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Submission date: 11-Sep-2020 06:16PM (UTC+0700)
Submission ID: 1384470802
File name: FmUNRI.docx (1.04M)
Word count: 3501
Character count: 18130

The Effect of Permanent Magnet on Dielectric Barrier Discharge (DBD) and Ozone Production

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Abstract. This paper reports the experimental results on the characteristic of ozone generator induced by a magnetic field from permanent magnets (ring PMs or combination of ring PMs and neodymium PMs) and a solid dielectric (floor ceramic/tile). Three electrode configurations (Models I, II and III) with ring PMs installed above and below the electrodes (anode and cathode of parallel plane type) were designed to examine the performance of an ozone generator. In addition, several small neodymium permanent magnets (neoPMs) were attached to the anode electrode for initiating plasma in the air gap. A ceramic was used in this study as a solid dielectric i.e. platinum brand ceramics made in Indonesia produced good plasma. The intensity of the light emitted by plasma in the gap, plasma position, relationship of current and voltage and amount of ozone production were measured experimentally. It is shown that the addition of PMs above and below the electrode greatly affects the performance of the ozone generator by the effect of the magnetic field.

1. Introduction

Dielectric barrier discharge (DBD) has been used by many researchers to convert oxygen to ozone. This is well-known as an ozone generator. The first step of this research began with the design of a high-voltage generator for plasma applications by designing a fly-back converter and H-bridge inverter with a solid dielectric of window glass sheet that was affected by a permanent magnetic field under the cathode electrode. The magnetic field and plasma that occur were designed in parallel. If the streamer discharge in the gas medium occurs towards the dielectric surface, it will produce the plasma. This is known as the surface barrier discharge or dielectric barrier discharge. In our previous research, there were four models of ozone generator induced by PM. Model I was DBD without a PM. Model II was DBD with a PM under cathode electrode. Model III was DBD with two PMs attached above anode electrode and under cathode electrode, and the condition of the magnetic force was attractive. Model IV was DBD with two PMs above and under each electrode which the magnetic force was repulsion condition. The gap distance between anode electrode and solid dielectric/tiles was about 4 mm [1-3]. On the other hand, the research conducted by Park et al. [4] used a needle as high-voltage electrodes (anode and cathode). The electric field generated in this study was non-uniform electric fields and the plasma produced was centred on the needle. This plasma was induced by a magnetic field and differed with the plasma without induction of a magnetic field. This electrode arrangement model was to create a gap between the needle electrodes and placed in the centre of a dielectric. Pakarek [5] investigated high-voltage plasma that was affected by permanent magnetic fields parallel to the direction of the plasma. The results of this study produced gas molecular ions which were exposed to high electric fields to become ozone gas. It is indicated that the discharge due to the influence of a magnetic field is different with the streamer discharge without the magnetic field effect. Liu et al. [6] examined the difference between the plasma induced by permanent magnetic fields and the plasma without induction of magnetic fields using a high-voltage generator with pulse scale in nanoseconds. The electrode arrangement used was a parallel plate with an arbitrary gap and a solid dielectric was placed on the cathode electrode. Plasma that occurs in a magnetic field rotates in the direction of the magnetic field and is slightly different from plasma without the induction of magnetic field.

The material of solid dielectric has also been investigated by many researchers. Abdelaziz and co workers [7] have completed research in describing hazardous compounds such as naphthalene using high- voltage plasma and the dielectric made of mica. Other dielectric materials such as alumina ceramics (Al_2O_3) can produce plasma in water as reported by Lukes et al. [8]. Nagahama et al. [9] used an alumina dielectric with the Kyocera A473 trade code which succeeded in producing plasma from several dielectric models that they had tested. Murdiya et al. [10] tested high-voltage plasma in mineral or vegetable oils at a voltage level of 30 kV with 60Hz frequency which was connected to the needle electrode as a high voltage electrode. The dielectric used was the high-density pressboard. Some patents have also been reported on the solid dielectrics made of quartz, mica, alumina solid dielectrics and sapphire insulators. The anode and cathode electrodes were made of metal which were coated by a solid dielectric. This tool/method is protected by U.S. Patent 9067788B1, Taiwan Patent TW467770B, U.S. Patent 10343940B1, U. S. Patent No. 4614573 and U. S. Patent No. 5549874 [11-15]. However, the above-mentioned tools/methods have several disadvantages including that the solid dielectric used is the result of a special manufacturer for ozone generators. These solid dielectrics are difficult to find in the market and the making of anode and cathode electrodes is more complicated because it needs to be coated with a solid dielectric. Furthermore, dielectric materials and arrangements are made in such a way as to improve the performance of ozone generators. Therefore, the ozone generator becomes more expensive because it uses a specific material.

This research seeks to overcome the problems mentioned above and find solutions for generators that are cheap and easier to find material on the market and recycle material. The author focuses on a solid dielectric that made of floor ceramic and attempts to combine it with recycle electrode that made of used steel. This technology also develops an ozone generator that induced by the ring PM which is a recycle material from a loudspeaker. This research also refers [18,19] that the ozone generator is supplied by non-sinusoidal inverter.

2. Methodology

Figure 1 shows a schematic of the experimental setup in this research. High-voltage plasma generators were designed using ring permanent magnets with a 12 cm in outer diameter and 2 cm thickness placed above and below the anode and cathode electrodes in order to inducing a barrier discharge in the air gap. Electrode arrangement models of the plasma generator designed in this study are shown schematically in Figure 2. Model I is a high-voltage plasma generator with a permanent magnet (ring PM) placed under the cathode electrode. Model II is a high-voltage plasma generator with two ring PMs placed above the anode electrode and below the cathode electrode so that two magnets repel each other. Model III is the same as Model II, but the state of the magnetic field attracts each other. The neodymium permanent magnets (neoPMs) of 20 pieces with a 8 mm in diameter and 2 mm thickness that attached on the anode electrode was also used for modification of Models I, II and III. This small permanent magnet was placed on the anode electrode to encourage the plasma which can develop on the surface of these neoPMs. Figure 3 shows the position of the neoPMs.

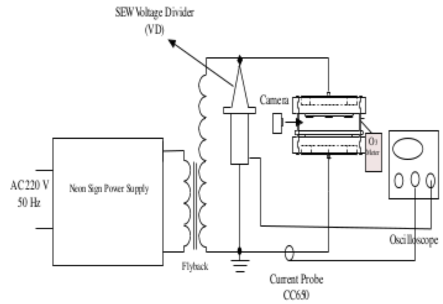
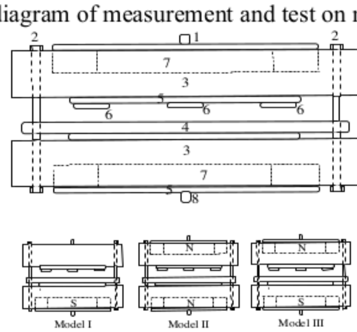
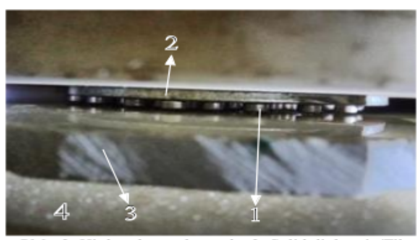


Figure 1. Schematic diagram of measurement and test on magnet ozone generator.



1: HV electrode termination, 2: Bolt and nut, 3: Nylon/holder, 4: Solid dielectric/Tile (Trademark platinum), 5: Electrode, 6: NeoPMs, 7: Ring PM, 8: Ground electrode termination

Figure 2. Schematics of Models I, II, and III.



1: Neodymium PMs, 2: High voltage electrode, 3: Solid dielectric/Tile, 4: Ground electrode

Figure 3. Position of neodymium PMs.

The plasma light intensity was measured by a digital camera connected to the Aspectramini software. The magnetic field intensity of ring PMs was measured using the FH51 Tesla Meter and it was 315 mT. While the magnetic field intensity of neodymium PM was 12 mT per piece. The number of neoPMs attached to the anode electrode was about 20 pieces. Solid dielectric placed on the surface of the cathode electrode was a ceramic floor/tile (made in Indonesia) with trademark “Platinum”. The dimension of the solid dielectric was of 200 mm length, 200 mm width and 8 mm thickness. In order to initiate plasma between the anode and the solid dielectric, the gap length was set at 7 mm. The high-voltage power supply used in this research was a neon sign power supply (made of China) with a voltage of 7-10 kV and frequency of 25 kHz and it was connected in both the anode and cathode electrodes. An applied voltage was measured by a Hantek 6204 BC digital oscilloscope using a SEW voltage divider which was connected to the anode terminal. The voltage divider ratio was 1000: 1. The discharge current was measured using a Hantek CC650 current probe. Plasma photographs were recorded using a digital camera on an android phone with a resolution of 8 megapixels. The air was injected in to the chamber by supporting a mini fan. Ozone measurements were carried out using HT-E-O3. A fan was used for blowing the air into the gap. All experiments were carried out at atmospheric pressure and room temperature.

3. Results and Discussion

3.1. Plasma Photographs and Light Intensity

All models (Models I to III) can generate plasma in the air gap. Plasma photographs and light intensity can be seen in Figures 4 and 5, respectively. The plasma occurs on the surface of neoPMs which is the anode electrode of the high voltage part of the power supply. Plasma that occurs at the air gap can be visually confirmed and each model produces a different plasma. By inducing the magnetic field of the ring PMs for all models, it has been proven that this ring PMs affects the development of plasma in the air gap. Figure 4 shows plasma photographs of three models. The plasma in Model I is a little poorer than that of Model II and Model III. While in Model III, it is indicated that the resulting plasma is denser than Models I and II.

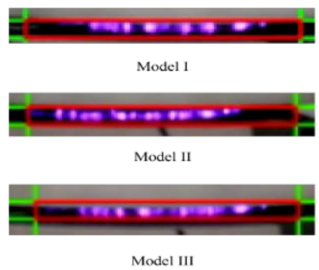
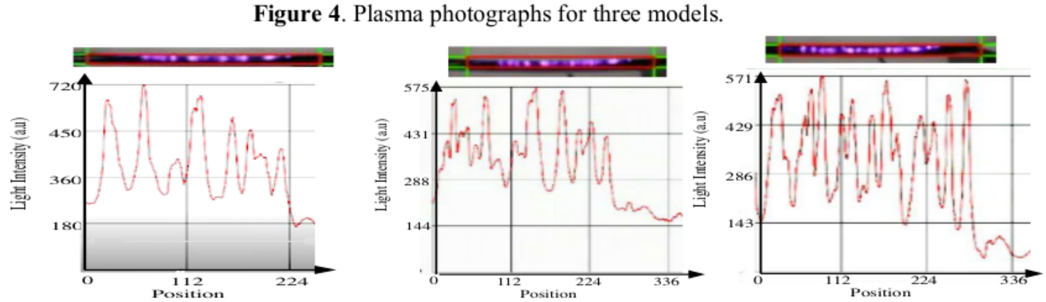


Figure 4. Plasma photographs for three models.



(a) (b) (c)

Figure 5. Light intensity for three models. (a): Model I, (b): Model II, (c): Model III.

A digital camera connected to the Aspectramini software was used to measure the light intensity of the plasma. The reference value from this software was 1000 in arbitrary unit (a.u.) for white colour. Light intensity for three models is shown in Figure 5. The highest light intensity in Models I to III was 720, 571 and 575 in a.u. on y-axis, respectively. The plasma in Model I expanded to the position 224 on the x-axis. However, Models II and III spread the plasma position up to 336. It is shown that the plasma in Models II and III is more evenly distributed and widely distributed than model I.

3.2. Discharge Current and Voltage

Discharge current and voltage for Models I, II and III are shown in Figure 6 a, b and c. Discharge currents were measured using a Hantek CC650 current probe after a few moments of discharge initiation. The peak current in Model I to III was around 25 mA for all models. The pulses of discharge current in model I occur at positive and negative cycle at maximum and minimum values. Then, these pulse also arise in model II and III for two cycles. These are start around maximum and minimum values of current with many pulses. These pulses in Model I has lower than that of Model II and model III. However, discharge currents between model II and III are slightly similar. The peak voltage generated at the anode electrode for Models I, II and III was around 5 kV at a frequency of 25 kHz. The effect of adding ring PMs on the top and or below the electrodes is significant. It is shown that the phase difference between the current and voltage changes by the presence of PMs.

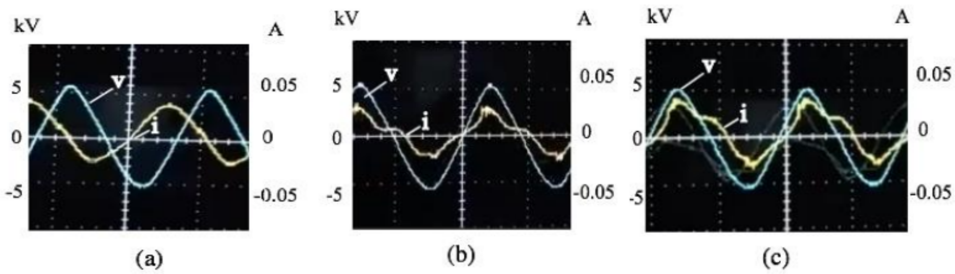


Figure 6. Discharge current I and voltage V. (a): Model I, (b): Model II, (c): Model III.

3.3. Ozone Production

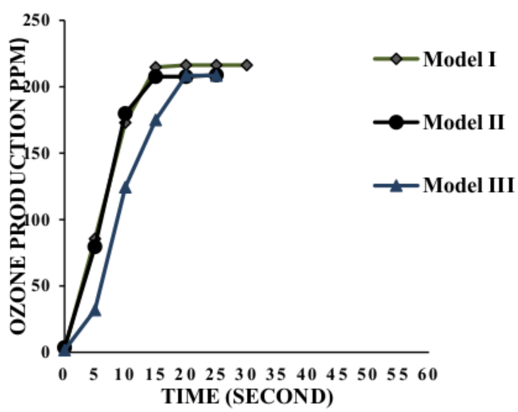


Figure 7. Ozone productions for three models.

Three models of an ozone generator produce ozone gases and they have already been confirmed in this study. The amount of ozone produced is shown in Figure 7. The effect of magnetic fields on ozone produced from ozone generators with the DBD technology is demonstrated in this study. Ozone production speed for Models I, II and III was 10.8, 10.3 and 10.4 in ppm/sec, respectively, for a discharge time of 20 seconds. However, an ozone generator without ring PM has a speed of 4.2 ppm/sec. It is seen that the ozone amount in ozone generators (Models I, II, and III) increases steeply in the process of reaching a maximum ozone value of ~ 200 ppm.

For three models of ozone generators, the magnetic field from the PMs has an important effect on the ozone production. In the previous study, Murdiya et al. designed four models of ozone generator induced by ring PMs and the ozone production after discharge times of 9 minutes was 60 ppm or less. It is shown in this study that the ozone production can be increased by neoPMs attached on high voltage electrode. The DBD induced by neoPMs promotes the effect of ozone production by the ionization process on oxygen molecules. The presence of a magnetic field in DBD broadens the path of free electrons in the ionization region (i.e. Larmor precession), and it bring down the mean energy of electrons to reach an high voltage electrode which will increase gradually by the collision with gas molecules [16, 17]. If the number of collisions with oxygen molecules increases, more ozone atoms will be formed. In the DBD induced by magnetic field, the effect of confinement is imposed on the electrons in the avalanche heads. When the direction of electric field is perpendicular to magnetic field, the electrons suffer a force. This is known as the Lorentz force in equation (1):

$$\boldsymbol{F} = e\boldsymbol{v} \times \boldsymbol{B} \quad (1)$$

where e is the electron, $\boldsymbol{v}$ the velocity of electron and $\boldsymbol{B}$ the magnetic field intensity, and this force is large. Hence, this condition reduces the processes of electron attachment and neutralization, and it decreases the decay of the surface electrons. As a result, the number of surface electrons is further increased before the discharge is initiated [3].

The effect of uniform electric field and magnetic field on DBD can be figured out by following considerations. The discharge consists of many micro discharge channels in the gap. These micro discharge channels are distributed evenly on the surface of high voltage electrode and barrier. Because the magnetic field vector is perpendicular to these channels, consequently, the Lorentz force will occur between the charge and the magnetic field. Then, it also contributes electric force (Coulomb force) acting on electric charge. We can create the formula which is represented by following equation (2).

$$\boldsymbol{F}_{total} = n\boldsymbol{F}_{e} + n\boldsymbol{F}_{m} = qn\boldsymbol{E} + qn(\boldsymbol{v} \times \boldsymbol{B}) = qn\boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B} \quad (2)$$

where n is the charge density, $\boldsymbol{F}_e$ the electric force, $\boldsymbol{F}_m$ the magnetic force, q the charge, $\boldsymbol{v}$ the charge velocity, $\boldsymbol{E}$ the electric field strength , $\boldsymbol{j}$ the current density and $\boldsymbol{B}$ the magnetic flux density. The Lorentz force will act on the charge in channels and it affects the micro discharge channels dimension and interaction between the micro channels, which can expand these channels on the surface of barrier. Model I is indicated that this process is easier to form the discharge channels and the intensity of plasma light is brighter than Model II and III. The effect of ring PMs above and under of both electrodes (Model II and III) leads to expansion of discharge channels under repelling and attracting magnetic field. It is shown that the parallel magnetic field in DBD leads to many electrons involved in the process of the development and propagation of the electron avalanches.

4. Conclusion

If each ceramic used in this study is used as a barrier of the ozone generator, the plasma occurs in the gap between the electrodes, although different types of plasma will be produced. From these observations, a ceramic with the trade mark Platinum (made in Indonesia) was recommended from this study. The highest light intensity of the plasma in Models I to III was 720, 571 and 575 for the reference value of 1000 in a.u., respectively. The plasma in Model I expanded to the plasma position 224 on the x-axis of an aggregate supply curve. However, the plasma position in Models II and III spread up to 336. The plasma in Models II and III was more evenly and widely distributed than Model I. The peak voltage generated at the high voltage electrode for Models I, II and III was around 5 kV at a frequency of 25 kHz. The effect of adding ring PMs on the top and or below the electrodes showed that the phase difference between the current and voltage changes by the presence of PMs. The ozone amount in ozone generators (Models I, II, and III) increased steeply in the process of reaching a maximum ozone value of ~ 200 ppm. It can be concluded that the magnetic field from the PMs greatly affects the ozone production for three models of ozone generators.

5. ACKNOWLEDGEMENT

The author thanks to LPPM Universitas Riau and DRPM for funding this research through Penelitian Inovasi dan Percepatan Hilirisasi year : 2019-2020, Contract No.:1026/UN.19.5.1.3/PT.01.03/2019, 842/UN.19.5.1.3/PT.01.03/2020

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