Electrical Science & Engineering
https://ojs.bilpublishing.com/index.php/ese

ARTICLE

Surface Dielectric Barrier Discharge

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ARTICLE INFO

Article history
Received: 1 April 2019
Accepted: 22 April 2019
Published Online: 30 April 2019

Keywords:
DBD (dielectric barrier discharge)
Lissajous figure
Paschen law

ABSTRACT

This project is concerned with surface dielectric barrier discharge (DBD), which involve designing the configuration of discharge and experiment, collecting and analysis data from experiment and simulation. Therefore, this report includes the objective of the project and general information of background. It also briefly introduces the history and theory of dielectric barrier discharge. For the experiment how to design the discharge implement and why. Then it will show the experiment in different configurations, and the analysis data collected in experiment also explain the data for finding out the properties of surface dielectric barrier discharge and what the difference between surface discharge and vertical discharge are. High frequency power supplied will be used for viewing the phenomenon of discharge. Compare the spectrums of discharge on dielectric and air discharge. Finally, it is the main conclusions and introduction of the difference of surface dielectric barrier discharge and vertical discharge. There are some conclusions. Discharge voltage increase linearly with applied voltage. Discharge power increase non-linearly with the discharge voltage. The gap of high voltage electrodes will not affect discharge voltage and discharge power. Discharge power increases with the frequency of power supply. Discharge area will expand when the applied voltage increases.

1. Introduction

1.1 Objective

The objective of this project is to investigate the properties of surface dielectric barrier discharge by experiment and simulation, design the surface discharge equipment for the experiment, compare and analyze the difference between surface dielectric barrier discharge and vertical discharge.

1.2 Background

The surface dielectric barrier discharge is a type of dielectric barrier discharge. Figure 1 shows the general structure of DBD. DBD is based on the theory of breakdown in gas, and the dielectric is the proper functioning of discharge. Mainly, there are two type of DBD, which are volume or vertical discharge and surface discharge. The characteristic of vertical discharge is initiate to a uniform field in gas gap, but surface discharge is in a non-uniform field along the surface of the dielectric. [1]

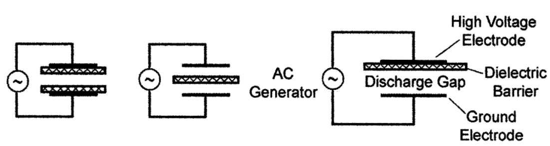

Figure 1. Three kinds of configurations of DBD [2]

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DOI: https://doi.org/10.30564/ese.v1i1.713

Figure 2. Configurations of volume discharge and surface discharge [1]

As the Figure 2, in the general DBD there is a gap between the parallel dielectric plates with electrodes outside, however, in the structure of surface DBD, the anode and cathode are interconnected by the dielectric, so there is no gas gap. There are lots of applications based on theory of DBD, as surface treatment, ozone generator. The first experiment investigation was reported in 1857. Then in the 20th century, there are extensive investigations on the nature of silent discharge. And some people have research about the characteristic of surface dielectric barrier discharge, but in this project, additional efforts have been made tofind out the discharge properties. [2,10]

Many discharge parameters are derive from Lissajous figure, the parallelogram which can shows the discharge voltage discharge power, capacitance and so on. The details will be explained in the data analysis section.

1.3 Previous Works

Much works have been done for research about surface discharge, such as a recent paper for this kind of investigation is "Surface dielectric characteristics for different types of applied voltage and different dielectric materials". In that paper, it introduces the properties of surface dielectric barrier discharge from multi electrodes on thin dielectric film made are different kinds of ceramic. They used impulse power supply to show the current impulse and intensity of ozone. But in my project the main investigation is about the characteristic of discharge, and the effect of different parameter on the surface discharge. [3]

1.4 This Project

The project is to investigate the characteristic of surface dielectric barrier discharge and the method is to use a single variable. The variables to be investigated are listed below:

(1) Applied voltage
(2) Discharge power
(3) Number of electrodes
(4) Distance of gap
(5) Thickness of dielectric barrier
(6) Power supplies 50Hz and 30kHz

Then I will change one of the variable in the experiment and keep the others same all the time. Compare the results to different variable.

1.5 Introduction of Experimental Facilities

Because the breakdown voltage in the implement of covered electrodes is about 8000V, it cannot show a clearly Lissajous figure. Then I have to use transformer 2. The red and blue ports on the transformer 1 are the output and the green one is ground electrode. On the transformer 2 the two slender wires are primary side and the large wire is second side. The ground electrode is at the back side cannot seen in this figure.

Figure 3. Transformer 1 0-8000V

Figure 4. Transformer 2, 1:50 up to 12000V

The probe is used to change the signal from circuit to the oscilloscope. Due to the voltage is too high to connect directly. The hook is connected to the high voltage side and the clip connects to ground side.

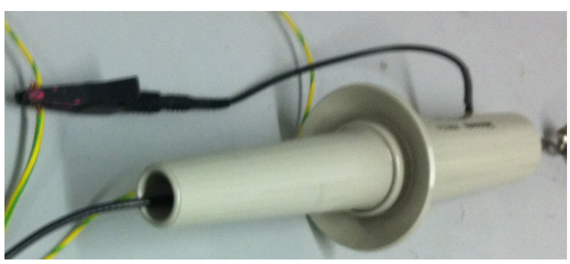

Figure 5. High voltage probe

DOI: https://doi.org/10.30564/ese.v1i1.713

2. Simulation

2.1 Introduction of Software

The software I use to simulate the experiment is "quick field".

It is designed to achieve the following goals:

Using scripts to obtain the solution of a series similar problem which is to be facilitated and accelerate. A series of calculations to examine what are the effects of input parameters of a modeled system on its output characteristic is needed to simplify and automate a parametric study. A seamless method to integrate "QuickField" with other CAD is provided to make the model and office software is used for state-of-the-art research and development. Also, a means of developing and marketing custom 3rd party application is provided to simplify field analysis, or more generalized tasks will be applied to by this. [4]

2.2 Simulation of Discharge between Covered Electrodes

Due to the implement is hard to process and the result of experiment is undesirability, then I have to simulate the result. The software is "quick field", because I cannot download the professional version, and some students' projects are just use the simulation, then the University lab does not have a free time for me. Therefore I download the student version. The student version of this software has a disadvantage is the simulated mesh of electric cannot exceed 225. Then I have to just simulate part of the whole discharge implement, and it will not influence the result.

When apply 3kV

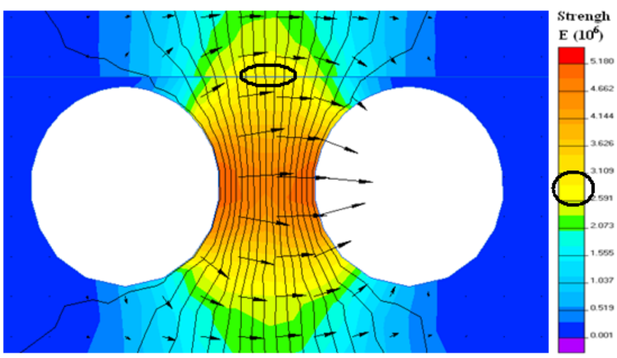

Figure 6. Simulation when applied voltage is 3kV

The line up to these two circle symbols the surface, separate air and dielectric.

The breakdown field strength of air is 30kV/cm, so in the Figure is circled by black.

The discharge area is very small on the surface. Then keep increasing the applied voltage to 5kV. The result of simulation is in Figure 7.

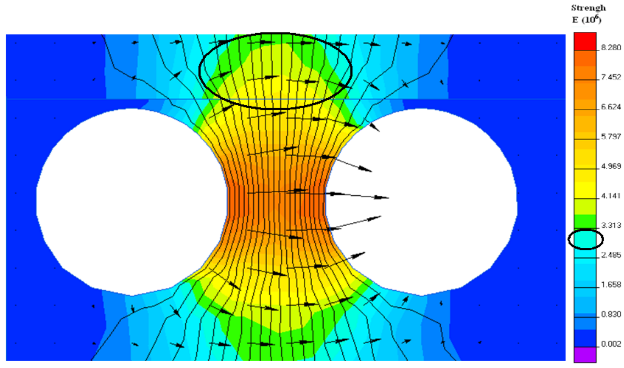

Figure 7. Simulation when applied voltage is 5kV

In Figure 7, it shows the discharge area expand obviously, most in the black circle. It proves the discharge area of surface discharge will expand with increasing of applied voltage. And go on increase the voltage to 10kV.

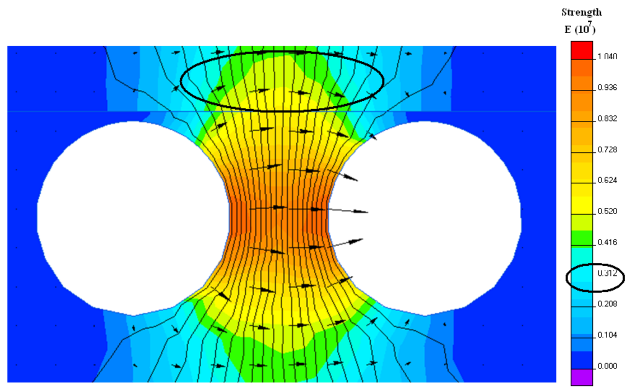

Figure 8. Simulation when applied voltage is 10kV

Compared with Figure 7, the discharge area keeps on expanding.

In the vertical discharge the discharge area will not be changed by applied area, due to the structure makes the electric field between two plate electrodes is uniformity. The gas gap will not changed during raising the voltage, so based on Paschen Law, we can find out the distance and atmosphere is constant, then the breakdown voltage will not be changed but other parameters. This is another difference between vertical discharge and surface discharge.

2.3 Simulation of Discharge between Uncovered Electrodes

The simulation is still used "quick field" student version. And the dielectric is 0.2mm and permittivity is 3.7.

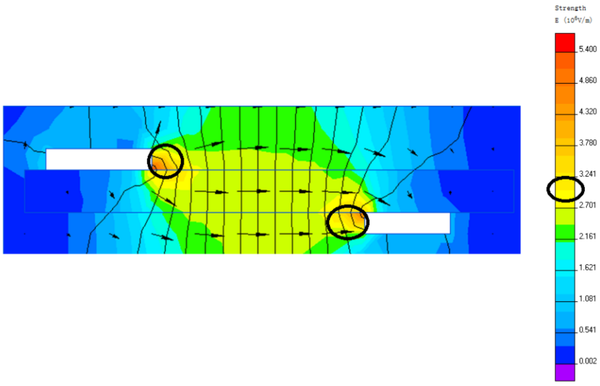

Figure 9. Applied voltage 3kV

The discharge area is circled by black circle. Checking the strength of electric field at the right legend, it shows the discharge area is yellow. That just happens at the edge of electrodes. And increase the applied voltage to 5kV. The result is in Figure 10.

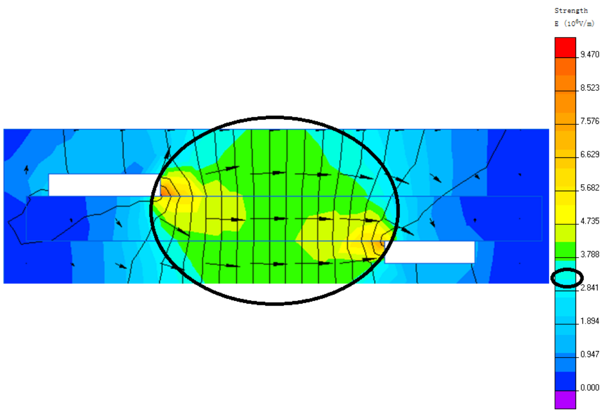

Figure 10. Applied voltage 5kV

In Figure 11 the discharge area is expand to the light blue area which can be checked from the legend. There is an obviously enlarge of the boundary. And keep increase the applied voltage.

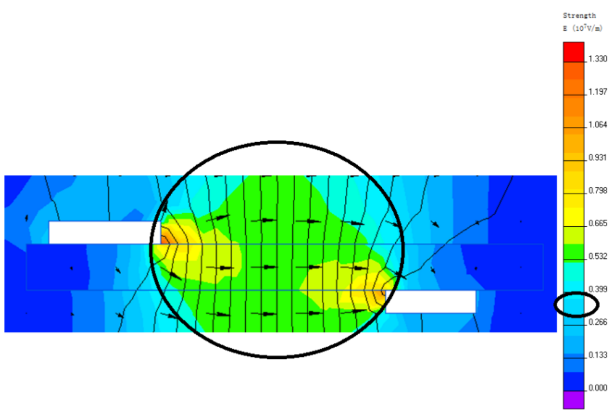

Figure 11. Applied voltage 7kV

In the Figure 11 the discharge area is larger, and almost breakthrough two electrodes. Then the conclusion that discharge area will expand with the rising of applied voltage is proved by the simulation once again.

In this configuration, the discharge implement can be look as a very small dielectric capacitance parallel with two air capacitance and a dielectric capacitance in series, as Figure 12 shows

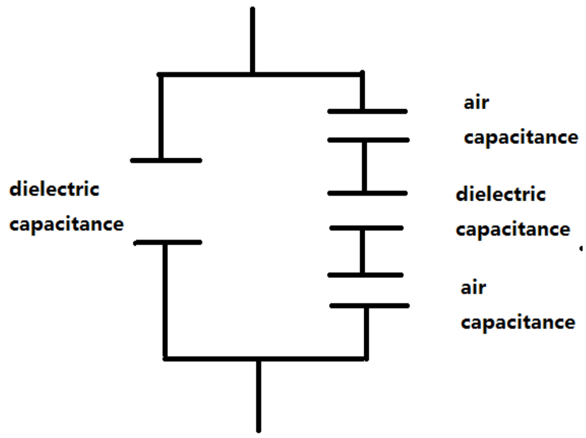

Figure 12. Equal capacitances

However, as the result of simulation, the discharge area can expand, that is means the air capacitance is be longer caused by the discharge channel expand. Then the total capacitance of this circuit will be smaller. Because at the beginning the air discharge channel is very small as the simulation result, there are two small air capacitances in series with the dielectric capacitance, and the total capacitance is very small. During the increasing of applied voltage, the capacitance of air will be smaller by the longer distance. Therefore, the total capacitance is going to be smaller.

2.4 Conclusion

Discharge area will enlarge with rising of applied voltage, and it expands in space not only surface. The difference between surface dielectric barrier discharge and vertical discharge is the discharge area will expand in surface discharge but in the vertical discharge it will not happen.

3. Experiment

3.1 Discharge between Covered Electrodes

3.1.1 Configuration 1

The Figure 13 below is the design of first configuration made up of Acrylic permittivity is 4.5.

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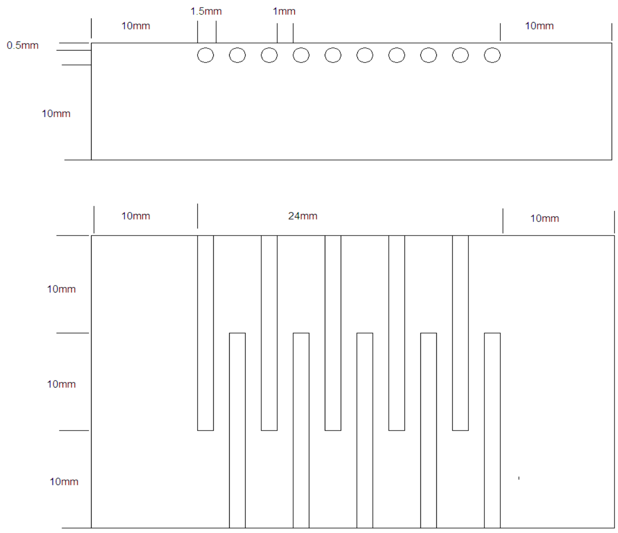

Figure 13. Side view and up view of the configuration 1

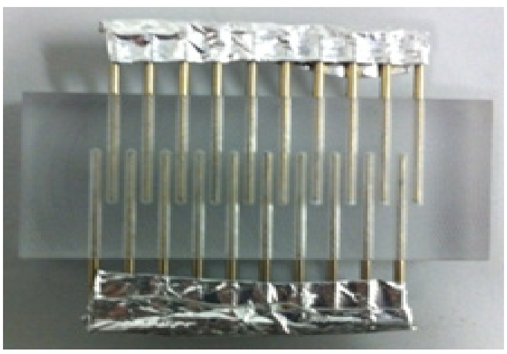

Figure 14. Appearance of configuration 1

This is one of the best kinds of design for application, as no bareness electrode is safety and hard to corrode. The cylinder holes are for electrodes which are 0.5mm to surface, and the distance between two electrodes is 1mm. The length of each electrode is 20mm, so the cross area is 10mm which is the discharge area.

In the Figure 15, we can view the electrodes are very close to surface. That is for decrease the applied voltage to breakdown, because the implement can be looked as capacities below approximately.

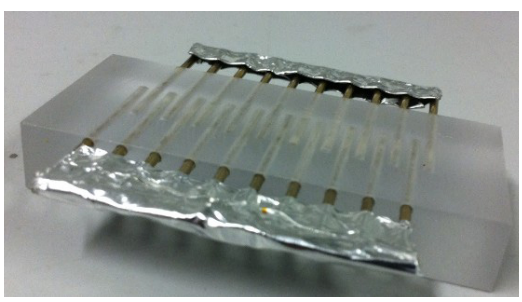

Figure 15. Side appearance of configuration 1

There is a 1mm dielectric capacitance parallel with two 0.5mm dielectric capacitance and a 1mm air capacitance in series. Thus the voltage applied on the air capacitance depends on how much voltage will drop on these two dielectric capacities. The dielectric is thinner, the capacitance is larger, and the impedance is smaller that cause the higher voltage can be applied on the air capacitance. In another way, the source will not use too higher AC voltage. That is the reason to make the distance from electrodes to surface as closed as possible.

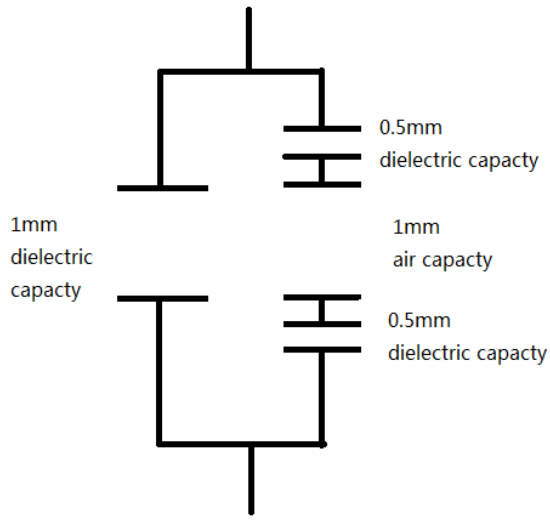

Figure 16. Equal circuit of configuration 1

However that is a disadvantage of this configuration, the processing become hard. As the distance between electrodes cannot be too far, because of larger gap need higher breakdown voltage which we can get from Paschen curve. Paschen's Law is named after Friedrich Paschen. First time to be used is in 1889. [12]

Paschen Law describes the relationship between the breakdown voltage and the product of gas pressure and gap distance, as Figure 17 shows. V_B is the breakdown voltage. Horizontal axis is the product of pressure and gap distance. dielectric barrier discharges their history dis-

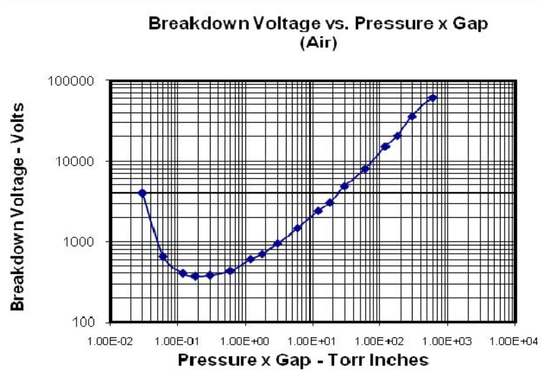

Figure 17. Example of Paschen curve [5]

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The minimum breakdown voltage is at pd approximately equal to 0.01 that means with general atmosphere the gas gap is 0.01mm. Thus the breakdown voltage will be increase almost linear with distance of gas gap from 0.01mm.

The introduction above is the reason why the distance between two electrodes cannot be too far.

However Paschen's Law will fails for some reasons at very low pressure and the explanations are below.

At atmosphere pressure the material of the electrode cannot effect on breakdown voltage, but if the pressure increases sufficiently, it will be an important affect.

If the voltage is applied since a low voltage, the breakdown voltage will increase on successive flashovers, until a constant value is reached. The increase is caused by the burning off by sparking of microscopic irregularities or impurities which may exist on the constant breakdown voltage is less than that obtained at the same pd value at a low pressure. These phenomena can be accounted for by field emission, which is known to depend on the smoothness and composition of the cathode surface. Field emission results in a current which distorts the electric field, and Paschen's Law fails because it applies to uniform fields only.[6] Another disappoint of this design is that due to the first time processing this kind of configuration with nylon, the material is not hard enough then the shape inside is changed caused by squeezing. When applied more than 1kV voltage there will be short circuit inside of dielectric.

3.1.2 The Experiment Set-up

It likes Figure 18 and 19. The capacitance in series with discharge implement is used for collecting Lissajous figure.

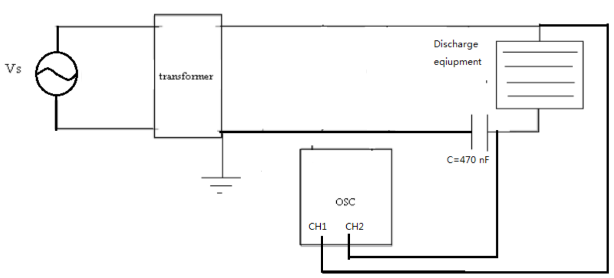

Figure 18. Experiment set-up

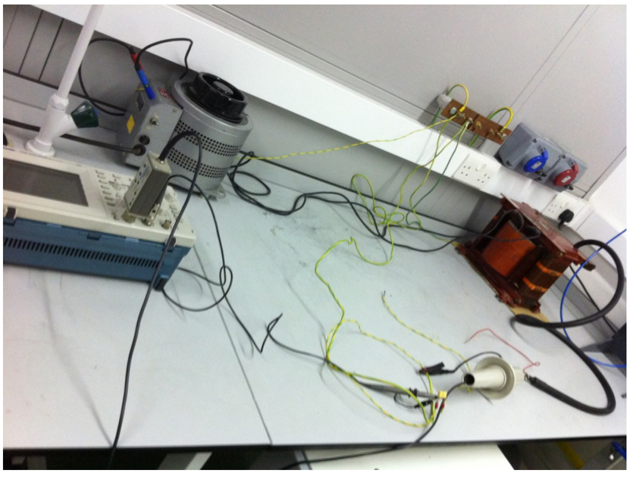

Figure 19. Experiment circuit

3.1.3 Phase Fault

The disconnect point is for the discharge implement. The holes in the implement made up of Acrylic are not fit to electrodes exactly, then while there is discharge the electrodes shock sharply that causes the Lissajous figure is very unstable. Therefore, here is the Lissajous figure of nylon.

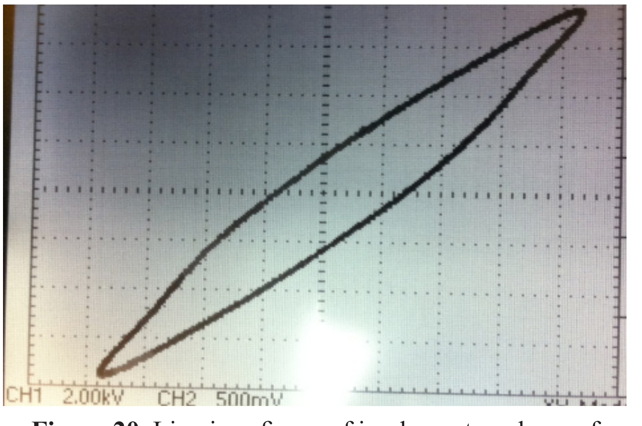

Figure 20. Lissajous figure of implement made up of nylon

The Lissajous figure is not a sharp parallelogram, and before the breakdown there is not a line but an ellipse in the screen, there is an importance difference between vertical discharge and surface discharge. That implement not shown in photo is because of it been breakdown and if the voltage applied to about 10kV there will be short circuit inside of the implement, and the capacitance in series will be breakdown, even can smell the burnt flavor.

The reason of this phenomenon is caused by the phase fault between voltage and current as shown in Figure 21.

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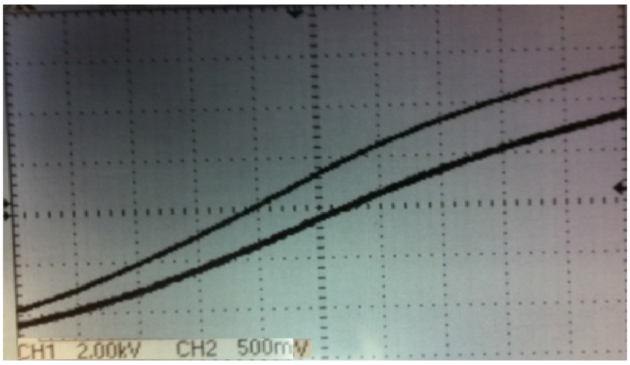

Figure 21. The phase fault between voltage on the implement and 470**μ**F capacitance

As the anode and cathode are connected by dielectric barrier, so it cannot be infinite large impedance. In another word, capacitance and resistance exist in the electric circuit at the same time, so there must be a phase fault. But with this phase fault I can calculate the resistance. The Δt=920μs which is collected on the oscilloscope. Then

$$\Delta\Phi = 360° \times 0.92\mu s / 0.02s = 16.56°$$

$$Z_C = 1/(j\omega C) = 1/(j \times 2\pi \times 50 \times 0.47 \times 10^{-6}) = 6.77 \times 10^3 \angle -90° \Omega$$

$$I = 0.6/Z_C = 0.6 \angle -16.56° / 6.77 \times 10^3 \angle -90° = 8.86 \times 10^{-5} \angle 73.44° A$$

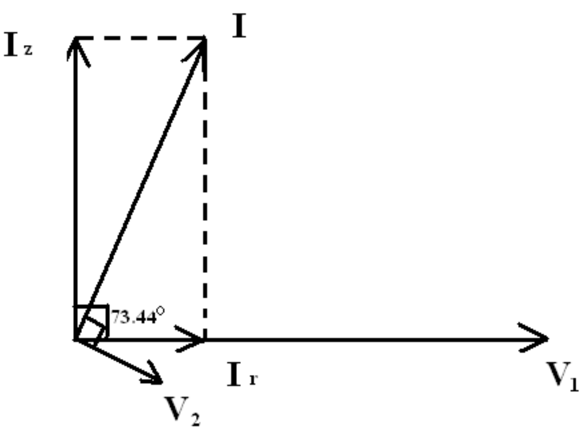

Figure 22. Phase graph

$$I_r = I\cos 73.44° = 2.44 \times 10^{-5} A$$

$$R = 3000/2.44 \times 10^{-5} = 122.7 M\Omega$$

However in the vertical discharge the capacitance of air is infinite large impedance so there will not be an ellipse and the Lissajous figure is sharp parallelogram.

Another probability is that the oscilloscope I use has error at channels, and the signal has a delay during transmitting. Therefore, the channels have a phase fault.

3.2 Properties of Surface Discharge

In this part, the configuration of discharge implement is as shown in Figure 23.

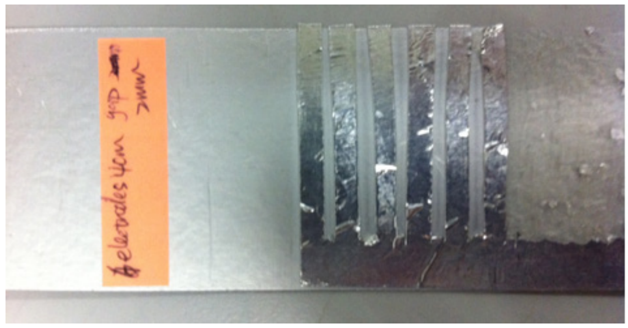

Figure 23. Photo of configuration 2 of discharge implement

The dielectric is the Acetate membrane and the anode is shown in the Figure 23, trip type of aluminum foil, the cathode on the other side of Acetate is a piece of aluminum. And the discharge will happen along the trip type of anode. Using configuration 2 for investigate the properties is because of that this kind of design can be made by myself and do not have to wait the workshop processing. Another reason is it is easy to change the parameters such as thickness of dielectric, applied voltage, electrodes number and so on. The parameters which maybe affect discharge had been listed at the beginning of this report. Later this report will introduce the effect of applied voltage on discharge voltage, applied voltage on discharge power, and the effect of number of electrodes, distance of gap, dielectric thickness. With two piece of aluminum foil as electrodes, and there is no gap between any electrode. And the figure is shown below.

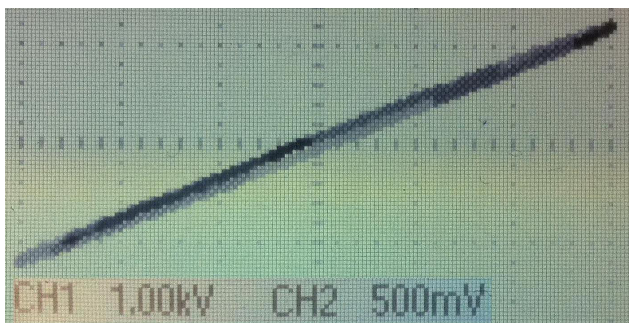

Figure 24. Figure of no gap on the electrodes

The figure presents a general line that can show the resistance in the electric circuit is infinite large, so the figure will not be an ellipse as the first configuration, and it is suitable for research the properties of surface discharge.

 DOI: https://doi.org/10.30564/ese.v1i1.713

3.2.1 Material: Acetate; Thickness: 0.2mm; Number of Electrodes: 6; Length of Electrodes: 4cm; Gap: 2mm

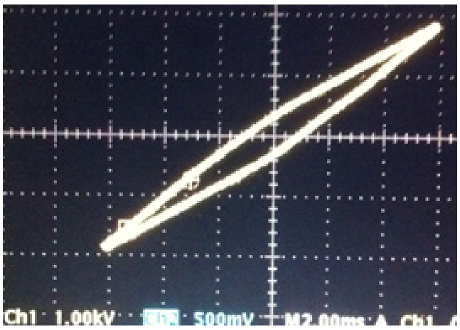

Figure 25. Lissajous figure of 3kV applied voltage

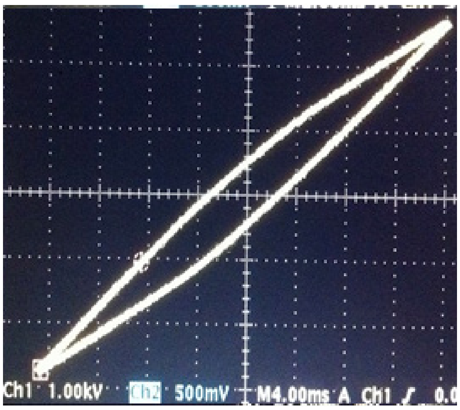

Figure 26. Lissajous figure of 4kV applied voltage

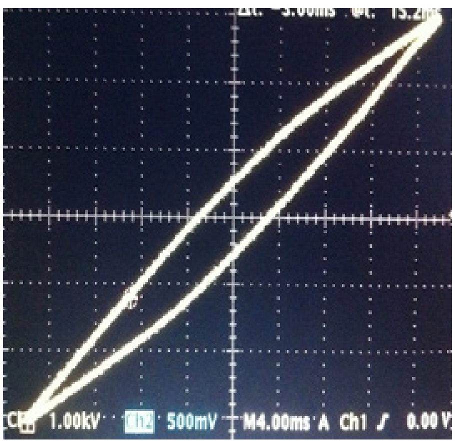

Figure 27. Lissajous figure of 4.5kV applied voltage

These three Figures at above hand are the Lissajous figure when apply 3kV, 4kV and 4.5kV on the 0.2mm Acetate, and the number of electrode is 6. Length of electrode is 4cm. Gap between anode is 2mm.

When the voltage applied to 1.5kV the discharge begin.

We can get the discharge voltage from the Lissajous figure which is the cross of zero axe and Lissajous figure. And the capacities before discharge and during discharge which are the slope of two edge of the parallelogram. And the formula of discharge power is

$$P= 4f\, C_d^2(C_d+C_g)^{-1}U_{min}(U-U_{min})$$ [7]

In this formula, f is frequency; C_d is the capacitance of dielectric; C_g is the capacitance of gas gap; U_{min} is the half of voltage before discharge which is the horizontal voltage between the lowest two points; U is the applied voltage. But in my experiment the C_g is hard to collect or calculate, so I have to use the area of the Lissajous figure to estimate the power. In my Figures both of the horizontal and vertical axes are voltage, horizontal one is the voltage applied on the discharge implement, and the vertical one is applied on the 0.47μF capacitance. By the 0.47μF capacitance, I can get the current of this circuit and calculate the discharge power.

So the power in per cell shown in oscilloscope

$$P=U\times I=U\times Q/t=U\times Q\times f=U\times U_C\times C\times f=1000\times 0.5\times 0.47\times 10^{-6}\times 50=0.0117W$$

Therefore, as the area of 3kV applied voltage is 2 cells, the power is

$$0.0117W\times 2=0.0234W$$

The area of 4kV applied voltage is 4.5 cells, the power is0.0117W×4.5=0.0526WThe area of 4.5kV applied voltage is 5.1 cells, the power is 0.0117W×5.1=0.0596WBased on the slope of Lissajous figure, under 3kV applied voltage, the capacitance before discharge is 0.132nF, when discharge the capacitance is 0.167nF. Under 4kV applied voltage the capacitance before discharge is 0.124nF and the capacitance during discharge is 0.176nF.From the Lissajous figure, the discharge voltage can be collected as 500V, 700V and 800V respectively under the applied voltage is 3kV, 4kV, 4.5kV.

3.2.2 Material: Acetate; Thickness: 0.2mm; Number of Electrodes: 6; Length of Electrodes: 4cm; Gap: 4mm

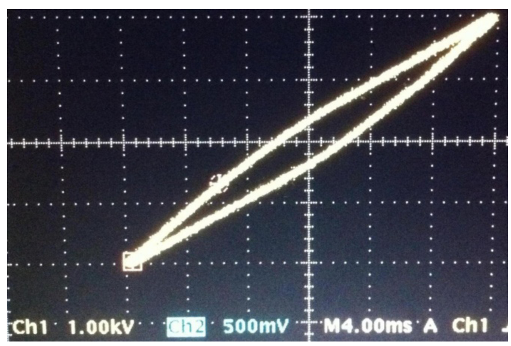

Figure 28. Lissajous figure when apply 3kV

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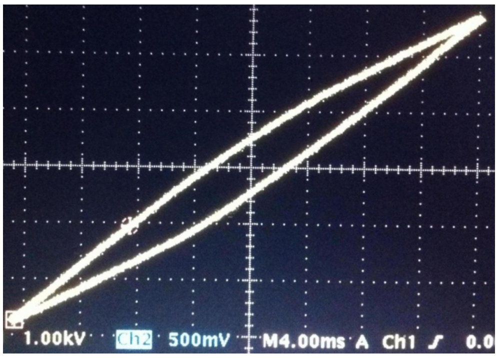

Figure 29. Lissajous figure when apply 4kV

The applied voltage for breakdown is 1.5kV.

From the Lissajous figure, when applied 3kV voltage the capacitance before discharge is 0.132nF and the capacitance during discharge is 0.185nF. When the applied voltage is 4kV, capacitance before discharge is 0.124nF; during discharge the capacitance becomes 0.192nF. Discharge voltages are 500V and 700V at applied voltages 3kV and 4kV.

Same as last section, the discharge power in per cell is 0.0117W.

Then the power under applied 3kV is

$$0.0117W \times 2 = 0.0234W$$

And while the applied voltage is 4kV, discharge power is

$$0.0117W \times 4.5 = 0.0526W$$

3.2.3 Material: Acetate; Thickness: 0.2mm; Number of Electrodes: 12; Length of Electrodes: 4cm; Gap: 2mm

The applied voltage when breakdown is 1.5kV.

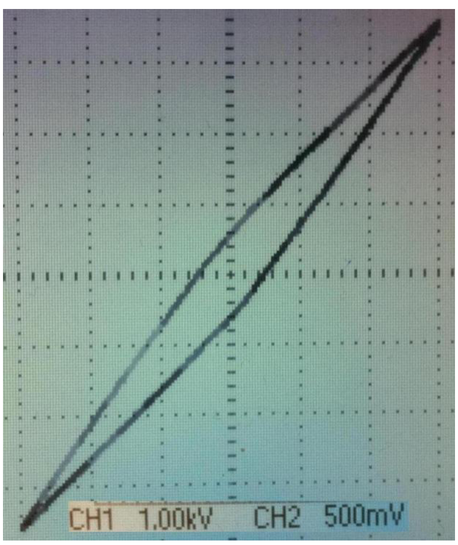

Figure 30. Lissajous figure of 3kV applied voltage

Discharge voltage is 500V. The non-discharge capacitance is C=0.223nF, and discharge capacitance is C=0.336 collected from the Lissajous figure. And the discharge power in per cell is still 0.0117W, so the power is

$$P=0.0117W \times 3.6=0.042W$$

Increase the applied voltage to 4kV. The Lissajous figure is below.

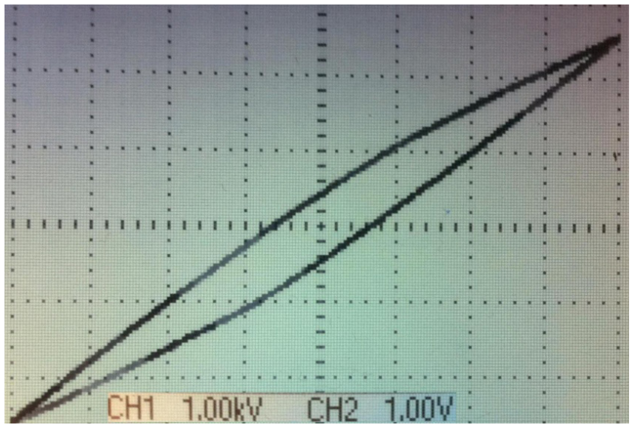

Figure 31. Lissajous figure of 4kV applied voltage

By the Lissajous figure, the non-discharge capacitance can be collected C=0.235nF and discharge voltage is 600V. The capacitance during discharge is 0.353nF. Due to the change of unit of channel 2, the power in per cell is

$$P=1000 \times 1 \times 0.47 \times 10^{-6} \times 50=0.0235W$$

Then the whole discharge power is

$$P=0.0235W \times 3=0.0705W$$

3.2.4 Material: Acrylic; Thickness: 0.2mm; Number of electrodes: 0.2mm; Length of electrodes: 4cm; Gap: 2mm

The applied voltage for breakdown in this implement is 1.5kV.

Applied 3kV voltage the Lissajous figure is shown below.

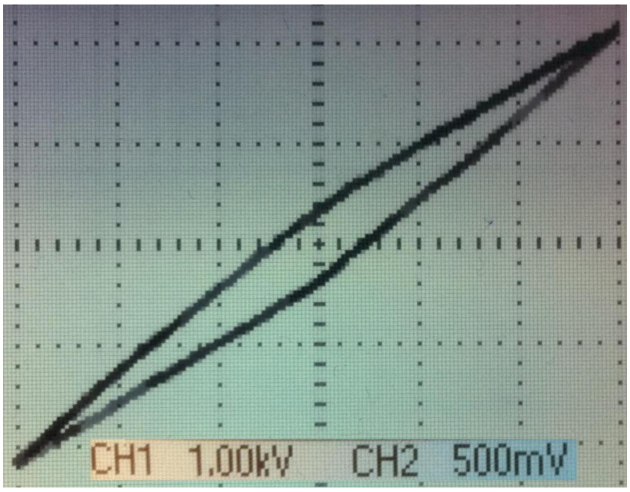

Figure 32. Lissajous figure of 3kV applied voltage

Discharge voltage is 440V which can be read on the Lissajous figure.

Non-discharge capacitance is C=0.141nF; discharge capacitance is C=0.204nF

Discharge power is

$$P=0.0117W\times1.76=0.0206W$$

Raise the applied voltage to 4kV.

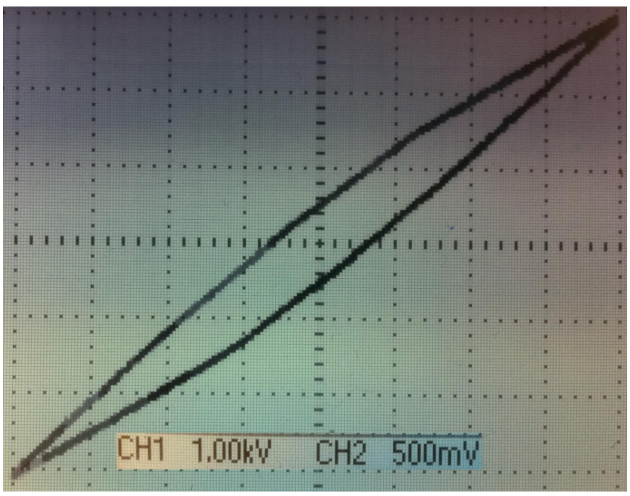

Figure 33. Lissajous figure of applied voltage 4kV

The discharge can be picked easily from Lissajous figure which is 600V.

Then the non-discharge get by calculated C=0.141nF; and discharge capacitance is C=0.207nF.

Discharge power is 0.0117in per cell, so the whole discharge power is

$$P=0.0117\times5=0.0585$$

3.2.5 Material: Acetate; Thickness: 0.4mm; Number of Electrodes: 6 Length of Electrodes: 4cm; Gap: 2mm

Due to there is only 0.2mm Acetate plat, for investigating the effect of thickness on discharge I use water to adhere two piece of Acetate as a 0.4mm membrane.

The applied voltage when the air is breakdown is 2.5kV.

There is the Lissajous figure under the applied voltage 3kV

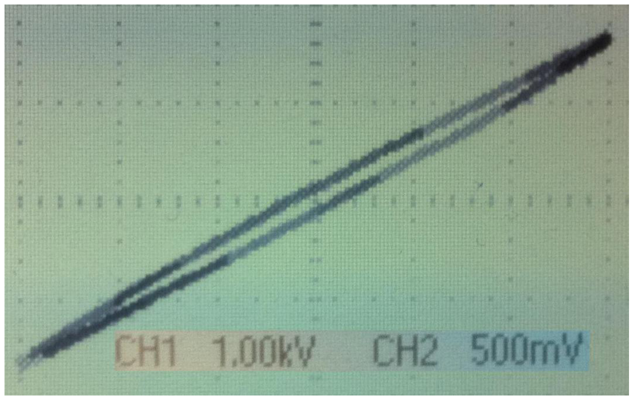

Figure 34. Lissajous figure of 3kV applied voltage

Discharge voltage 200V. It is unclear to find the slope so the capacitance is hard to calculate, so here ignore the capacitance and then calculate the discharge power directly.

Power in per cell is 0.0117W, so the discharge power is

$$P= 0.0117W\times0.64=0.0075W$$

When applied voltage is 4kV.

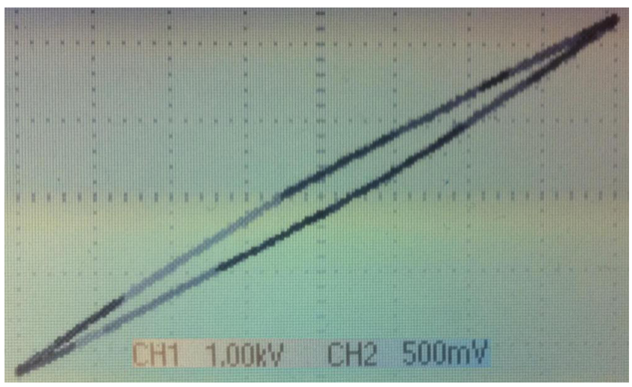

Figure 35. Lissajous figure of 4kV applied voltage

Discharge voltage is 400V. Non-discharge capacitance is C=0.125nF. Discharge capacitance is C=0.166Nf. And the discharge power is

$$P=0.0117W\times1.92=0.0225W$$

Because of the dielectric membrane thickness is in-

  DOI: https://doi.org/10.30564/ese.v1i1.713

creased, so I can apply higher voltage, because of it is not easy to be breakdown. Then the applied voltage rise to 5kV. The Lissajous figure is below.

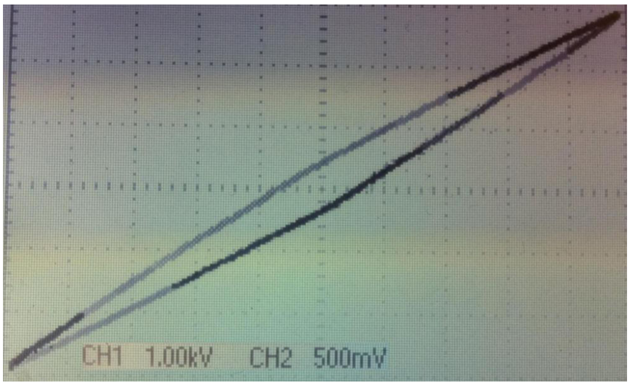

Figure 36. Lissajous figure of 5kV applied voltage

From the Lissajous figure, the discharge is 600V. Non-discharge capacitance is 0.118nF, and discharge capacitance is 0.171nF. Discharge power is

$$P=0.0117W\times2.4=0.0281W$$

3.2.6 Material: Acetate; Thickness: 0.6mm; Number of electrodes: 6; Length of electrodes: 4cm; Gap: 2mm

The 0.6mm Acetate plat is made up by the same way with 0.4mm one.

When apply 3kV voltage, because of the thickness of dielectric, the air is just breakdown, then the figure cannot show any data. The Lissajous figure is below.

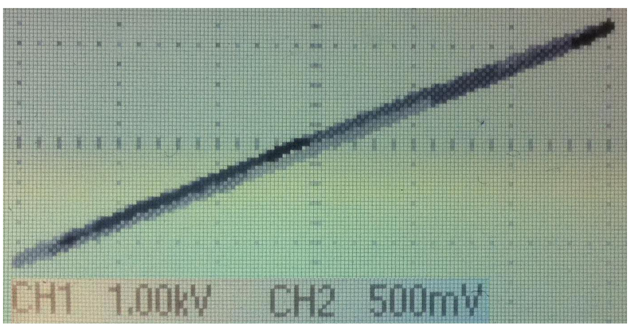

Figure 37. Lissajous figure at 3kV applied voltage

When apply a voltage of 4 kV.

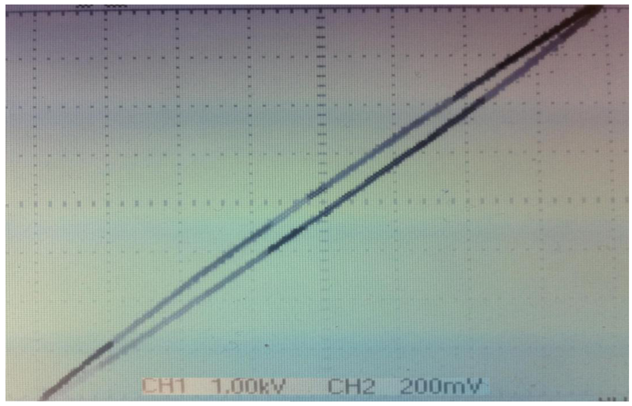

Figure 38. Lissajous figure at 4kV applied voltage

Discharge voltage is 300V. Non-discharge voltage is C=0.09nF; discharge voltage is 0.10nF. Discharge power in per cell is

$$P=1000\times0.2\times0.47\times10^{-6}\times50=4.7mW$$

The whole power is

$$P=4.7mW\times1.6=7.5mW$$

When applied voltage is 5kV.

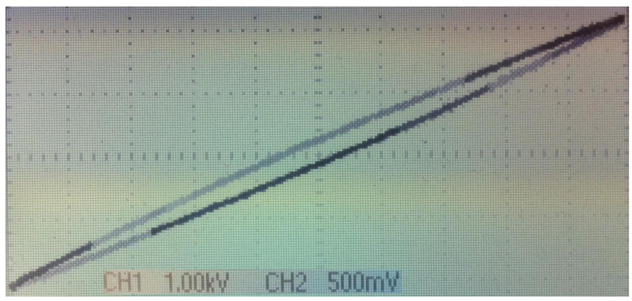

Figure 39. Lissajous figure at 5kV applied voltage

Discharge voltage is 500V. Non-discharge capacitance is 0.09nF; discharge capacitance is 0.137nF. Discharge power in per cell is 0.0117W, and then the total discharge power is

$$P=0.0117W\times2.2=0.0257W$$

3.3 Data Analysis and Results

Clear up all the data collected from experiment by a table like below. After compare the different condition of discharge and I will give the rustles.

3.3.1 Effect of Applied Voltage

For find out the effect of applied voltage, we use the two series of data which are acetate, 0.2mm, 6 electrodes, 4cm, 2mm gap and acetate, 0.4mm, 6 electrodes, 4cm,

Table 1. Total data from experiment

Material	Thickness	No. of electrode	Length of electrode	gap	applied voltage when breakdown (kV)	applied voltage (kV)	discharge voltage (V)	capacitance before dis-charge(nF)	capacitance during discharge (nF)	discharge power (mW)
Acetate	0.2mm	6	4cm	2mm	1.5	3	500	0.132	0.167	23.4
Acetate	0.2mm	6	4cm	2mm	1.5	4	700	0.124	0.176	52.6
Acetate	0.2mm	6	4cm	2mm	1.5	4.5	800	0.118	0.186	59.6
Acetate	0.2mm	6	4cm	4mm	1.5	3	500	0.132	0.185	23.4
Acetate	0.2mm	6	4cm	4mm	1.5	4	700	0.124	0.192	52.6
Acetate	0.2mm	12	4cm	2mm	1.5	3	500	0.235	0.336	42.1
Acetate	0.2mm	12	4cm	2mm	1.5	4	650	0.235	0.353	70.5
Acrylic	0.2mm	6	4cm	2mm	1.5	3	440	0.141	0.204	20.6
Acrylic	0.2mm	6	4cm	2mm	1.5	4	600	0.141	0.207	58.5
Acetate	0.4mm	6	4cm	2mm	2.5	3	200			7.5
Acetate	0.4mm	6	4cm	2mm	2.5	4	400	0.125	0.166	22.5
Acetate	0.4mm	6	4cm	2mm	2.5	5	600	0.118	0.171	28.1
Acetate	0.6mm	6	4cm	2mm	3	3		0.094		0
Acetate	0.6mm	6	4cm	2mm	3	4	300	0.09	0.1	7.5
Acetate	0.6mm	6	4cm	2mm	3	5	500	0.09	0.1137	25.7

Table 2. Effect of applied voltage

Material	Thickness	No. of electrode	Length of electrode	gap	applied voltage when break-down (kV)	applied voltage (kV)	discharge voltage (V)	capacitance before discharge (nF)	capacitance during dis-charge (nF)	discharge power (mW)
Acetate	0.2mm	6	4cm	2mm	1.5	3	500	0.132	0.167	23.4
Acetate	0.2mm	6	4cm	2mm	1.5	4	700	0.124	0.176	52.6
Acetate	0.2mm	6	4cm	2mm	1.5	4.5	800	0.118	0.186	59.6
Acetate	0.4mm	6	4cm	2mm	2.5	3	200			7.5
Acetate	0.4mm	6	4cm	2mm	2.5	4	400	0.125	0.166	22.5
Acetate	0.4mm	6	4cm	2mm	2.5	5	600	0.118	0.171	28.1

2mm gap as examples. Compare the applied voltage and discharge voltage and power.

In the table, it shows both of discharge voltage and discharge power increasing with applied voltage. The increase trend of discharge voltage is mostly shown in the two figures below.

Figure 40 and figure 41 show that discharge voltage increase linear with the voltage applied on the same implement. This is the difference between surface discharge and vertical discharge. As the discharge voltage in the vertical discharge will not be changed while applied voltage increase. The reason causes the difference of this phenomenon is the discharge area in the vertical discharge is stable, just the gas gap, but in the surface discharge the discharge area will expend with the raising of applied voltage, then with the electric field stronger the discharge channel expand on the surface as I show at before in the simulation. The channel's expand can be counted as the distance of capacitance increase. Therefore, on the basis of Paschen Law, we know the distance increase cause higher breakdown voltage. While the stable gas gap always keep the same distance, and at the same atmosphere the breakdown will not be changed and the discharge voltage is constant.

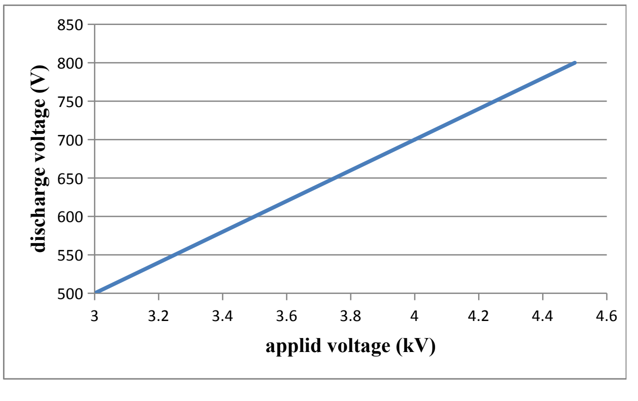

Figure 40. Relationship of applied voltage and discharge voltage at 0.2mm Acetate

 DOI: https://doi.org/10.30564/ese.v1i1.713

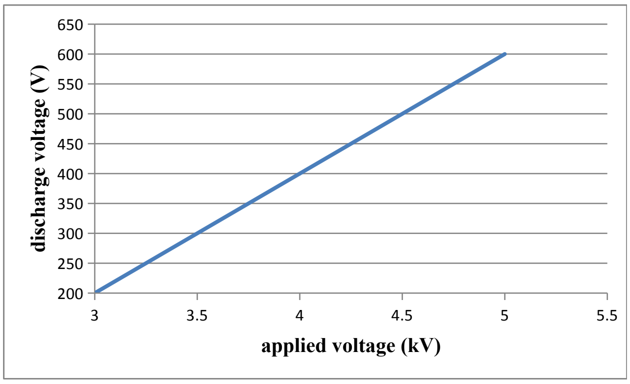

Figure 41. Relationship of discharge voltage and applied voltage at 0.4mm Acetate

The figures below are still about 0.2mm and 0.4mm Acetate, but they are the relationship between discharge voltage and applied voltage.

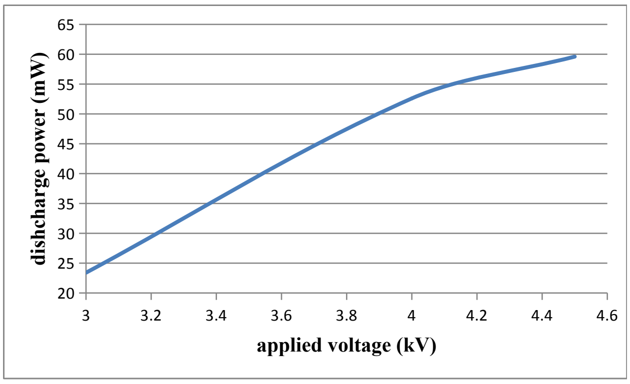

Figure 42. Relationship between applied voltage and discharge power at 0.2mm Acetate

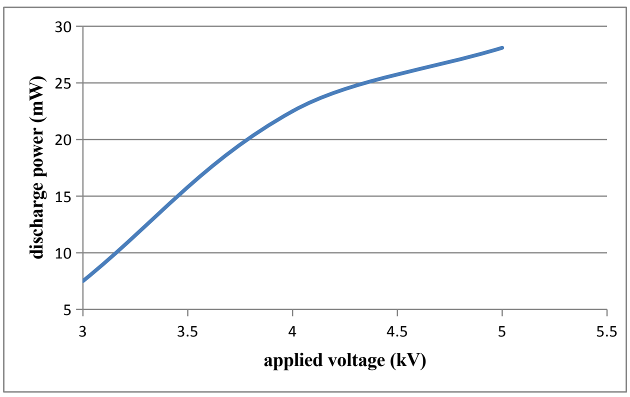

Figure 43. Relationship between applied voltage and discharge power at 0.4mm Acetate

From these two figures, the discharge power increase with applied voltage non-linear. The ratio of increase will slow down. Based on the $P=U^2/Z=U\times Q\times f=U^2\times C\times f$ where C is the capacitance, Q is the charge go through the capacitance and f is the frequency. U is increasing by linear, so U^2 increase disproportionate with C decrease. Then the result of power is increase follow the trend in the figure.

On the other hand, the capacitance is going to be smaller.

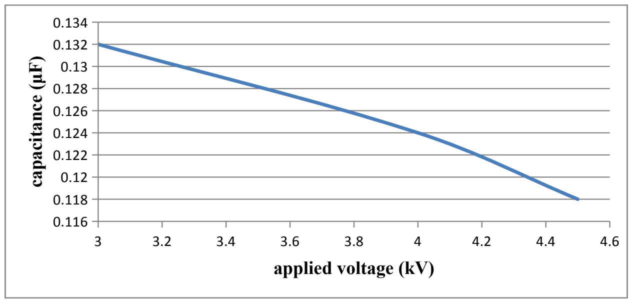

Figure 44. The relationship between capacitance and applied voltage

The capacitance decreasing is because of that the circuit of implement can be look as the capacitance in Figure 45.

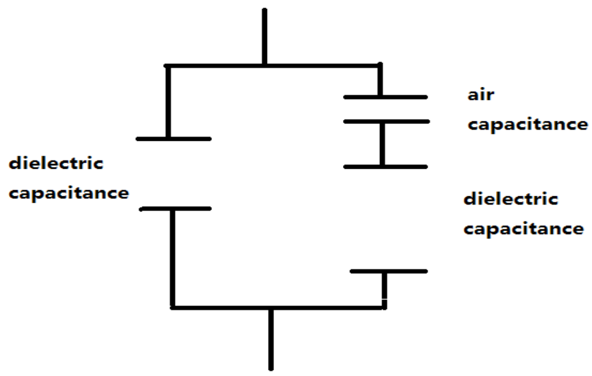

Figure 45. Equivalent circuit of capacitance

With the increasing of applied voltage the air discharge channel will expand which can be look as the gap of air capacitance becomes longer. Then the air capacitance becomes smaller as the formula of capacitance

$$C=\varepsilon_0\varepsilon_r S/d$$

Where ε_0 is 1, the constant permittivity, ε_r is the relative permittivity, S is the area of capacitance and d is distance of capacitance gap. The area is not changed but distance enlarges, the capacitance must be smaller. And due to two capacitance are in series the total capacitance's reciprocal equal to the sum of these two capacitances' reciprocal, and the total quantity of capacitance depends on the smaller one. Therefore, the air capacitance becoming smaller the total capacitance will be smaller at the same time.

Table 3. Effect of number of electrodes

Material	Thickness	No. of electrode	Length of electrode	gap	applied voltage when breakdown (kV)	applied voltage (kV)	discharge voltage (V)	capacitance before discharge (nF)	capacitance during discharge (nF)	discharge power (mW)
Acetate	0.2mm	6	4cm	2mm	1.5	3	500	0.132	0.167	23.4
Acetate	0.2mm	6	4cm	2mm	1.5	4	700	0.124	0.176	52.6
Acetate	0.2mm	12	4cm	2mm	1.5	3	500	0.235	0.336	42.1
Acetate	0.2mm	12	4cm	2mm	1.5	4	650	0.235	0.353	70.5

Table 4. Effect of gap

Material	Thickness	No. of electrode	Length of electrode	gap	applied voltage when breakdown (kV)	applied voltage (kV)	discharge voltage (V)	capacitance before discharge (nF)	capacitance during discharge (nF)	discharge power (mW)
Acetate	0.2mm	6	4cm	2mm	1.5	3	500	0.132	0.167	23.4
Acetate	0.2mm	6	4cm	2mm	1.5	4	700	0.124	0.176	52.6
Acetate	0.2mm	6	4cm	4mm	1.5	3	500	0.132	0.185	23.4
Acetate	0.2mm	6	4cm	4mm	1.5	4	700	0.124	0.192	52.6

Table 5. Effect of dielectric thickness

Material	Thickness	No. of electrode	Length of electrode	gap	applied voltage when breakdown (kV)	applied voltage (kV)	discharge voltage (V)	capacitance before discharge (nF)	capacitance during discharge (nF)	discharge power (mW)
Acetate	0.2mm	6	4cm	2mm	1.5	3	500	0.132	0.167	23.4
Acetate	0.2mm	6	4cm	2mm	1.5	4	700	0.124	0.176	52.6
Acetate	0.2mm	6	4cm	2mm	1.5	4.5	800	0.118	0.186	59.6
Acetate	0.4mm	6	4cm	2mm	2.5	3	200			7.5
Acetate	0.4mm	6	4cm	2mm	2.5	4	400	0.125	0.166	22.5
Acetate	0.4mm	6	4cm	2mm	2.5	5	600	0.118	0.171	28.1
Acetate	0.6mm	6	4cm	2mm	3	3		0.094		0
Acetate	0.6mm	6	4cm	2mm	3	4	300	0.09	0.1	7.5
Acetate	0.6mm	6	4cm	2mm	3	5	500	0.09	0.1137	25.7

3.3.2 Effect of Number of Electrodes

From this table we can find out larger number of electrodes will not affect on the breakdown, because of the breakdown is the area along the edge of electrodes. But the capacitance increase with the electrodes, due to the raising length of electrodes will cause the cross area of anode and cathode rising. Therefore, the capacitance has a large area, and the capacitance increase.

In this table, it also shows the discharge voltage do not have an obviously change. The discharge power of 12 electrodes is about twice larger than 6 electrodes. The reason is the increasing of discharge area. Then the conclusion cannot be that the discharge power increase with the number of electrodes, but the increasing is depended on discharge area.

3.3.3 Effect of Gap Size

Compare these two series of data, first two rows show the discharge data with 2mm gap. And the lower two series of data are at 4mmgap.

It is not hard to find the discharge voltages and powers do not have any difference. It introduces that in this configuration the discharge will not be influenced by the distance of gap. At the same time, it also explains the discharge power is depended on the discharge area, because in this configuration the longer gaps do not cause the discharge area which is around the anode larger.

3.3.4 Effect of Dielectric Thickness

The table shows that the increasing of thickness makes the discharge voltage, discharge power and applied voltage for breakdown all decrease.

DOI: https://doi.org/10.30564/ese.v1i1.713

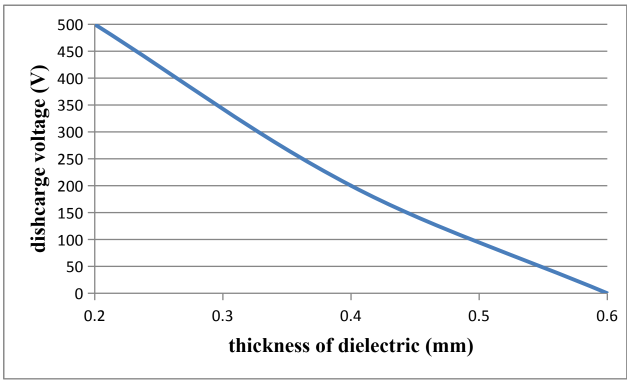

Figure 46. Relationship between thickness of dielectric and discharge voltage

The figure is under the applied voltage 3kV and it shows the discharge voltage decreases in a curve but not a straight line

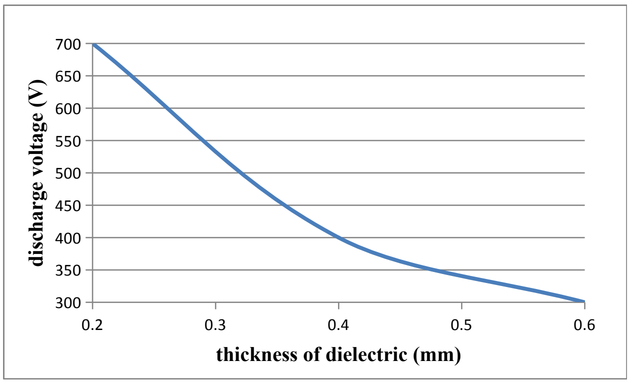

Figure 47. Relationship between thickness of dielectric and discharge voltage

This figure is under the applied voltage 4kV. It has a higher ratio of decreasing than 3kV applied voltage.

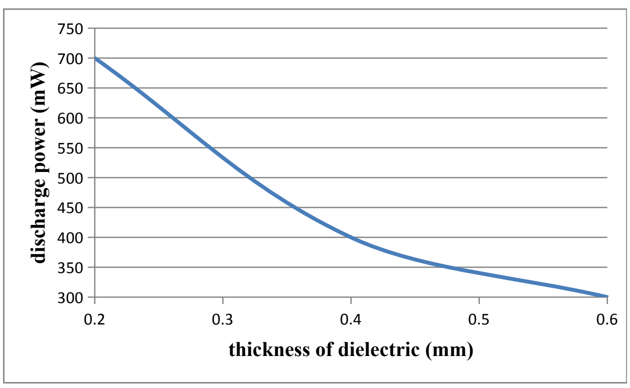

Figure 48. Relationship between discharge power and thickness of dielectric

This figure is under 4kV applied voltage the decrease of discharge power has the same trend with discharge voltage.

That introduce the increasing of dielectric thickness will cause the discharge voltage and discharge power decrease. And the ratio of decreasing will be rising with the thickness of dielectric. Therefore, for different material, the best way to save energy is to find the best distance between electrodes and electrodes to surface. If the distance is too large, it will spent larger applied voltage, but if the distance is too close, the dielectric will be breakdown easily. And the electrodes cannot design as close as possible to the surface, as if this part is breakdown is breakdown the whole circuit will be shot circuit, and it is very dangerous in discharge, maybe that will cause burning.

3.3.5 Under High Frequency Power Supply (30 kHz)

As I introduce before in 3.1.1 the formula of discharge power is:

$$P= 4f\, C_d^{\,2}\,(C_d + C_g)^{-1}\, U_{min}\,(U - U_{min})$$ [7]

The power is depend on the frequency at the same applied voltage, so under high frequency power supplied the discharge power will be large and can be seen.

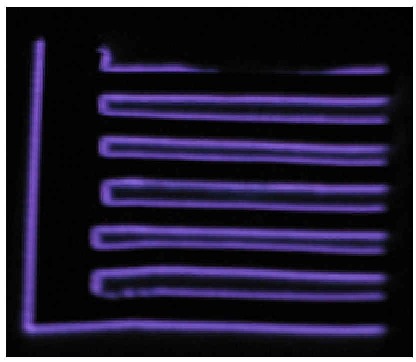

Figure 49. Discharge under high frequency power supplied (30 kHz)

This is at the implement of 0.2mm Acetate, 6 4 cm electrodes, and 0.2mm gap.

As I introduce before the discharge area is around the electrodes. Same as capacitance, it can pass high frequency voltage and resist low frequency voltage. However, at the same time using high frequency power supplied, due to the power is large with the power supplied, then if keep it under discharge status the dielectric will be melted by heat. The thinner, even breakthrough, dielectric is easy to be breakdown and burning. During the experiment, I have experienced several times about the burning. Not only discharge too much time but also proceed the experiment with the same implement too many times will lead to burning. Then it is a dangerous factor in my experiment, and I have to keep making new implement for save them will not be melted and burning. Actually, in the Figure 44 there can be find some shape change at the discharge area. The electrode is not straight, that is caused by the heat of high frequency power supplied.

3.4 Discharge between Uncovered Electrodes

This section concentrates on the expanding of discharge on the dielectric surface. Firstly it shows the photos of experiment, and then I use the result of simulation.

3.4.1Experiment on Configuration 3

The configuration 3 has two electrodes made by tow aluminum foils at different side of dielectric barrier which is 0.2mm Acetate film and anode and cathode not have crossing area. The gap of anode and cathode is 0.1mm, due to if the gap is 2mm the breakdown voltage will be 6kV while the Acetate film cannot endure.

Because of the low frequency power supply cannot lead to obvious discharge, then for watch expand of discharge I still use the 30 kHz power supply. First time during the experiment there is a phenomenon like this.

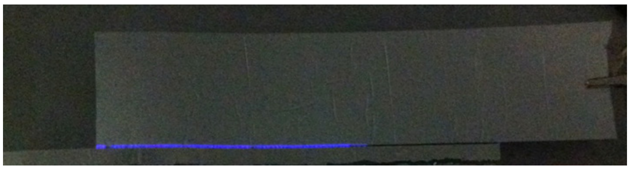

Figure 50. Discharge on configuration 3

And the Lissajous figure is very unstable.

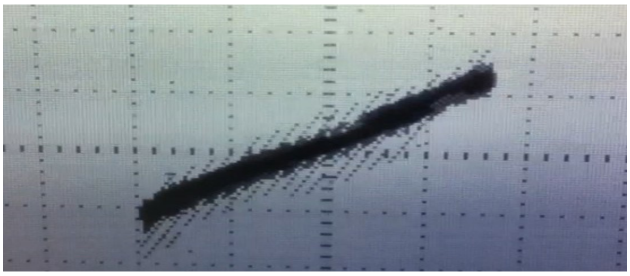

Figure 51. Lissajous figure at beginning seconds of discharge

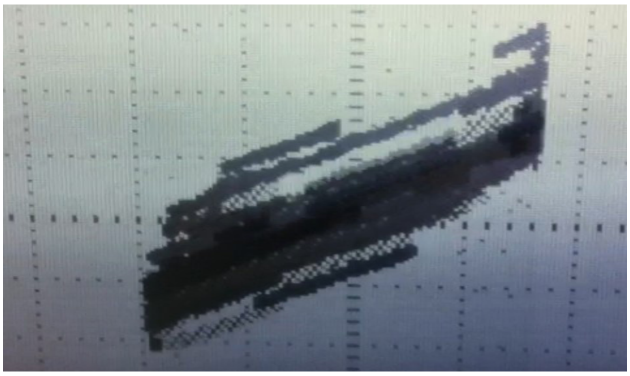

Figure 52. Lissajous figure at later time

The reason of this phenomenon is the voltage just arrive the breakdown, while the electrodes are plastered by hand, the gap is not uniform. In Fig. 50 there is a part do not have discharge that is the larger gap area. And the Lissajous figure will change is because the voltage just arrive the breakdown voltage, the air between the gaps can be breakdown and discharge, but it still cannot be breakdown and discharge. Therefore, the Lissajous figure open and close, discharge or not, now and then.

And for check the discharge area, the view is from the different direction.

The photo is taken from flank side of the discharge implement. It is not very clearly but it shows the discharge at the anode side and cathode side. And the discharge area is not through the whole gap. However, I do not have a professional camera to take photos clearly enough to view the discharge area expanding or not. I have to use simulation to show the results of discharge area expanding.

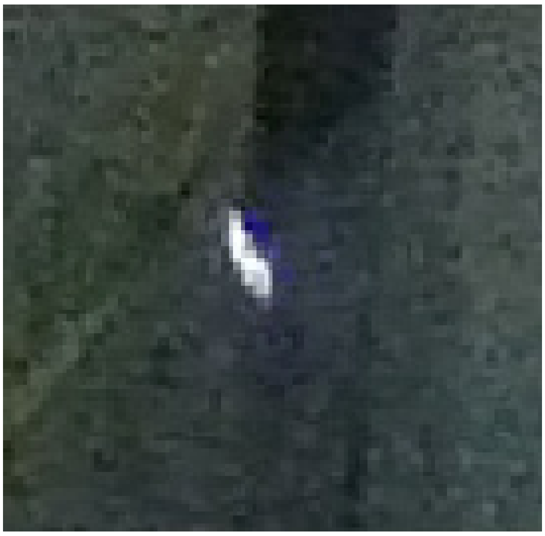

Figure 53. Discharge area view from flank

3.5 Spectrum

Discharge always happen with glow, while the spectrum is an important data of discharge. Later this report will compare the spectrum of surface dielectric barrier discharge and the spectrum of air discharge. Although in the surface discharge the gas which is breakdown is air, but it should be different from air discharge.

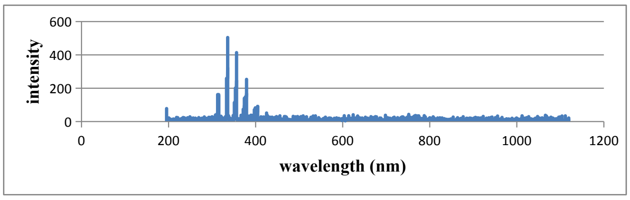

Figure 54. Spectrum of surface dielectric barrier dis-

DOI: https://doi.org/10.30564/ese.v1i1.713

charge, material is Acetate

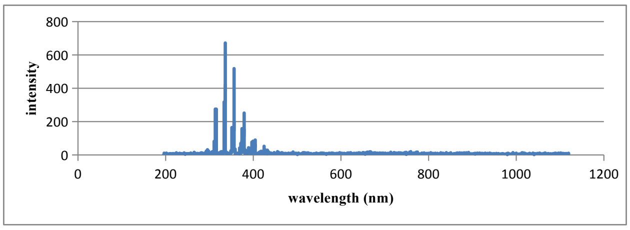

Figure 55. Spectrum of pure air discharge

Compare the Figure 54 and Figure 55 (copy from Wang Guantian, a project group mate) we can find the wavelength of the light almost the same at 315nm, 336nm, 357nm and 379nm. But the intensity has obvious difference. At the points which are the wavelength of air light the intensity of air light is larger than surface dielectric barrier discharge, while the other points of wavelength the intensity of air light is smaller than surface dielectric barrier discharge. What makes this result is maybe the main part which is emitted is air, so the wavelength are the same generally, never less the material still has some emitter electrons and these emitter electrons cause the light, then the spectrum has difference with air. Then I use the intensity of surface dielectric barrier discharge subtract the intensity of air to find out an approximate spectrum of Acetate the material of my dielectric.

Because I do not have enough time to find out the effect of dielectric on the spectrum, I did not do a deep investigation of the spectrum. If I have chance to go on doing this project I will investigate about the effect of different material on the spectrum.

3.6 Conclusion

In surface dielectric barrier discharge, discharge voltage increases with applied voltage in linear. Also introduce the discharge channel is longer with rising of applied voltage. The discharge power of surface dielectric barrier discharge increase with applied voltage by a curve, the ratio of increasing will slow down with applied voltage. And the capacitance before discharge decreases with applied voltage, but it is not by linear. Compare with the linear increasing of discharge voltage, it shows the discharge area's expanding is not only at length but also at width, otherwise the capacitance should decrease by linear same with discharge voltage. If the cathode covers the anode, or in another word, the discharge only happens on anodes or cathode, the distance of gap will not effect on discharge. The discharge in this kind of configuration only happens along the edge of electrodes. Discharge power is based on frequency of power supply, and it is proportional to the frequency. However the high frequency will cause a large number of noises both in the Lissajous figure and lighting emission. From the simulation, the discharge area will expand with applied voltage in the surface dielectric barrier discharge. The area expanding is both in length and width, in another word it expands in space. The thicker of dielectric will lead to a higher applied voltage for breakdown, and the discharge voltage will be lower when applying same voltage.

4. Discussion

The first difference between surface discharge and vertical discharge is the configuration, in vertical discharge the anode and cathode are separated by gas gap, but in surface discharge the electrodes are connected by dielectric barrier. Then before discharge the Lissajous figure of vertical discharge is a straight line and when discharge the Lissajous figure is a general parallelogram. In the surface discharge the Lissajous figure before discharge is an ellipse, and during discharge the Lissajous figure does not have sharp angle, but the whole figure is smooth. That is because of the configuration. The dielectric which connects electrodes has a large resistance but it cannot be infinite large, then it is not a capacitance but an impedance. Therefore, the phase fault exits in the circuit and before discharge the figure is not a line. Another difference is about discharge voltage. In this report I have shown the relationship of discharge voltage and applied voltage. It is a linear increase, but in the vertical discharge we know the discharge voltage will not change and it is a constant. Because the gas gap of vertical discharge is settled, base on Paschen Law at the same temperature, atmosphere and distance of gap the breakdown voltage, i.e. discharge voltage, follows the Paschen curve. In the surface discharge, the discharge capacitance does not exist before discharge, and the discharge area is along the surface and not a constant gas gap, then with the increasing of applied voltage, the discharge area or discharge channel expand on the surface. Therefore, the distance of gas gap rising with the discharge channel, and from the Paschen Law the rising of distance will cause the higher breakdown voltage, i.e. discharge voltage. The other aspect of difference is about the capacitance, because of the change of discharge channel, the capacitance will be changed certainly. In the experiment the capacitance of surface dielectric barrier discharge is decreasing with the rising of applied voltage. Then the discharge power of surface discharge is difference from vertical discharge. Because in the Lissajous figure the peak point is the applied voltage which will keep enlarge and the slope of edge at bottom is the capacity of capacitance before discharge, in the surface discharge the slope will be smaller with applied voltage decreasing, but in the

 DOI: https://doi.org/10.30564/ese.v1i1.713

vertical discharge the slope will not change. And the cross of zero axes with the Lissajous figure is discharge voltage that will not change in vertical discharge but change in surface discharge. Therefore, it is not hard to find out the increasing of surface discharge power will be larger than vertical discharge power, as increase applied voltage by the same quantity the changed area of discharge voltage will be larger than the vertical discharge.

5. Conclusions

Base on the experiment and simulation result, from the data and curves I can give the conclusions below.

In surface dielectric barrier discharge, discharge voltage increases with applied voltage in linear. Also introduce the discharge channel is longer with rising of applied voltage. The discharge power of surface dielectric barrier discharge increase with applied voltage by a curve, the ratio of increasing will slow down with applied voltage. And the capacitance before discharge decreases with applied voltage, but it is not by linear. Compare with the linear increasing of discharge voltage, it shows the discharge area's expanding is not only at length but also at width, otherwise the capacitance should decrease by linear same with discharge voltage. If the cathode covers the anode, or in another word, the discharge only happens on anodes or cathode, the distance of gap will not effect on discharge. The discharge in this kind of configuration only happens along the edge of electrodes. Discharge power is based on frequency of power supply, and it is proportional to the frequency. However the high frequency will cause a large number of noises both in the Lissajous figure and lighting emission. From the simulation, the discharge area will expand with applied voltage in the surface dielectric barrier discharge. The area expanding is both in length and width, in another word it expands in space. The thicker of dielectric will lead to a higher applied voltage for breakdown, and the discharge voltage will be lower when applying same voltage. Thicker dielectric is hard to be breakdown, but it will waste lot of energy, then chose the best thickness and the position of electrodes is the best way for application. The spectrum of surface dielectric will be different by different material of dielectric that is a significant element for application. The difference between the surface discharge and vertical discharge mainly express on the structure, discharge voltage. In the surface discharge electrodes are connected by dielectric, and discharge voltage will increase with applied voltage. And the ratio of discharge power increasing of surface discharge is large than vertical discharge.

6. Further Work

Now this project have been finished, but there are something I could do further investigation. If I can get a pulse power supplied, I will apply it on the circuit, and then collect the Lissajous figure under a pulse power supplied and compare the difference between pulse power supply and general power supply. Then the result of effect of power supply on the discharge will be overall conditions. In another way, surface discharge will produce ozone during discharge in the air or pure oxygen, so I will investigate the production of ozone by different type of configuration or material of dielectric. I know the efficiency will not keep increasing with applied voltage, and it will star to decrease at a point and become a constant gradually. Then I will try to find out the best configuration for producing ozone, and in different configurations and materials the highest efficiency point. The dielectric material will influence the lightning emission, so I will investigate the spectrum of different kind of material. That is important for application.

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