT, Ede, The Netherlands
3 Zhejiang University, Hangzhou 310028, PR China. E-mail: kyan@zju.edu.cn)

**Abstract:** Gas cleaning techniques using non-thermal plasma are slowly introduced into industry nowadays. Here 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. Also reactor parameters, 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.

**Keywords:** Power modulator, streamer corona plasma, ozone yields, O radicals

## 1 INTRODUCTION

Gas cleaning techniques using non-thermal plasma are slowly introduced into industry nowadays. Still several challenges arise, like increasing the scale, safety, life-time, and reducing costs. In 2006 we demonstrated a large scale (20 kW average power) nano-second pulsed corona system [1]. The electrical efficiency (mains to reactor) was >90%. Yields of O-radicals were found to be very high, in the range from 3 mol/kWh -7 mol/kWh [2].

However, to be competitive, high costs of the pulsed power technology are still a major hurdle. Here we present a novel 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. 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 costs for state-of-the-art pulsed power technology range from 20 kEuro/kW - 30 kEuro/kW.

## 2 EXPERIMENTAL SETUP

A schematic overview of the AC/DC power modulator is shown in Fig. 1.

A two step process is used to generate the high voltage pulses. First, $C_L$ is resonantly charged to $V_{CL+} \approx 1$ kV via 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 $C_L$ is resonantly discharged (to $V_{CL-}$) via transformer $TR$ to the corona reactor with capacitance $C_R$. The reactor voltage rises to a peak voltage $V_P \approx nV_{CL+}$, as in Fig. 2 ($n$ is winding ratio of $TR$) within time $T \approx \pi^2 L_2 C_L$ ($L_2$ is stray inductance of $TR$ and as small as possible, $C_L \approx n^2 C_R$).

When the voltage on the reactor reaches the plasma inception voltage, streamer formation is initiated and plasma is created. The plasma dissipates the energy which has been transferred to $C_R$, 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 total energy that is dissipated by the plasma $E_t$, and the plasma energy $E_P$, dissipated during the slope $V_{DC} \rightarrow V_P$.

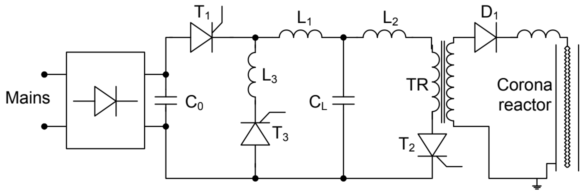

**Fig. 1** AC/DC Power modulator

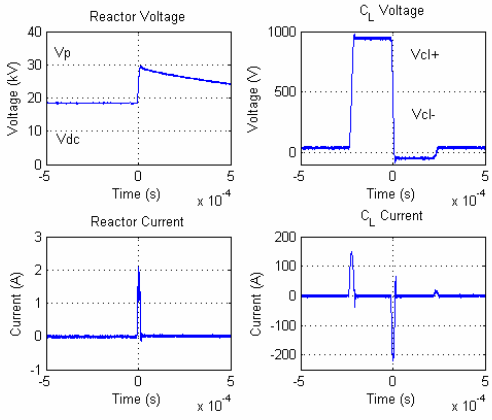

**Fig. 2** Typical voltage and current waveforms

$$E_{CL} = \tfrac{1}{2} C_L (V_{CL+}^2 - V_{CL-}^2) \tag{1}$$

$$E_t = \int_0^{t(V=V_p)} VIdt + \tfrac{1}{2} C_R (V_P^2 - V_{DC}^2) \tag{2}$$

$$E_P = \int_0^{t(V=V_P)} VIdt - \tfrac{1}{2}C_R(V_P^2 - V_{DC}^2) \qquad (3)$$

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

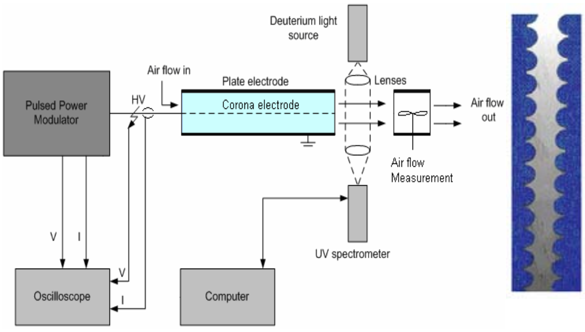

**Fig. 3** Experimental setup and picture of an electrode

The experimental setup to study AC/DC corona generation is shown in Fig. 3. A parallel plate reactor (1x1m, distance of 5 or 5.5 cm) with a saw tooth shaped electrodes was used. The capacitance $C_R$=0.25 nF. Several parameters were varied to study the effect on the system:

- $C_L$: 3 µF or 6 µF
- 1, 2 or 4 reactor channels in parallel
- Extra capacitance in parallel to the reactor $C_H$’: 0, 0.5, 1, 1.5, 2, 4, 8 or 12 nF.
- Pulse repetition rate: 100-1000 pps.

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 nm-290 nm). From these ozone measurements, the yields of O-radicals can be calculated by means of a detailed kinetic model. This method is described in detail in [2-3]. For this model, 71 chemical reactions, involving 17 species, were used. Besides the relative humidity RH of the air, the kinetic model requires the (initial) O* radical concentration as produced by the plasma, which is the unknown parameter. The calculation starts with a “best guess” for this value, and iterates to a final value. Another input parameter is the ratio between the concentration of O, N, OH and H radicals as produced by the electrical discharge. We use the ratio:

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

The remaining unknown parameter is the plasma volume. By means of fast imaging (i.e. ICCD camera), this volume was determined. Ambient air properties as temperature, relative humidity and air flow were monitored as well.

## 3 RESULTS AND DISCUSSION

With $C_L$=3 µF, the experiments could be performed without problems. However, with $C_L$=6µF, breakdowns were observed frequently. The most important parameter that was varied during the experiments is the total reactor capacitance $C_R$ (so 0.25 µF/channel and the extra capacitance $C_H$’ added in parallel to the reactor).

Both the peak-value $V_P$ and the DC level $V_{DC}$ of the reactor voltage are affected by $C_R$ (Fig. 4). A low value of $C_R$ results in a high peak voltage and a low DC voltage. A higher value of $C_R$ means that the reactor is charged and discharged slower. During slower charging, the voltage is not able to overshoot the plasma inception as far as with a low $C_R$ value, which results in a lower peak voltage. Also the number of reactor channels has an effect on the $V_{DC}$ level ($V_{DC1}$.. $V_{DC4}$ in Fig.4). This can be explained by the fact that more channels imply more plasma and as a result, a lower plasma “resistance”. The reactor discharges faster.

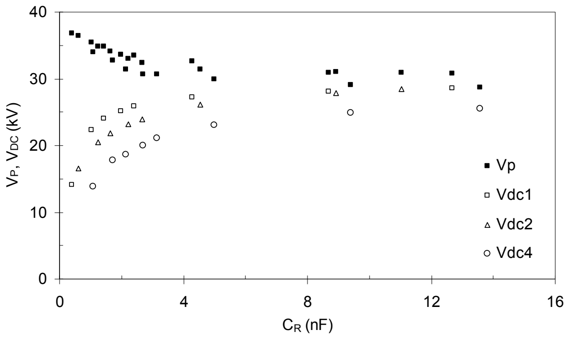

**Fig. 4** Effect of the total reactor capacitance on the peak and DC-level of the applied reactor voltage, at a pulse repetition rate of 800 pps

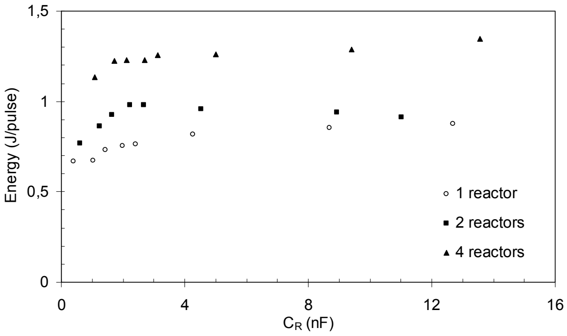

**Fig. 5** Energy-per-pulse versus total reactor capacitance for 1-4 reactor channels (550-800 pps)

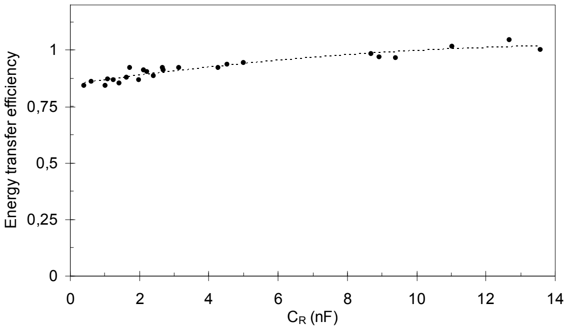

**Fig. 6** Energy transfer efficiency versus total reactor capacitance (550-800 pps)

Fig. 5 shows the effect of the total reactor capacitance $C_R$ on the energy per pulse. It can be seen that more energy is dissipated by the plasma when $C_R$ is increased. When $C_R$ 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 reactors 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 $C_R$ (see Fig.6), and does not depend on the number of parallel channels. The overall efficiency is high: around 92%±6%.

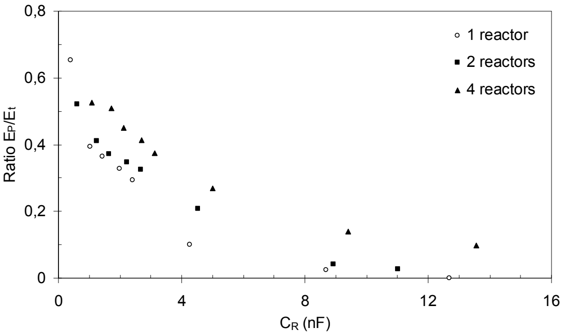

**Fig. 7** Energy ratio $E_P/E_t$ versus total reactor capacitance for 1-4 reactor channels (800 pps)

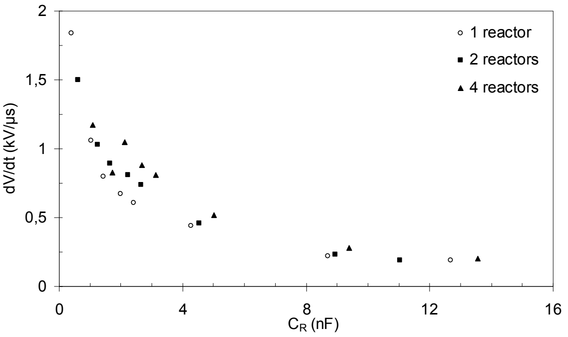

**Fig. 8** d*V*/d*t* of the applied reactor voltage versus the total reactor capacitance for 1-4 reactor channels (800 pps)

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 $E_P$ (so 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 $C_R$ (see Fig. 7). A higher $C_R$ implies that less energy is dissipated during charging of the reactor. A low value for $C_R$ results in a high voltage rise rate d*V*/d*t* on the reactor (Fig. 8). Consequently, for high d*V*/d*t* the plasma is more intense and a large portion of the energy is already dissipated during the charging of the reactor.

In order to study the spatial development of the plasma, and to estimate the plasma volume several photographs were taken under different conditions (Fig.9). The plasma depends on the 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 $V_{DC}$=20.3 kV) streamers cross the complete gap (Fig.9a). However, if the applied voltage is low (i.e. $V_P$= 23.8 kV and $V_{DC}$=19.5 kV), streamers are only visible in the vicinity of the electrode (Fig. 9d). 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 [4]. From the photographs with crossing streamers the average streamer width was determined to be 737 µm and the plasma volume was estimated to be about 0.5-2.0 dm$^3$/channel.

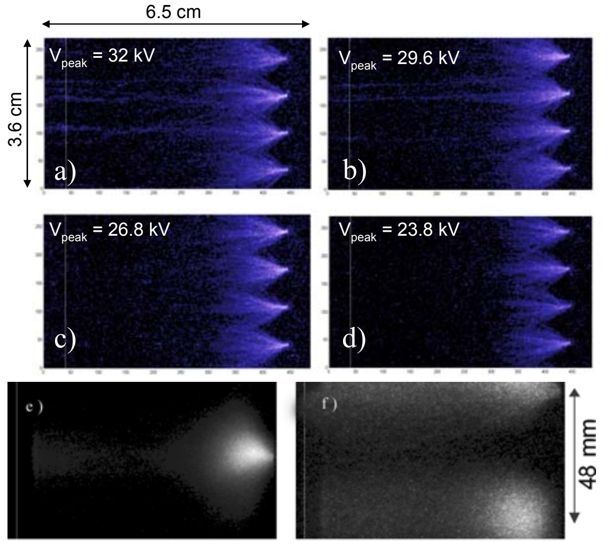

**Fig. 9** Effect of peak voltage on streamer appearance
a) Reactor voltage: $V_P$ =31.9 kV, $V_{DC}$ =20.3 kV
b) $V_P$ =29.6 kV, $V_{DC}$=20.2 kV
c)$V_P$ =26.8 kV, $V_{DC}$=19.9 kV
d)$V_P$=23.8 kV, $V_{DC}$=19.5 kV
e-f) Top-view photographs with
e) only one electrode in the reactor, and
f) effect of adjacent electrodes (distance between electrodes was 48 mm).
For both pictures: $V_P$ = 31.9 kV, $V_{DC}$ = 20.3 kV, 100 pps

Results regarding ozone yields are summarized in Fig. 10. 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 self destruc-tion of ozone is not significant in this regime. No significant difference can be observed between measurements with *CL* =3 µF and 6 µF.

The ozone yield depends on both the ratio $E_P/E_t$ (Fig. 10a) and on the d*V*/d*t* of the reactor voltage (Fig. 10b). The higher these ratios, the higher the ozone yield. This implies that ozone is created more efficiently when the energy is dissipated during the charging stage of the reactor. A high ratio $E_P/E_t$ and a high d*V*/d*t* are obtained when $C_R$ is low. The plasma is most efficient for a high peak voltage $V_P$ and a low $V_{DC}$ 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.

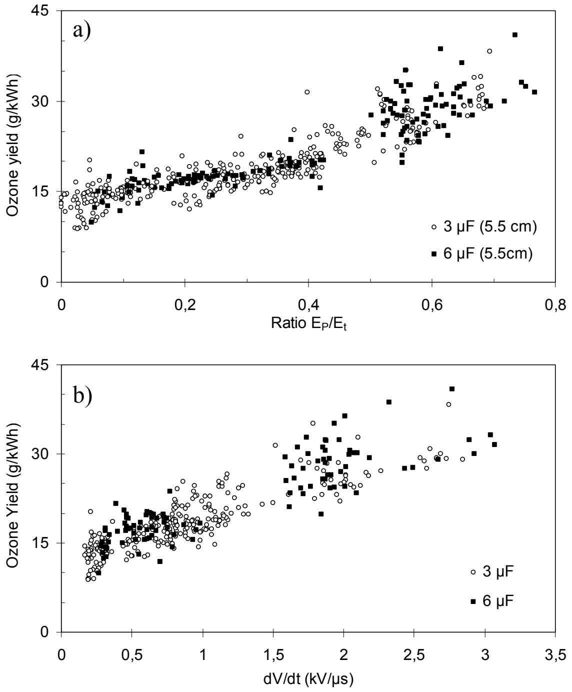

**Fig. 10** a) Ozone yield versus energy ration $E_p/E_t$. b) Ozone yield versus d$V$/d$t$ of the applied reactor voltage. Both plots for $C_L$ = 3-6 µF

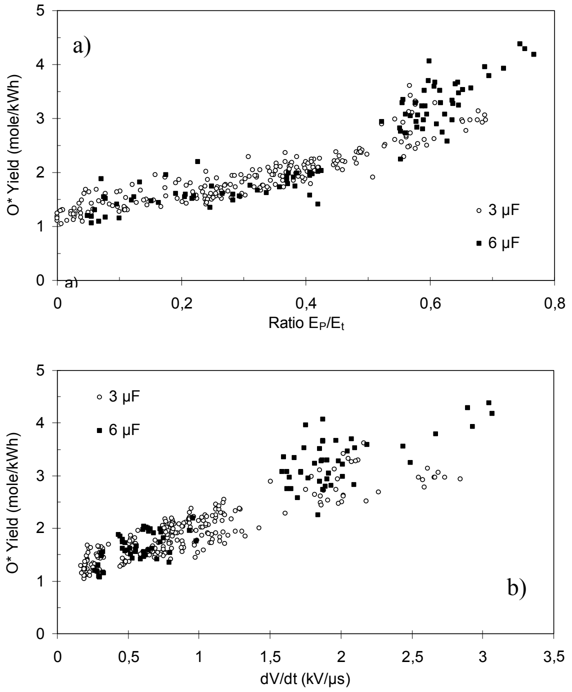

**Fig. 11** a) O-radical yield versus energy ration $E_p/E_t$, b)versus d$V$/d$t$ of the applied reactor voltage. Both plots for $C_L$ = 3-6 µF

The O* yield also depends on the ratio $E_P/E_t$ and on d$V$/d$t$, and is controllable between 1 mole/kWh -4 mole/kWh (see Fig. 11). The higher the $E_P/E_t$, 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, $C_R$ needs to be low. This corresponds to a high $V_P$ and a low $V_{DC}$ (inclined towards pulsed corona plasmas). With ns-pulsed corona, typical values of 3 mole/kWh -7 mole/kWh can be obtained, whereas the yields >4 mole/kWh require voltage pulse widths <50 ns. For the more common pulse widths of >100 ns, radical yields are comparable with the yields reported here for an AC/DC based system.

## 4 CONCLUSIONS

AC/DC-pulsed plasma is a good alternative for ns-pulsed corona plasma.

- For all parameters, an energy transfer efficiency (from mains to corona plasma) of more than 90 % could be obtained.
- With optical measurements, the average streamer width was found to be ~740 µm. With this streamer width an estimate for the plasma volume was made.
- The obtained yields of O-radicals (typically 2-4 mole/kWh) are excellent. 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 high voltage capacitance and the total dissipated energy). This experimental condition can be obtained when d$V$/d$t$ is chosen high.

## 5 ACKNOWLEDGEMENT

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## 6 REFERENCE

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