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DESIGN AND WORKING CHARACTERISTICS OF A MULTI-KILOWATT PLANAR TYPE DBD PLASMA GENERATOR FOR USE WITH ATMOSPHERIC AIR IN GAS CLEANING APPLICATIONS

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ABSTRACT

The paper reports on the construction and operating characteristics of a planar dielectric barrier discharge (DBD) plasma generator. The generator was powered from a commercial frequency inverter at 400 Hz through an high voltage transformer. It could be operated up to an specific energy density (power per gas flow) of 20 Wh/m³. The corresponding power density was about 0,5 W per cubic centimetre of discharge volume.

Special emphasis was given to a simple and reliable construction, which was easy to assemble and is based on a new, nonexpensive barrier material with excellent electrical, mechanical and thermal properties. The modular reactor design allows simple plasma power scale-up.

The reactor works with undried ambient air without additional cooling. In the range up to 10 Wh/m³ the ozone generation from ambient air was directly proportional to the energy density at a rate of 60 g O_3 per kWh or 30 ppm/Wh/m³. Thus the generator can serve as an effective source for chemically active radicals in plasma gas cleaning applications.

INTRODUCTION

Dielectric barrier discharges (DBD) and corona discharges can be used to produce large volume non-thermal plasmas at atmospheric pressure. Such plasmas are sources of highly reactive species (radicals, ozone, excited atoms and molecules), which can be utilised to oxidise volatile organic compounds in industrial off-gases to harmless or less toxic compounds. Such plasma-assisted oxidation can be combined with conventional catalytic incineration. Due to a well pronounced synergism, the energy demand for the whole cleaning process can be substantially lowered, especially for the case of relatively low contamination levels (< 100 ppm) of the input gas[1,2]. Another perspective application of non-thermal atmospheric plasmas is the plasma-assisted selective catalytic reduction of NOx in car engine exhaust gases[3-5]. In both mentioned application fields there is a need for reliable, highly effective plasma generators, stable working under changing operating conditions and gas compositions. A simple, robust design using non expensive construction materials and an easy assembling will support the acceptance and introduction of these new technologies.

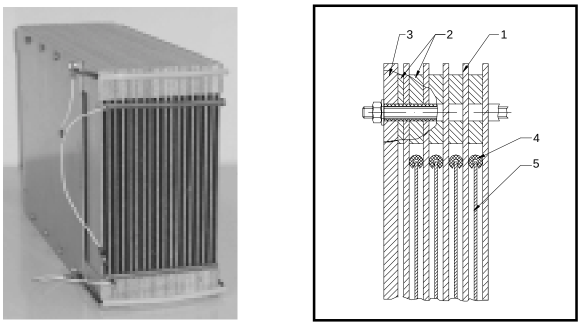

Fig. 1: Photograph and principal construction of the discharge module

In this paper we report on the design and operating characteristics of a plane DBD plasma generator together with scaling suggestions. The generator needs no additional cooling, its plasma power can be adjusted instantaneously to the actual demand up to large values.

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DISCHARGE MODULE DESIGN

For the applications mentioned in the introduction one has to treat in most cases huge volume flows ranging from hundreds to several ten thousands of cubic meters per hour. Suitable plasma reactors therefore consist of a large number of identical discharge modules. It was our intention to find a module design, which is easy to produce and to assemble, which is built using low cost barrier material rather than expensive ceramics and which is uncomplicated in service. Because we wanted to work without gas cooling these design goals resulted in the construction of a symmetrical plane barrier discharge as shown in Fig. 1. The discharge module is assembled as a batch of equally spaced rectangular plates of the dielectric barrier material. The size of these plates is 245 x 370 mm² with a thickness of 2 mm. Spacer strips (5 mm thick) were made from the same material and mounted along the larger rectangular side. The whole stack is then tightened by means of isolated threatened rods. Stainless steel plates (182 x 280 mm², 1 mm thickness) have been inserted into the 5 mm slots as the discharge electrodes. The electrodes were fixed and centred midways between the barrier plates, using slotted PTFE tubes. The electrode plates have wire hooks on alternating sides, which were used for grouping and electrical connecting them. The example module, shown in Fig. 1, has 18 x 2 discharge gaps, resulting in a total discharge volume of 3,67 litres. Its overall dimensions are 245x370x140 mm³. For given discharge volume the discharge gap determines the required working voltage and the number of single pieces, forming the module. Choosing a small gap allows one to work with moderate voltages, which are easier to handle and result in a quite uniform discharge. On the other hand there are substantially more parts needed and the whole assembly with narrower slots results in a greater flow resistance. The actual total 4 mm gap we have chosen for our device seems to be a reasonable compromise.

For the barrier material as well as for the spacers we used a special patented compound, made from mica and high temperature silicon resin. This material is available in large size plates, can easily be machined, drilled and cut and can withstand temperatures up to 400 °C. It has a dielectric strength of 20 kV/mm and a permittivity of about 5. The dielectric losses of the material show only a weak temperature dependence (tg(δ)=0,017 @ 30 °C/1 kHz, 0,166 @ 200 °C/1 kHz) in contrast to borosilicate glass (tg(δ)= 0.05 @ 25 °C/1 kHz, 7,44 @ 200 °C/1 kHz) . The barrier is chemically inert and not brittle. Even after long term usage there could not be observed any erosion traces. All these properties and the moderate price give the mica compound precedence over quartz, borosilicate glass or alumina ceramics.

POWER SUPPLY

The power supply and control unit are contained in a separate rack. The control unit has a unified interface, which makes it easy to integrate the plasma generators into existing technological processes. The working voltage comes from a special high voltage transformer, which is fed by a three-phase frequency inverter. This way, all the usual control, tuning and supervision possibilities of an industrial frequency inverter can be used for operating the generator. In particular, a nearly instantaneously power control can be realised in order to response to changing plasma power demand. Furthermore, any possible malfunctions of the plasma generator (flashover, barrier breakthrough ...) can be detected and will shut down the power supply, thus preventing the device from further damage.

MEASUREMENTS

The electrical measurements on the plasma generator have been made using a Tektronix TDS 520 digital storage oscilloscope. Data acquisition from the oscilloscope was done by means of the scope GPIB interface and visualised and interpreted through a HP VEE application program. The barrier discharge voltage was measured by a Tektronix high voltage probe P6015A, discharge current was measured with 20 MHz current transformer type 2-0.1W from Stangenes Ind. Inc. The electrical energy, delivered to the plasma during one discharge cycle, could be derived directly from the scope, multiplying voltage and current in the scope's math channel and integrating the product over a period. Another method for obtaining the plasma power is using the discharge Lissajous figure, when plotting transported electrical charge Q through the discharge as a function of the applied periodical voltage U (see Fig. 2). Experimentally the charge Q can be derived either as the time integral of the measured discharge current (preferentially used in the present paper) or from the voltage drop Um across a measuring serial capacitor Cm>> Cb,Cg according to the relation Q= Cm∗Um.

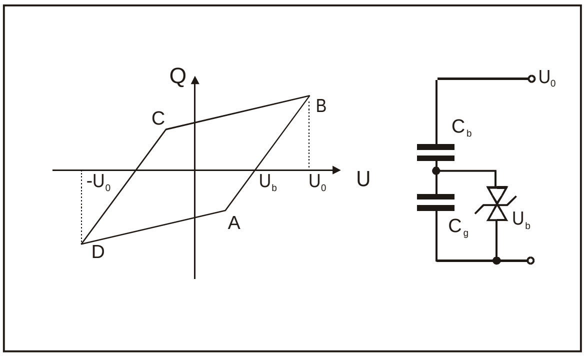

Fig. 2: Equivalent electrical scheme for a barrier discharge and resulting Q-U-characteristic (Lissajous figure)

The cycle energy is then simply the area of the characteristic figure (which in most cases is nearly a parallelogram). Both methods have been proven to give the same results under our measuring conditions.

A common interpretation of this Q-U-plot is as follows[6]. The barrier discharge can be represented as a series connection of two capacitors Cg and Cb, where Cg is the capacitance of the air gap and Cb the capacitance of the adjacent dielectric barrier. When the voltage across the air gap exceeds a certain value Ub multiple filamentary discharge channels begin to bridge the gap and continue developing till the voltage reaches its maximum U0 at point B. These behaviour is represented by the bipolar Zener diode with breakdown voltage Ub. From B to C there is no discharge and the gap charge, produced in the preceding period, is changed to the opposite sign due to displacement current. At C the breakdown conditions for the reversed polarity are reached, starting a new discharge phase from C to D. Thus lines AB and CD represent burning discharge, where the air gap is (at least partially) shortcut. The slope dQ/dU of the lines is the effective capacitance and should be equal to Cb for fully bridged gap. On lines BC and DA, where there is only displacement current, the slope dQ/dU is lower and corresponds to Ct=(Cb∗Cg)/ (Cb+Cg) – the series capacitance of Cb and Cg.

The air flow through the discharge module was measured with a rotameter, the gas temperature before and after the stainless steel vessel, containing the module, was monitored as well as the air humidity. The ozone concentration was determined by UV absorption with an Ozomat device from Anseros.

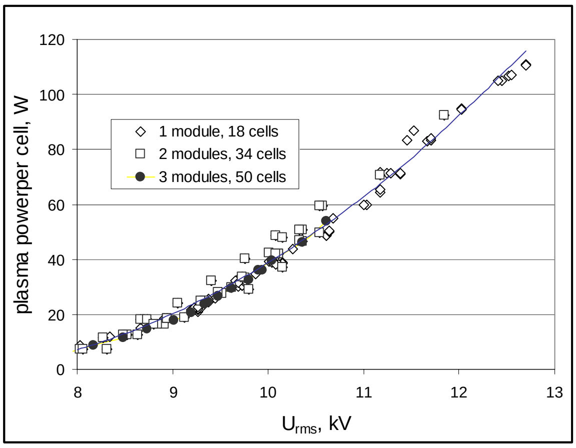

Fig. 3: Normalized power per discharge cell as function of applied discharge voltage

RESULTS

Plasma Power

The electrical power deposited into the discharge has been determined in dependence from the applied voltage at a frequency of 400 Hz as shown in Fig. 3. These measurements have been made with one, two or three discharge modules, connected in parallel, and the obtained power was normalised to the number of discharge cells involved. For the given design and conditions this normalised power can be used as a basic parameter for scale up. At a rated rms voltage of 13 kV this power is about 110 W, thus a module, consisting of 18 discharge cells, as described above will deliver a total power of 2000 watts. It has to be noticed that when operating with constant supply voltage, the plasma power will rise substantially from switching on due to the decreasing gas density during warm-up, till a thermal steady state is reached. We found, that the plasma power can be stabilised more easily by setting the frequency inverter output current. The temperature rise of the gas, passing through the discharge, should correspond to the plasma power in input per unit flow an can roughly be estimated assuming an adiabatic heating of the flow. The example curves from Fig. 4 show, that this measured and calculated temperatures for two different gas flows are in a good agreement, thus confirming the consistency of electrical and thermal measurements. Measuring the consumed power from the plug with a three phase electricity meter and relating it to the plasma power we found that the overall efficiency of the plasma generator is better than 90 %.

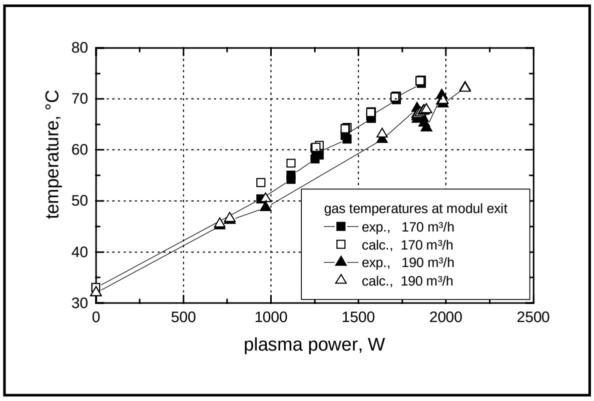

Fig. 4: Measured and calculated gas exit temperatures on dependence generated plasma discharge power

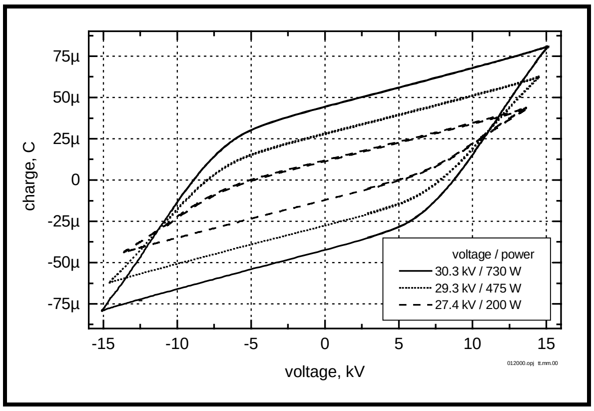

Fig. 5: Influence of reactor voltage amplitude on the shape of Lissajous figures

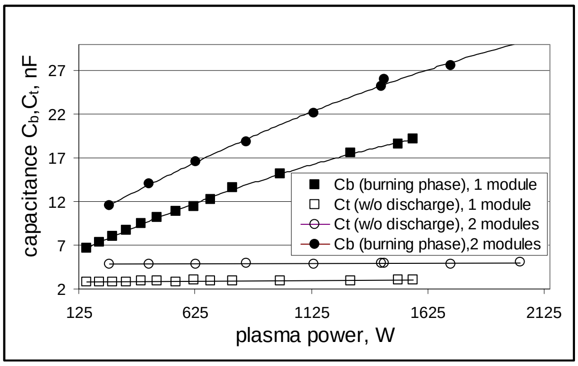

Fig. 6: Module capacitance for discharge and non discharge conditions, as derived from Lissajous figures. The total geometrical barrier capacitance for one module was 23 nF

Apparent capacitance

In our experiments we found that increasing the discharge voltage did not simply blow up the Lissajous figures, preserving the Ct and Cb slopes, but also results in a rising slope Cb for the discharge part of the curve (Fig. 5 and 6) approaching to the pure “geometrical” capacitance of the dielectric barriers. This behaviour can be explained from the observation, that with increasing discharge voltage more and more discharge filaments built up and fill a growing part of the electrode area until finally the whole gap area is bridged and covered with discharge filaments. This circumstance has to be taken into account when applying the well known relation[6,7]

$$P = 4 * f * V * [Cb * U - Cb/(Ct + Cb) * V]$$

between the capacitances Cb, Ct, the burning voltage V, the driving voltage U and the frequency in order to estimate the possible plasma power P for a given reactor design: Taking for Cb the geometrical capacitance of the barrier will result in an upper limit for the power.

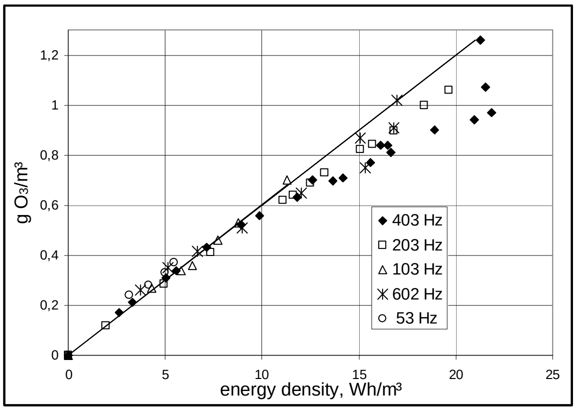

Fig. 7: Ozone production in the discharge module as a function of applied plasma power per unit flow, when operated with normal room air (30 °C, 17 % relative humidity at reactor entrance, flow 30 m³/h), indicated is the working frequency

Ozone production

For VOC removal by plasma or plasma-catalytic treatment the ozone generation capability is an essential feature of a given reactor design, because it mainly will determine the operating costs. We measured the ozone production as a function of applied energy density (plasma power input per unit flow) for several working frequencies in ordinary atmospheric air (flow 30 m³/h with 30 °C and 17 % relative humidity at the reactor entrance). In the range up to 10 Wh/m³ the ozone generation is directly proportional to the energy density with a rate of 60 g O_3 per kWh or 30 ppm/Wh/m³ (Fig. 7). This efficiency compares quite well with the reported values of 80-95 g/kWh[8], which have been achieved however in cooled devices with dried air. That means that the described discharge module is capable to generate 120 g/h of ozone in a gas flow of 200 m³/h of atmospheric air from an electric power of about 2 kW.

For higher energy inputs the rate decreases due to temperature effects and NO generation. In the investigated region from 50 to 600 Hz there was no frequency effect of the applied sinusoidal voltage, despite the fact that the discharge character turned from pronounced filamentary type to more homogeneous with increasing frequency.

SUMMARY

We have presented a simple and reliable design of a barrier discharge reactor working with atmospheric air, operated through an standard high voltage transformer from an commercial frequency inverter. Due to the modular reactor design, the ease of manufacturing and assembling it can be scaled up for large power and gas flow levels. The use of a non expensive special mica compound material with high electric and thermal strength as dielectric barriers results in a great construction flexibility and high reliability of the device. The reactor is capable to generate ozone from ordinary atmospheric air without additional cooling with an efficiency of 60 g/kWh.

ACKNOLEDGEMENT

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