Double Dielectric Barrier Discharge Chamber for Ozone Generation

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***Abstract*— The paper proposes an ozone generation generated by double dielectric barrier discharge chamber which is operated at atmospheric pressure discharge and supplied by high frequency power converter. The air fed or oxygen is bombarded inside chamber that is constructed by a planar type chamber using double aluminum mesh on a metal plate and a double mica sheet as dielectric material. The power converter utilizes the class E parallel resonant converter operated at 39 kHz and maximum voltage 3 kV peak to peak.. The system is able to produced ozone product more than 150 ppm. Due to the simplicity and low cost design, it can be suitably used for low-density application such as home water treatment.**

Keywords—dielectric barrier discharge; ozone generation; resonant converter

I. INTRODUCTION

Ozone gas (O3) is widely used in deodorization, decolourization, disinfection, bleaching processes, gas/air treatment, chemical synthesis and recently in medical applications [1]. In many of the applications mentioned above, it is crucial to deliver O3 within the correct dosage. Over- or under-dose of O3 may have ineffective or destructive effects. The dosage can be related to ozone gas concentration, measured in part per million (ppm) or mg/m3. One example to illustrate the importance of exposing the correct ozone concentration is in the bacteria disinfection for post-harvest treatment of fruits. It is reported in reference [2] that when the ozone concentration is not delivered in appropriate dosage as illustrated in Table 1, the skin colour can be changed and the quality of the fruit is reduced [3]. Hence the importance of knowing the concentration of ozone gas produced by the ozonizer.

Table 1 Ozone treatment on Post harvest [2]

Name of fruit	Ozone concentration	Treatment Time
Apple	0.4 ppm	daily
Citrus	0.3 ppm	daily
Lemon	0.3 ppm	daily
Pear	0.4 ppm	daily
Strawberry	0.35 ppm	2 days

Several mechanism of ozone generation had been studied namely corona discharge, pulse streamer discharge, and silent discharge [4]. Nowadays, the silent discharge ozonizer is preferable [4] because it requires lower inception voltage and reduced power consumption. Furthermore, the discharge occurred homogenously throughout the entire volume of the reaction chamber, resulting in lower temperature thus eliminating the need for a cooling system. The silent discharge chamber is formed by two metal electrodes with dielectric layer and air gap in-between them. It is also known as dielectric barrier discharge (DBD) [4]. The chamber is subjected to a high voltage across its electrodes which supply the energy for the micro discharges to take place. These micro-discharges break the oxygen molecules into single oxygen atoms, which the combine with oxygen molecules to form ozone gas [5].

The use of high frequency ac power supply (in the range of tens to hundreds of kHz) allows for an increase in the discharge power to the DBD chamber [5]. In effect, the application of high frequency decrease of the required amplitude of the applied voltage. The main advantage of having a lower applied voltage is the opportunity to build ozone generators using non-conventional dielectric materials which are known to have much lower dielectric breakdown voltage such as mica, alumina ceramic, and polymer. Furthermore, high frequency transformer requires much smaller footprint than the conventional 50/60Hz transformer.

The power delivered (P) in ozone chamber, as it is reported in reference [5] can be obtained by approximated formula as follow:

$$P = \frac{1}{T}\int V(t) \cdot I(t)dt \qquad (1)$$

$$W = \int V(t) \cdot I(t)dt \qquad (2)$$

Where W is energy loss per cycle inside the chamber, V(t) is the voltage across the chamber, and I (t) the current flow through the ozone chamber. After having the energy lost per cycle, the power consumed by the silent discharge can be obtained by multiplied the energy lost per cycle with the frequency (f) of applied voltage. The equation becomes:

$$P = W \cdot f \qquad (3)$$

Regarding the equation above (3), the use of supply frequencies above 50-60 Hz allow to increase the power density applied to the electrode surface inside chamber and increase ozone production for a given surface area, while decreasing the necessary peak voltage. The higher the frequency, the higher the power density and the lower the applied voltage. The use of switching converters based on fast power electronic devices such as metal oxide semiconductor field effect transistors (MOSFETs) or insulated gate bipolar transistor (IGBT) will give the possibility to increase the frequencies up to several kHz [6, 7].

The chamber where the ozone generated is constructed by a planar type chamber using double aluminum mesh on a metal plate and a double mica sheet as dielectric material. The present of double dielectric inside the chamber during discharge makes this chamber is known as double dielectric barrier discharge (DDBD) and operated at atmospheric pressure and ambient temperature.

II. THE DDBD CHAMBER

The proposed DDBD chamber is designed with simplicity and practically in mind. It is to be operated at atmospheric pressure and ambient temperature condition without the need to use special gas. In addition, it requires no or water cooling. The geometrical configuration is a simple rectangular shape with a planar dielectric barrier, and the chamber is constructed in 70 x 140 mm square as shown in Fig.1.

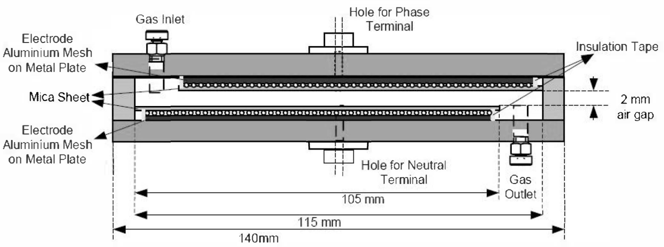


Fig.1 DDBD chamber

The proposed dielectric material is muscovite mica. Muscovite mica is tough, less flexible, and is known to have high abrasive resistance with excellent durability. It is possible to construct a wide plane dielectric shape muscovite mica with 0.1 mm thick without a crack. The dielectric strength is more than 20 kV/mm with dielectric constant between 6 to 7. The maximum operating temperature is about 500^{o}C. The air gap inside the chamber is designed at 2 mm. The high voltage and ground electrode is constructed using aluminium mesh placed on a metal plate. The small wire of aluminium mesh form a rough and non homogenous geometrical surface. The rough and non homogenous surface is known to assist the creation of electrostatic field emission to release electron from the electrode [8]. A high voltage insulation tape is wrapped around the edges sides of electrode to prevent the spark or arch to occur.

The advantages of planar chamber shape are simple construction, easy adjustment for air gap with filler materials, simple replacement and arrangement for different type of electrode and dielectric. Furthermore the electrodes are easily connected to the high voltage phase and neutral wire by means of alloy solder. The casing and spacer is made from acrylic or polymethyl methacrylate so the prototype can be constructed rapidly.

When the input gas is injected into chamber, it is desirable that the injected gas should flow smoothly from inlet to outlet. By using a Fluid Flow Simulation provided by QuickSTREAM version 2.0, the gas flow inside the chamber in Fig.2 can be visualized. The simulation is conducted by using air with dynamic viscosity 1.56.10^{-5} kg/(m.s), density 1.2041 kg/m^3 and temperature 27^{o}C. The position of inlet tube in vertical and in front of the spacer gives the laminar flow of the gas. It ensures that the gas has no swirling motion.

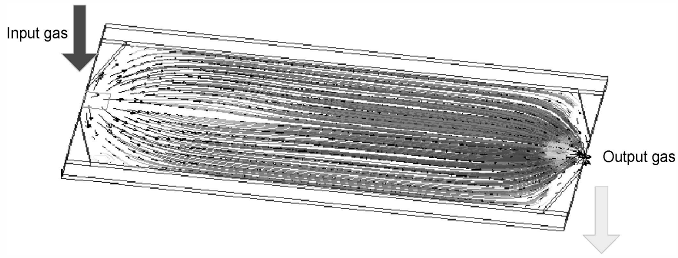


Fig. 2 Simulation result of gas flow inside the chamber

III. CONVERTER FOR OZONE GAS GENERATION

The class E resonant converter is very attractive as it utilizes only a power semiconductor switch and therefore exhibits low power losses [6, 9]. Output frequency can be varied by simply varying the switching frequency. The basic configuration of class E resonant converter connected to RC load is shown in Fig.3.a. To increase the voltage by, a high voltage high frequency transformer is added as shown in Fig. 3.b. It is normally constructed using ferrite core. The secondary winding of transformer (L_o) is included as part of the resonance tank. The RC load in the circuit represents of equivalent circuit of ozone chamber.

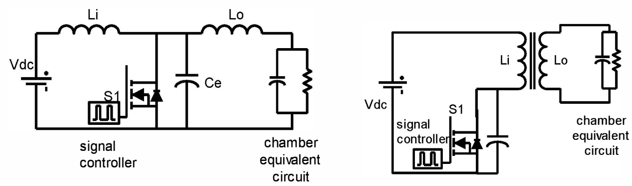


Fig.3 Circuit of Class E resonant converter (a) basic configuration, (b) with step up transformer

The modified converter is designed to operate in wide range of frequency. Pulse Width Modulation integrated circuit (PWM IC) controller (TL 494) is used to produce pulses in the range 10 < f < 100 kHz. This is achieved by varying the value of variable resistor as it is shown in Fig. 4.

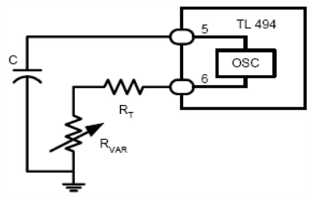


Fig. 4 Circuit for frequency adjustment in IC TL 494

The control signal frequency generated by TL 494 is determined by the following equation:

$$f_{oscillator} = \frac{1.1}{(R_T + R_{Var}) + C} \qquad (4)$$

Where R_T is a fixed resistor and R_{var} is the tuning resistor respectively. For example by selecting C=10nF, R_T=1 kOhm and R_{var} in the range 0 to 20kOHm, the possible generated frequency is in the range 5.2 kHz to 110 kHz.

To isolate the control circuit and power circuit and also to drive the power MOSFET, a gate drive opto coupler 3120 is selected. With regard to high voltage stress (V_{DS}) that might occur at the drain to source, the IRF 640 MOSFET is selected. It has V_{DS} breakdown voltage up to 200 V and continuous drain current 18 A. The converter is supplied by standard laboratory DC source. The complete circuit of purpose converter is shown in Fig.5.

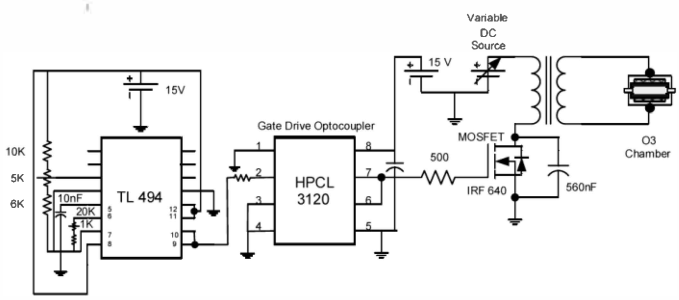


Fig.5. Circuit of power supply

IV. EXPERIMENT AND RESULT

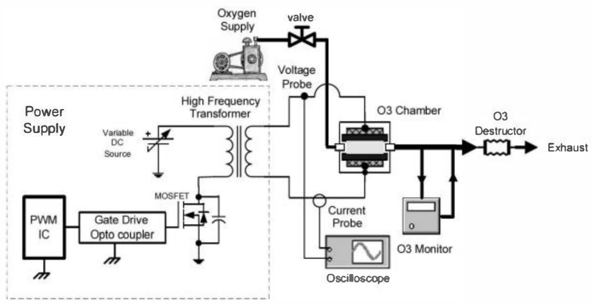
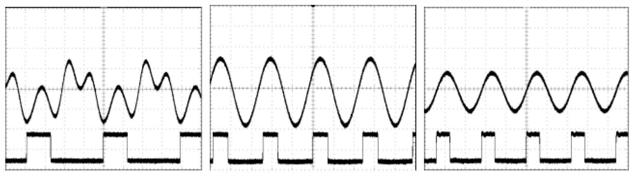


Fig.6 Experimental Set Up

The experimental setup of the complete ozone generation system is shown in Fig.6. It consists of PWM IC, gate drive opto-coupler MOSFET, high frequency transformer, ozone chamber, ozone destructor, variable DC source, gas supply, oscilloscope, high voltage probe, current probe, and ozone monitor.

During the experiment, the frequency of sinusoidal output voltage is controlled by adjusting the tuning resistor. The waveform of output voltage at the chamber side and control signal at different frequencies are shown in Fig.7. Below ω_o , the sinusoidal waveform is distorted. At resonant, a highest sinusoidal amplitude is achieved. Above ω_o , perfect sinusoidal achieved but at lower amplitude.



(a) (b) (c)

Fig.7. The different output voltage at terminal chamber with different frequency with attenuation 1000 V/DIV (upper), and the different frequency control signal 10 V/DIV (lower), (a) 10μs/DIV (b) 10μs/DIV (c) 20 μs/DIV

The ozone chamber was fed with 1 liter per minute input gas flow. Three type of input gas is used, namely natural air, dry air and oxygen. The experiment is conducted at 30^o Celsius and 734.3 Torr or 101.328 kPa which is approximately at atmospheric pressure and ambient temperature. In Fig. 8 at 3.5 kV the ozone product has reached 40 ppm and 60 ppm O_3 with regular air and dry air as an in put gas respectively. The use of oxygen is possible to increase ozone production until 157.28 ppm.

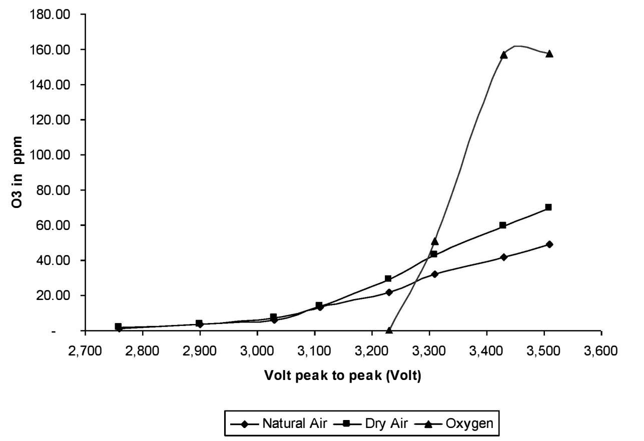


Fig.8 The ozone product in ppm by volume as the function of voltage for different input gas

The different results occur in ozone generation using air and dried air as the gas feeder. The present of CO_2 and H_2O in the gas feeder also gives effect in the deformation of ozone as it is shown by the following reactions [1].

$e + CO_2 \rightarrow CO + O$ (R.1)

$O + O_3 \rightarrow 2O_2$ (R.2)

$CO + O \rightarrow CO_2$ (R.3)

$O + O \rightarrow O_2$ (R.4)

$O2 + N2 \rightarrow 2NO$ (R.5)

$2O + O_3 \rightarrow N_2O_5$ (R.6)

$N_2O_5 + H_2O \rightarrow HNO_3$ (R.7)

The use of dry air reduces the content of CO_2 and H_2O in input gas. As the oxygen is applied as input gas, there is only few or no nitrogen gas present at input side[1].

In Fig.8, the formation of ozone fed by air and dry air has occurred early than oxygen fed. At low voltage there are two step of reaction[1, 5]. First, an oxygen molecule is dissociated to oxygen atom as in reaction (R1). Second, atomic oxygen reacts with the third body to create an ozone molecule as it is shown in reaction (R2).

$$O_2 \xrightarrow{e} O + O \quad (R8)$$

$$O + O_2 + M \rightarrow O_3 + M \quad (R9)$$

In air or dry air, the third collision body (M) is nitrogen atom (N^+, N_2^+) which is possible to be formed in the lower voltage and energy and the formation of this atoms accelerate the reaction (R9) to form ozone [1]. But it is also noted [10, 11] that in other hand, this atomic nitrogen leads to the chains reaction in that reduce both oxygen and ozone concentration. This is the reason why ozone concentration produced by air or dry air is lower than ozone production by oxygen fed.

As the oxygen is injected to the chamber in Fig. 8, at the lower voltage, ozone is formed at onset voltage above 3.25 kV and follows the reaction (R8) and (R9) without nitrogen atom as third body involved [10], to produce atomic oxygen which recombine with oxygen molecule to produce ozone, and hence ozone detected. The ozone concentration increases at slow rate up to certain voltage and current, then it then to increase at higher concentration.

When voltage and current at ozone chamber is increased then the discharge power injected to the chamber is also increased as seen in Fig.9. At certain value of voltage the ozone concentration in ppm and ozone yield in g/kWh shows saturated curve in Fig.8 and 10. This shows that the excessive power inside chamber give the deformation of ozone [5, 10].

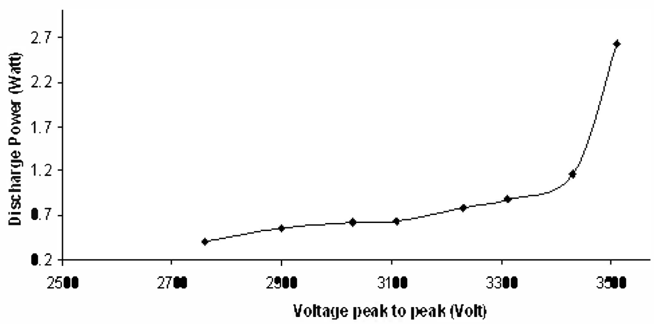


Fig. 9 Discharge power as the function of applied voltage peak to peak

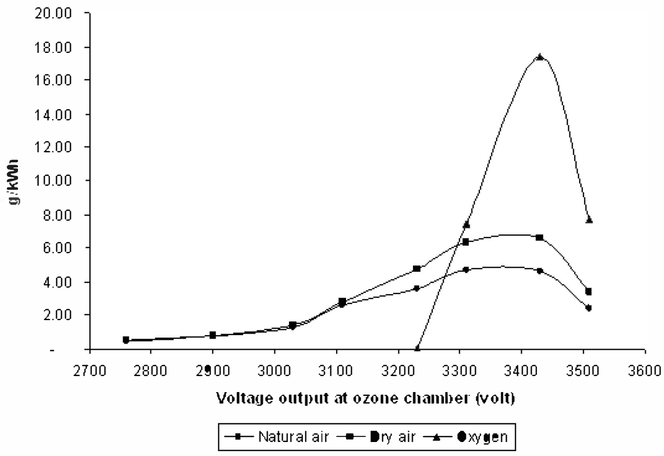


Fig.10 Ozone yield in mg/Wh as the function of voltage at different voltage and input gas

V. SUMMARY

A DDBD chamber supplied by resonant converter has been successfully designed and operated. The experiment successfully operated at atmospheric pressure and ambient temperature for home appliance usage. It was found that by using the proposed DDBD chamber the ozone product obtained has reached 40, 60, and 157 ppm O_3 with natural air, dry air and oxygen as an in put gas respectively.

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