Influence of Grounded Back Electrode on AC Creepage Breakdown Characteristics

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2014 by the
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May 2014

ABSTRACT

This thesis focuses on the influence of a grounded back electrode on the breakdown characteristics. The back electrode is an electrode which attaches at the back side of solid insulation. Insulation with grounded back electrode is a common type of insulation which is adopted in many high voltage power devices. While most of the power equipment work under AC voltage, most of the research on back electrode is focused on the DC voltage. Therefore, it is necessary to deeply investigate the influence of the back electrode under AC applied voltage.

To investigate the influence of back electrode, the research is separated into two phases, which are the experiment phase and the electric field analysis phase. In the experiments, the breakdown voltages for both with and without back electrode are obtained. The experimental results indicate that the grounded back electrode does have impact on the breakdown characteristics. Then with the breakdown voltage, based on real experiment model, the electric field is analyzed using computer software. From the field simulation result, it is found that the back electrode also influences the electric field distribution. The inter relationship between the electric field and breakdown voltage is the key to explain all the results and phenomena observed during the experiment. Additionally, the influence of insulation barrier on breakdown is also investigated. Compared to the case without ground electrode, inserting a barrier into the gap can more significantly improve breakdown voltage.

ACKNOWLEDGEMENTS

I want to express my deepest gratitude first and foremost to my thesis advisor, Prof. George Karady, for his guidance, caring, encouragement, motivation, enthusiasm, patience, and all the assistance he offered in all phases during the research project. He inspires me when I encounter problems, and tries to bring me up to a higher level. I could not have thought having a better supervisor for my Master thesis. Besides my thesis supervisor, I would like also thank the rest members of my thesis supervisor committee: Dr. Raja Ayyanar and Dr. Keith Holbert, for their time and profound comments in my Master thesis defense.

I would like to also appreciate the assistance from Ahmad Alhabib, Hassan Alamer, and Qixing Yan, who are the members of the senior design group. I want to also express my gratitude to my dear friends, and fellow labmates for the continuous and unconditional support. Last but not least, I especially would like to thank my parents, for their financial support and spiritual encouragement throughout my life.

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NOMENCLATURE

a	The distance from the high voltage electrode to the barrier
d	Barrier thickness
E	Electric field strength
E_m	Maximum electric field strength
E_S	Tangential component of the total electric field
E_{S_ave}	Average value of tangential electric field
E_{Sm}	Maximum value of tangential electric field
F	Electric field force
H	Barrier height
l	The integration gap length
L	The gap distance from the high voltage electrode to ground electrode
L_C	The critical gap distance
q	Quantity of electric charge
V_B	Breakdown voltage
W	Required kinetic energy for breakdown

Chapter 1. LITERATURE REVIEW

1.1 Overview

Breakdown is one of the most common causes to affect the reliable operation of the power insulation equipment. The aftermath of the breakdown can be the damage of the power equipment, short circuit of the system, or even hazardous fire. Some of the power equipment, such as transformers, generators and circuit breakers, are working under high voltage condition. To ensure safe operation, the insulation of these devices must be well designed so that they can sustain the high electrical stress. It is known that when the electric field is above a certain critical value, which is typically 20-30 kV/cm, there will be corona, or even partial discharge streamers generated from the electrodes. Theses streamers can cause the surface degradation of the insulation material. Therefore, to avoid damage of such phenomena, it is needed to investigate the creepage discharge characteristics of the insulation material.

1.2 Achievements made by other researchers

Bedoui et al. [1] discussed the characteristics of discharges on the interface of liquid/solid insulating material. All the tests are conducted in the test cell under both AC and DC conditions. In the experiment, the point-plane electrode configuration is adopted. The barrier is a circular insulation film. The authors placed the barrier on the plane electrode. The liquid is filtered transformer oil. In the experiment, the electrical and optical signals were recorded and analyzed. From the observation, the DC discharge patterns are dependent on the polarity of the applied voltage. In negative discharge, there are more branches and the discharge is more luminous. This is due to ten times higher discharge current in the negative discharge. However, despite the high current in the negative discharge, the corresponding discharge charge and final length of discharge remain almost the same. The higher current of negative discharge also makes negative discharge contain more discrete components. In the AC discharge, phenomena similar to both negative and positive DC discharge appear in one cycle. However, the final length of discharge is longer. With the increase of the voltage, the final length will be longer. However, the final length reduces almost linearly with the pressure. With increased pressure, the duration, discharge branches, emitted light and the number of pulses decreases. This phenomenon shows that the streamers are gaseous when the insulating material is immersed in the liquid.

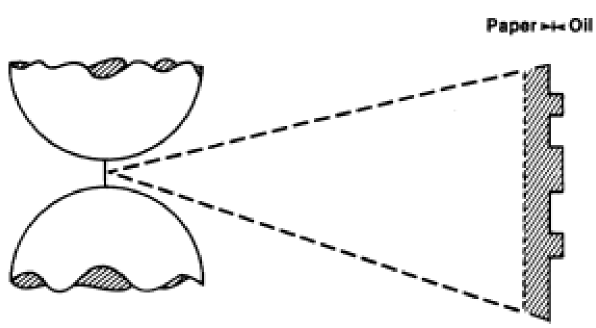


Figure 1.1 The model of the paper-oil interface discussed in Reference [2]

In literature [2], to study the electrical breakdown at the oil-paper interface at 60 Hz and impulse, the authors' purpose is to obtain the measurements required for thoroughly understanding the mechanism of breakdown. The oil used in the test is filtered commercial oil. The insulation paper is fixed and it is parallel to the electric field, which is like Figure 1.1. The electrodes have different radii. The test result shows that the oil/paper interface is not the only place that breakdown may happen. The breakdown also can occur elsewhere. At the interface, the breakdown voltage may still be higher than the breakdown happening somewhere else. However, if the paper is not dried or contaminated with gaseous voids, the breakdown will likely occur in the interface. In this case, the breakdown voltage will be lower. The authors indicate that future researchers can focus on studying how to reduce the impact of moisture and gaseous voids if they are the dominant restrictions of improving breakdown voltage. Moreover, more factors are needed to take into consideration. For example, since the breakdown voltage distribution is statistical, using a geometry scaling factor, it may be feasible to develop a two-variable expression to calculate the breakdown voltage by possibility distribution function. Such a scaling factor is proposed but not verified experimentally yet.

In literature [3], K. Wechsler and M. Riccitiello investigated the breakdown process when the high voltage stress is in parallel to the flat side of the insulation. The test specimen is immersed in oil to avoid flashover. The voltage stress between electrodes is increased in a prescribed rate until breakdown occurs. The pins are also immersed in the oil. The breakdowns can occur both between the pins and between solid dielectrics mounted on the pins. After conducting experiments, the authors found that all the data is in agreement with previous experiment results except data of epoxy glass. This difference is due to the difference in the electrode type. The washer-type electrode utilized in tests before does not have enough distance beyond the solid-air interface to avoid fringing effects, while the fringing effect can be neglected in this test. The fringing effect can cause the electric field to concentrate near the edges. The results obtained in previous experiments can be explained by the fringing. The insulating properties are changed by the fringing effect. So the tapered-pin parallel electrode arrangement cannot be used to define the creepage insulation strength of the solid insulation. In a solid/liquid insulation system, the dielectric constant and the physical surface condition of the solid material determine the breakdown properties of the liquid. Since the insulating strength of the solid material is always higher than liquid, in the liquid/solid insulation system, the possibility of breakdown occurring in the liquid is lower. Moreover, a smooth interface can also reduce the possibility of breakdown.

In literature [4], the authors discussed the impact of the insulation barrier on the breakdown characteristics of transformers. The experiments are carried out to find the appropriate failure mechanisms for both new and aged power transformers. The experiments are conducted on pressboard with needle-to-plate electrodes. The gap distance between electrodes is adjustable. The tests are conducted on new, wet and aged pressboard samples. The results indicate that the relationship between the breakdown voltage of the oil gap E and the gap distance d is in good accordance with the equation $E = Ad^{-B}$. It should be noted that the electrical strength around the needle is much high than the average. Moreover, the dielectric strength of the oil gap and the dielectric strength of the oil-pressboard interface are almost the same. That means that dry new pressboard has no significant influence on the insulation level of the gap. Another test on dry pressboard confirms that with a clean and dry pressboard, the quality of the oil controls the discharge characteristics. The tests then conducted on wet pressboard to simulate the conditions in aged transformers. The results show that although the wet pressboard can reduce the flashover voltage, the flashover voltage does not significantly drop even when the moisture content is up to 3%. However, the PD voltage is greatly reduced when the moisture content is more than 1%. This is because when moisture is more than 1%, water molecules can concentrate into bulks and the ionization requires less energy. Then the authors also performed experiments to study the impact of continuous partial discharge on pressboards. When moisture is low (< 0.5%), the area near the needle is carbonized, which effectively enlarges the needle. When moisture is high (> 1%), around the tip of the needle electrode, there will be white marks generated due to higher discharge and they propagate towards the ground electrode. The white marks indicate the existence of gaseous channels. After more tests, the result shows that the fault gas in the oil pores in the pressboard produces these white marks. The discharge occurs not only in the bulk of oil but also in the microscopic oil pores in the pressboard. That is because when moisture is high, the discharge current also increases, which break down the oil molecules into gases and thus develop the gaseous channels.

Pfeiffer et al. [5] discussed the electric strength of small creepage distance under the exposure of different natural environmental conditions. To accommodate the small dimensions of modern electrical devices, the designers prefer to use the minimum allowable creepage distance rather than empirical data, which includes too much safety margin in the design process. To avoid the dispersion of the flashover voltage, pulsed ultraviolet radiation is utilized so that the micro-climate and distribution of space charge around the specimens are the same. To simulate the real natural environment, twelve locations, including busy street, power plant, industrial area and coastal area, are selected for the exposure of the experiment specimens. During the exposure process, a stressing voltage is applied on almost every specimen. The specimens are kept under the test climate for a few days then the breakdown voltage is collected by computer. The impulse withstand voltage of clean specimens shows that in dry climate, the impulse withstand voltages behave a similar way for different electrode shapes. At small creepage distance (d < 1mm), the humidity does not affect the electric strength except in the extreme humidity while the insulating material has some impacts. For the polluted specimens, without voltage stress applied in the exposure process, the impulse withstand voltage greatly reduces with the increasing of humidity at small distance while at big distance (d > 1mm) the impulse withstand voltage is not much influenced by the climate. With voltage stress applied, the situation is similar while the withstand voltage is a little lower. But the impact of climate is not so strong compared with small distance. The comparison between these two cases shows for short creepage distance, if the climate is dry, the impulse withstand voltage is reduced by pollution. However, at large distances the breakdown voltage is not influenced by climate except in high humidity. Moreover, the difference of surface properties of the materials make the adhesion ability to pollution particles different, which leads to the distinct test results of specimens made of different insulating materials. The withstand voltage of materials with low comparative tracking index (CTI) is likely to reduce more than high CTI. The conductive pollutants also can reduce the electric strength. For the dimensioning, the measurements show that the rated impulse with-stand voltage is lower than the IEC standard. That means if small clearance is admissible, reducing the creepage distance is allowable. With high CTI material, a much higher operating voltage can be achieved. But the ability to withstand the overvoltage is reduced at small dimensioning.

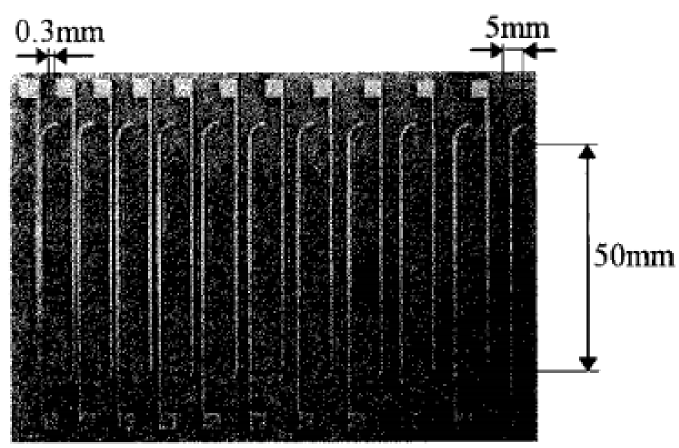


Figure 1.2 The electrode pattern for the experiment in Reference [6]

In literature [6], AC and DC breakdown characteristics of printed wiring board are investigated. The authors selected several different environments in the experiments for further discussion. These environments are: I: The experiment specimens are kept for 24 hours in normal humidity atmosphere; II: The specimens will be sprayed by salty water first, then kept in the same environment as I; III: The experiment specimens are kept for 96 hours in high humidity atmosphere; IV: The specimens will be sprayed by salty water first, then kept in the same environment as III. The experiments were conducted on three different kinds of specimens. All of the specimens have parallel type copper foil electrodes. The electrode pattern is shown in Figure 1.2. The insulation layer in type A specimen is glass-epoxy. Type B specimen is a type A specimen with a grounded back electrode attached. Type C specimen is just like Type A specimen except that the surfaces of the glass-epoxy layer and the electrodes are coated by the film of polyurethane. The AC breakdown test employs the rapid-rise method, and the up-and-down method. For the impulse breakdown experiments, the applied voltage is a positive impulse voltage with a standard waveform. The critical impulse breakdown voltage is calculated after 40 times of repeating the experiment on each specimen. The target of the experiments is to find the relationship between the breakdown voltages and the creepage distance. The results show that for type A and B specimen, the distribution of creepage breakdown and pulse creepage flashover voltages at environment I, II and III are almost identical. At environment IV, the breakdown voltages are much lower.

Comparing the results obtained from specimen A and B, the background electrode reduces the flashover voltage at environment I, II and III. When the creepage distance is equal to the insulation thickness, the flashover voltages have the most significant drop. However, at environment IV, the flashover voltage is not impacted by the background electrode. This is because at environment IV, on the surface of type A and B specimen, which is partially polluted by conductive material, the distribution of the electric field is determined by the specimen's electric conductivity. For specimen C, due to the existence of the coating, the breakdown voltages are almost the same at four environments, which is higher than A and B. The value of the impulse breakdown voltage divided by the AC flashover voltage of specimen C is apparently higher than A and B. That phenomenon indicates that influence of the coating less on the AC flashover voltage than on the impulse breakdown flashover voltage.

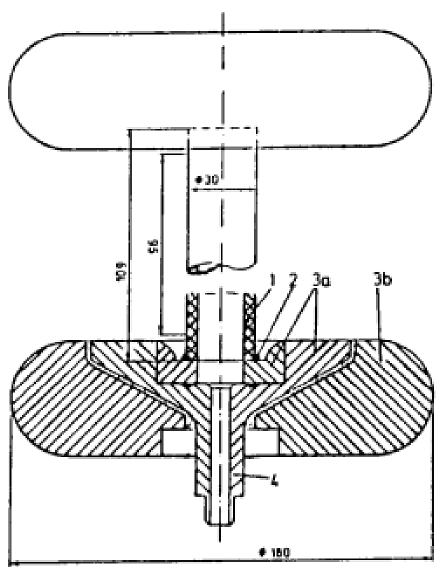


Figure 1.3 The insulator specimen for the experiment in Reference [7]

D. Konig et al. [7] investigated the partial discharge characteristics on the insulator surface. The insulator adopted in the research is the epoxy resin insulator with surface contamination. The shape of the insulators implemented in the experiments is hollow cylinder, which is shown in Figure 1.3. The surface electric field of the insulator is homogenous. The contamination layer is considered to have high resistance if the current is not high enough to influence the properties of the moisture layer. Four test specimens are utilized, which correspond to factory-new surface, first state of ageing, advanced state of the early ageing, and changeover from early ageing to late ageing respectively. The test results on type 1, 2 and 3 specimens indicate that with the increase of condensed water volume and the conductivity of the layer, the partial discharge (PD) inception voltage will be lower. By measuring the surface charge, the authors find that micro discharges are supposed to be the starting factor of the ageing process. Later, the long-term PD behavior is also investigated. However, the intervals without pulses appear alternately with partial discharges of irregular time durations. This is because the microscopic properties can also vary even if the macroscopic properties do not change greatly. Besides that, the PD impulses can also react with droplets. So a new measurement quantity, compared to apparent charge, can be helpful. The authors proposed new equivalent circuit diagram for the surface of insulators with drop condensation, since PD impulses can occur before, at or even after the maximum test voltage. The diagram is consisted of several resistors, inductors and capacitors connected in a complex topology. The numerical values of the components determine which kind of components dominates the properties of the circuit. The domination of *R*, *C* and *L* corresponds to the PD impulse occurrence at, before, and after the maximum test voltage.

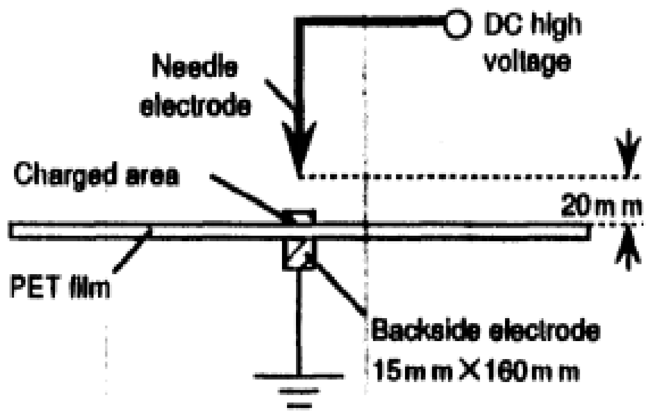


Figure 1.4 Configuration of charging PET film in in Reference [8]

H. Okubo et al. [8] investigated the impact of the surface charges on the propagation characteristics in both air and SF_6 in practical gas insulated switchgear (GIS). In the experiments, the authors used PET film to simulate the solid insulators inside GIS. On the surface of the PET film, a needle electrode is adopted to generate corona discharge. The experimental setup is shown in Figure 1.4. By changing the gap distance, shape and position of the backside electrode, the distribution, amount and area shape of charge can be controlled. To generate corona, the needle electrode is energized by an impulse voltage. The maximum impulse voltage is 5 kV. The authors employ the probe method to measure the surface charge and the surface potential. The initial charge is eliminated by acetone or ethyl alcohol to ensure the accuracy of the experiment. The charged

PET film is placed on the surface of the back electrode. By assuming a parallel plane capacitance, the relationship between surface potential and surface charge can be established. The discharge length is observed and measured. For each surface charging potential V_S, the discharge extension length l_e increases with the increasing of negative impulse voltage V_a. When the charging voltage V_S is in the range of 2 to 3 kV, l_e is 2 to 6 times higher than that in uncharged specimens. With the increase of V_S, l_e increases when the surface charge is positive while for the negative surface charge l_e decreases. This result reveals that the addition to l_e is the extension length incremental equivalent to V_S. The cause of this phenomenon is that the electric field at the streamer, which leads to the change of l_e, is determined by the difference of V_a and V_S. After investigating longer samples, a relationship $l_e = k|V_a|^n$ is found, in which $n = 3$ or 4 and k is a constant. This equation is applicable in conditions with and without charging. In SF_6 atmosphere, l_e increases almost linearly with the increasing of V_a. In both air and SF_6, the flashover voltage V_f reduces by the power of 0.3 of C_s. For PET film with surface charges, V_f decreases with V_S. From the result it is obvious that it is the surface potential controls the length of surface discharge and the breakdown voltage and rather than surface charge. The discharge current pulse, which flows into the back electrode, is also measured. The current pulses in SF_6 have the peak value ranging from half to one third of that in the air under same condition. Different discharge propagation ways in SF_6 and air can explain this phenomenon. Moreover, the discharge current is independent of V_S while l_e and the discharge propagation time

t_p rise with the increasing of V_S. This means higher surface charging voltage V_S leads to longer duration time and higher propagation velocity, which leads to longer l_e.

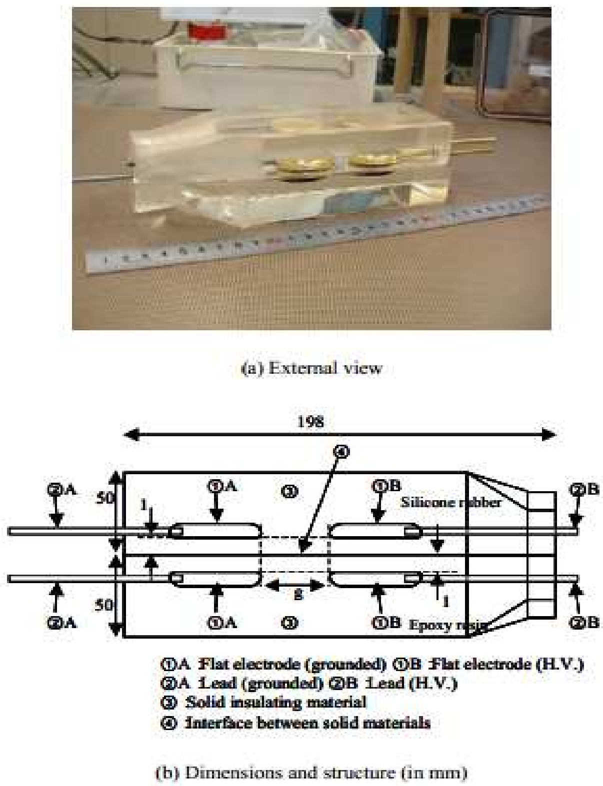


Figure 1.5 The developed electrode system to measure ac PD inception stress in Reference [9]

In literature [9], the interfacial breakdown between a soft dielectric and a hard dielectric material is investigated. The materials used in the experiment are silicon rubber and epoxy resin. To study the AC partial discharge (PD) inception electrical stress, the electrodes should be arranged in a way that the electrical field is parallel with the interface. So the authors chose two pairs of two identical flat-and-round shaped electrodes molded by epoxy resin and by silicone rubber. The epoxy resin and silicone rubber are pasted together with mineral insulating oil. The right two electrodes are connected to high voltage AC source while the left two are grounded. The electric field at the interface is calculated through the charge simulation method. The field distribution at the center of the gap is almost uniform. The partial discharge is observed by a PD measuring system. The measured PD inception is 10 kV/mm. However, in aged electric apparatus, some air will penetrate into the interface. To simulate this situation, another new system is introduced. The electrode configuration is two disc electrodes with one back electrode. Due to the existence of the back electrode, at some places, the electric field is perpendicular to the interface. The air layer thickness d can be adjusted by the spacer. Oil will not be applied to the interface of this system. The AC and impulse breakdown voltage V_B and surface potential are measured during the experiment. Same experiments will also be conducted on same samples without back electrode. Moreover, a molded sample without air layer is also used for comparison. In the experiments, the relationship between V_B and d for samples without back electrode is measured. When AC voltage is applied without the back electrode, due to the edge effect or strong non-uniform electric field, the result of V_B is lower than expected. With increasing of d, V_B decreases. One possible explanation is that with larger d or air layer volume, the possibility of electrons initiating positive streamer will increase. Another possible explanation is that with smaller d, the field intensity will be more reduced by the positive charges, thus making V_B higher. The discharge trace shows that the discharge is more influenced by epoxy resin when d is small. When impulse voltage is applied without back electrode, there is no significant difference between positive and negative voltage. The relationship between V_B and d is similar to AC but the dependence is weaker. This is because there is very little surface charge when impulse voltage is applied. With the back electrode, compared to the results without back electrode, the result for applying negative voltage is different while the result for applying positive voltage is similar. V_B increases with increasing of d. This is caused by the high electric field strength in the region near the positive electrode when positive impulse voltage is applied, and the high electric field in the region near the negative electrode when negative impulse voltage is applied due to the existence of the back electrode. V_B also increases with the increasing of electric field if positive charges remain on the bottom of epoxy. With larger d, this phenomenon is more notable. When AC voltage is applied with back electrode, the breakdown is determined by positive or negative discharge depending on d value. When d is small than the critical value, V_B is higher in the positive half cycle while V_B is higher in the negative half cycle when d is large. When the air layer disappears, such surface breakdown will not occur until a puncture breakdown connecting the high voltage electrode and back electrode takes place when the applied voltage is high enough. Another experiment also confirms that positive charge has significant impact on the surface breakdown.

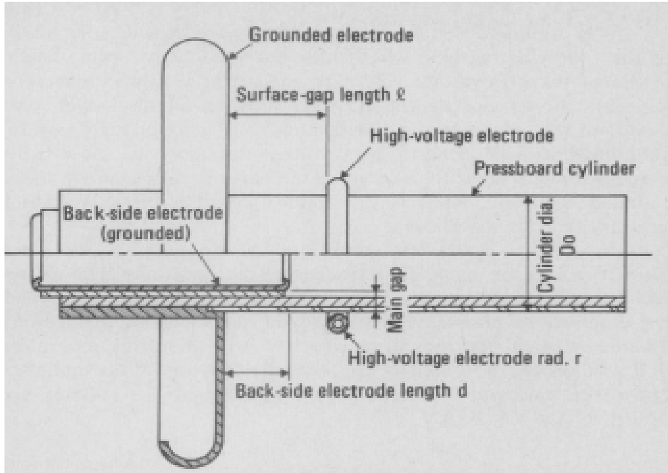


Figure 1.6 The standard model in Reference [10]

In literature [10], the authors investigated the creepage breakdown with impulse voltage applied, as well as the scale effect of the test sample. The experiments are conducted in transformer oil and have two phases. The first is conducting the experiments on the “standard model”. The standard model is a pressboard cylinder insulator, which is like Figure 1.6. The insulator has two layers. After each experiment the outer layer is changed. In the tests, a coaxial electrode system is used. The high voltage electrode, which is like a ring, is located outside the insulator. The ground electrode is a plane electrode. Both the ground electrode and back electrode are located inside the insulator. The authors use this model to study how the parameters of the model influence the creepage breakdown, such as the influence of back electrode and the impact of different creepage length. The second is conducting breakdown experiment by employing the “scale models”, which are scaled-up models with geometrical parameters proportional to the standard model. The objective of this test is to see how the scale affects the breakdown properties. Scales of half size, 3 times size and 6 times size are used. The cross-sectional radius *r* of 5, 15, 25 mm of the high voltage cross- sectional are used. Before the test, the test samples are dried in 100 °C oven for over 80 hours. Then the samples are put in a tank filled with transformer oil. The water content is limited to 10 ppm during the tests. The impulse test voltage is applied in a step of 20 kV till around fifty to eighty percent of the estimated breakdown voltage. The applied voltage is measure through a voltage divider with resistance. The high frequency current flowing over the resistance connected to ground is also measure to determine the partial discharge current. When the back electrode can cover the whole gap distance, then the back electrode is defined as “strong effect” to the system. If the back electrode can only cover part of the gap, then it is called “weak effect”. The results of strong effect show that for all the *r* values, the dependence of the breakdown voltage on the gap length can be divided into two parts. When the gap distance is small, for each *r* value the breakdown voltage is constant. With larger *r* the breakdown voltage will be higher. When the gap distance is larger, the breakdown voltage increases with the gap distance. In this part for different *r* value the breakdown voltage is the same. The reason is that there is big difference between with and without discharge happening at the high voltage electrode. When the gap distance is short, all the discharges will lead to breakdown. But if the gap distance is longer, the discharge inception voltage is lower than the breakdown voltage. This phenomenon is confirmed by the detected discharge current. For the weak effect, almost all the electric field lines will be centralized in the region between the high voltage electrode and the top side of the back electrode. The “effective gap length”, which is the distance from the high voltage electrode to the tip of the back electrode, controls the breakdown voltage. The field calculation shows that the electric field near the high voltage electrode also has a significant influence on the breakdown voltage. It is also found that after insulating the high voltage electrode with a thin film of insulation material, the breakdown voltage is raised. The breakdown voltage is independent of the gap distance. There is no partial discharge observed either. This is because the insulation can make the travelling velocity of the discharges faster. So once the discharges are generated, they will definitely result in flashover. The results of the scale experiments indicate that the flashover voltage is corresponding to the scale size. The normalized breakdown voltage is proportional to S^m, in which S stands for the size scale and the m is a scale effect constant. In their experiment m is about 0.7. All the results show that the stressed oil near the electrodes and the electric field on the surface of the electrodes have great effect on the creepage characteristics. Additionally, the breakdown point at the high voltage electrode can vary between the contact point with the surface and the outmost point to the ground electrode. Then the angle between the breakdown point and the contact point with the surface is denoted as θ. θ equals 30° is the most common case in the experiment. When the length of back electrode is shorter than the sum of the gap distance and the high voltage electrode cross-sectional radius, the electric field strength is increasing with the back electrode length. When the back electrode length is longer than that, the electric field strength is a certain value irrespective to the back electrode length. The authors calculate the stressed oil volume (SOV), and found the flashover electric field strength is linear with $SOV^{-1/11}$. Considering the scale effect, the flashover electric field strength is linear with $S^{-3/11}$ and the breakdown voltage is proportional to $S^{8/11}$. Previously they have found that the breakdown voltage is proportional to $S^{0.7}$. So the calculated result matches the experiment data.

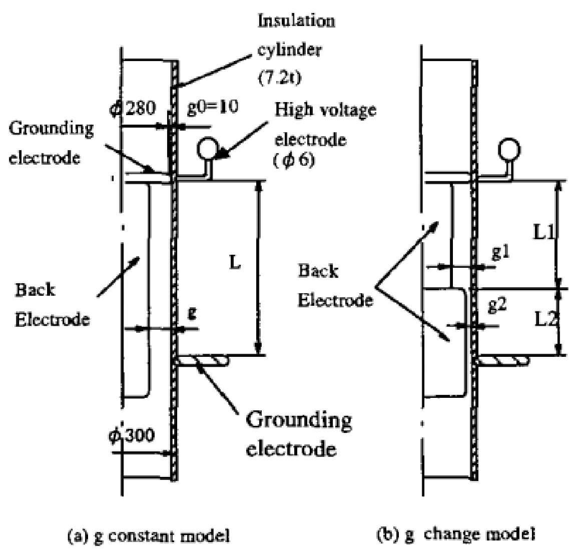


Figure 1.7 The experimental electrode configuration in Reference [11]

In literature [11], the influence of back electrode on creepage discharge over oil- immersed insulation under lightning impulse voltage is investigated. The test setup is shown in Figure 1.7. In the test, every model is coaxial. The high voltage electrode is copper pipe while the grounding electrode is disk-like. Both of these electrodes are placed outside the pressboard insulation cylinder. The cylinder-like back electrode, which is connected to ground, is arranged inside the pressboard insulation cylinder. The high voltage electrode is fabricated to make observation easy. There are two kinds of models. In one kind model the distance *g* between the back electrode and insulation surface is constant vertically along the insulation surface. In the other kind of model, this distance *g* is not vertically constant and can be 10 or 55 mm. Each vertical distance *g* value occupies some portion of the total surface length. To make the start time of partial discharge almost the same for all the models, the disk-like ground electrode is placed to counter with the high voltage electrode inside the insulation cylinder. The distance between them is set to be 10 mm. The experiment voltage is an impulse voltage with positive polarity. This voltage is increased to the flashover voltage from a low voltage in 10-15 kV steps. The streamer propagation can be observed during the test. The results show that for *g* constant models, flashover voltage is higher if distance *g* is larger if surface length is large enough. If the surface length is not long, the breakdown voltage is regardless of distance *g*. For distance g variable models, the flashover can be higher or lower than *g* constant models. Moreover, the propagation of the *g* variable models is controlled by both distance *g* values. The propagation characteristic is controlled on the boundary where the distance between the back electrode and insulation surface changes. So this distance *g* should be related to such phenomenon. After further investigation, if back electrode occurs, with increasing of creepage length, the flashover voltage increases and saturates. The smaller the distance *g* is, more obvious this tendency is. To investigate the flashover characteristics, the author introduces the voltage addition method and distance addition method to estimate the flashover voltage for longer distances. For both methods, the curves of flashover voltage vs creepage length for both distance *g* values are plotted. In both curves, with larger creepage length, the increasing rate of breakdown voltage gradually drops. For the voltage additional method, if the flashover voltage at surface distance L_1 is known as V_{L1}, the flashover voltage at distance L_1+L_2 is obtained by adding V_{L1} to the increment between V_{L1+L2} and V_{L1} found on the curve. For the distance addition method, the difference ΔV between the flashover voltages for distance L_1+L_2 and distance L_1 for one distance *g* value is known. For the other distance *g* value, if the flashover voltage at distance L_1 is also known, then the flashover voltage at distance L_1+L_2 can be obtained by adding ΔV to the flashover voltage at distance L_1. From the estimation results, the voltage additional method is better to estimate the flashover voltage.

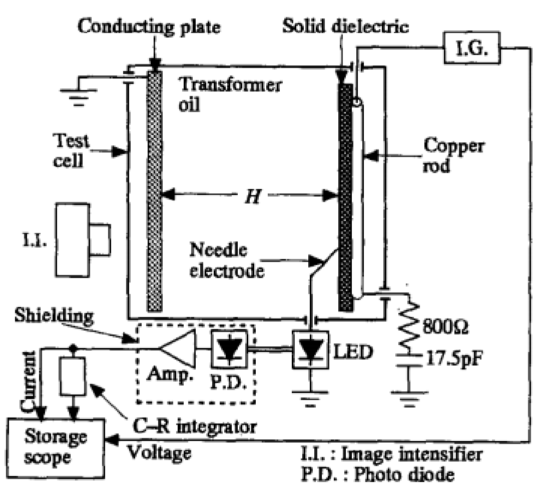


Figure 1.8 The experimental setup configuration in Reference [12]

In literature [12], the authors investigated the influence of side electrode. The experimental setup is shown in Figure 1.8. The test sample is immersed in the oil and the side electrode is grounded. In the experiment, three kinds of solid dielectric board are used as test samples. A copper rod is coherent to epoxy on one side of the boards. A tungsten needle is arranged beyond the copper rod. The distance to the board surface is 0.2 mm. The needle is grounded through LED (Light-Emitting Diode). The light emitted of LED is proportional to the current flowing through LED. The current flowing through the needle can be measured by the LED. The grounded conducting square plate, which is the "side electrode", is placed at the same side as needle opposite to the surface of the board. The distance from the side electrode to board surface H varies from 2 to 15 cm. A DC impulse voltage V_m is applied on the rod. The streamers are generated from the needle tip and propagate along the side of the rod since the streamer polarity is opposite to the voltage. The discharge length L_m is measured using camera. For uncharged surface, the board surface will be grounded after each voltage application. For charged surface, charges are deposited by applying impulse voltage on the copper rod. The surface potential is measured by a probe. The polarity of the potential and the streamer is the same. The charging area also reflects the region of discharges. In the test the relationships between L_m and V_m are derived as H varies. For all the samples, the shape of positive streamers is like a tree while negative streamers exhibit fuzzy aspects like a bush. After the peak of the first current pulse there are some intermittent current pulses. The first current is due to the injection and charging current while the intermittent pulses are related to specific branches of streamers. The velocity of growth of the streamers is L_m over pulse sustaining time T_P. For both polarity streamers, L_m is linear with the increasing of V_m. Under a certain voltage, L_m decreases with decreasing of H. This shows that for the streamers, H has influence on electric field strength on them. This is because when voltage is applied on the needle, the streamers are generated from the needle tip, where the electric field is highly divergent. These streamers contain charges, which can change the electric field. The highly non-uniform electric field generated by the streamers can enhance the propagation of the streamer. When the distance H reduces, the potential on the streamer is almost equal to the needle electrode due to the electrostatic shielding effect. This effect results in a reduced field strength on the streamer. The potential at solid-liquid interface V_b decreases with decreasing of H and it is also relevant to the permittivity of the solid dielectric. For both positive and negative streamers, L_m increases linearly with increasing of V_b independent of H. But for each different material the relationship between V_b and L_m is different for negative streamers while it is the same for positive streamers. The reason of this phenomenon may be the rough conditions of the solid surface since negative streamers propagate along the surface of the insulator while the positive streamers do not. From the surface potential distribution the authors find that the propagation of the streamers is influenced by surface charging. For positive samples, L_m is shorter than uncharged samples while for negative samples L_m is longer. That is because when positive streamer is travelling along the surface of the insulation, the electric field in the streamer will be raised by the negative surface charge. The consequence of this effect is that the more energy is injected to the streamer and the propagation distance of the streamer will be longer. On the contrary, the positive charges will prevent such energy injection. Another experiment shows that inside the streamers, the potential drop V_d is independent of V_m or surface potential. The propagation of the streamer is limited by the finite value of V_d. The measurement of time and streamer length shows that the positive streamer propagation speed is about 1.6 times of negative streamers. Surface charges have little impact on the speed of the streamers.

A. Maglaras and F. V. Topalis [13] investigated the impact of grounding on the insulation properties of small air gaps under DC voltage. The electrode arrangements investigated are rod-rod and rod-plate with different geometry. The electrodes are made of brass. The diameter of the rod electrode is relatively small while the diameter of the plate is much larger. The electrodes are energized in two ways. One way is one electrode is energized with positive or negative DC voltage while the other electrode is grounded. The other way is equal voltage with different polarities is applied on both two electrodes. The environmental conditions are strictly controlled to avoid the impact of surroundings. The electrical field is calculated by commercial software using finite element method. The initial condition is determined by a series of equations. For both arrangements, the simulation result shows that the grounding electrode has great influence on the distribution of the electrical field. For the rod-plate arrangement, the influence of grounding becomes significant with large enough gap distance (larger than 2 cm). The field distribution is more inhomogeneous and corona onset voltage is lower when the plate is grounded than the rod is grounded. The difference depends on the gap length and gap geometry. With increasing plate radius, the influence of the grounding decreases. For the rod-rod gap, if one of the electrodes is grounded, the distribution of the electric field will be less homogeneous. The difference also depends on the gap length and gap geometry. Due to the inhomogeneity, the breakdown voltage is a little lower than symmetrically charged electrodes if the gap distance is less than 5 cm. The impact of grounding, which can make the corona current increase up 2 to 5 times, is much more intense than on electric field and the influence strongly depends on the diameter of the rod. The result also indicates that the corona current is not influenced by the polarity of the DC source except the known polarity effect. Grounding also impacts the breakdown voltage and the influence has relationship with the gap distance and polarity of the applied voltage. With negative applied voltage, the influence of the corona current minimizes the influence of grounding, while with positive applied voltage the influence of corona current enhances the influence of grounding. With gap distance larger than 2 cm, there is small corona current flowing through the gap, which reduces the inhomogeneity of the electrical field. So with increasing corona current, the corresponding breakdown voltage will also increase.

In literature [14], the influence of sustaining AC voltage on the V-T properties is investigated. The researchers use the epoxy as the insulation material. In the experiment, the embedded plate-to-plate aluminum electrodes are used. The electrode gap distance is 2-3 mm. The test consists two major parts: one is to determine the V-T characteristics of the epoxy, the other is to investigate the degree of deterioration caused by long-term stressing. The test result shows that the life in minutes L has the relationship of $L = (E/30)^{-16}$. The result also indicates that an identical status exists between 15-30 kV/mm. With several thousands of hours of 12 kV/mm pre-stress, the PDIS (Partial Discharge Inception Stress) is identical as unstressed specimen while with 15-20 kV/mm pre-stress, the PDIS is reduced. The breakdown stress (BDS) is 7% lower at maximum than unstressed specimens. These phenomena demonstrate that even void-free epoxy mold insulation can be deteriorated under high voltage stress. Small partial discharge such as 0.1 pC can harm the epoxy and reduce the electrical life. The authors also found that at the boundary between the electrode and epoxy,. There is small partial discharge tracing on 15 kV/mm pre-stressed specimens while no such traces on unstressed or 12 kV/mm pre-stressed specimens. So it’s expected that discharge less than 0.1 pC does not harm the epoxy insulation. The tests with different electrode material show that the PDIS depend largely on the electrode material. The cause for small PD cannot be simply attributed to the thermal expansion of electrode material or small voids. The PDIS is related to the protrusion shape of the electrode, specimen with sharper shape, which can concentrate the electric field, has lower PDIS. Besides that, the PDIS is also determined by epoxy de-bonding from the electrodes, which is caused by the difference of thermal of the thermal expansion coefficients at the boundary. Moreover, the authors concluded that the degree of deterioration is not only dependent on the voltage stress, but also the existence of small partial discharge.

In literature [15], the influence of diameter of the barrier on the AC discharge characteristics of the transformer oil is investigated. In the experiment, the electrodes are in a point-plate arrangement and placed horizontally. The distance between the electrodes can vary from 1 to 12 cm. The barrier is a circular plate. Two kinds of barrier which are made of different materials are used. The barrier is inserted between the electrodes. The authors use the a/d ratio to control the location of the barrier. The a/d ratio stands for the ratio of point-barrier distance divided by the point-plane distance. The experiments first use the barriers with the same thickness but different diameters. The results shows that for both kinds of materials, the ratio of the breakdown voltage with barrier to without barrier U_{ab}/U_{sb} reaches maximum at a/d equals to 0.2. So the inserted barrier can increase the breakdown voltage up to 180% of the breakdown voltage without barrier. However, if the permittivity of the barrier is low and the distance from the point electrode to the barrier is very small, the breakdown voltage can be even lower than without barrier. With larger diameter, the flashover voltage also increases. The reason is that the minimum disruptive discharge channel becomes longer. The residual charge increases with higher pre-breakdown voltage regardless of where the barrier is. This confirms that the experimental setup has capacitance. The position of the barrier has no effect on the residual charge except the distance between the point electrode and the barrier is very small. When the distance between the point electrode and the barrier is very small, the capacity will be higher and the value depends on the material and the geometry of the barrier. The ratio of charge with barrier to without barrier Q_{ab}/Q_{sb} reduces to minimum value when a/d = 0.2. This result is effective with different barrier diameter. With larger barrier diameter, the pre-breakdown charge will be also higher. The insertion of barrier can lower the pre-breakdown charge and system capacitance, especially when a/d is equal to 0.2. So the best position of barrier insertion is a/d equals to 0.2.

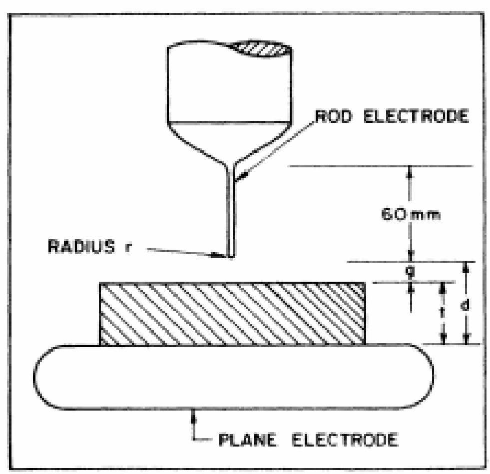


Figure 1.9 The experimental electrode geometry in Reference [16]

V. Maller and K. Srivastava [16] investigated the corona inception breakdown characteristics in non-uniform field in air. The test adopted the point-plane electrode with vertical arrangement, which is shown in Figure 1.9. The plane is fixed on the bottom side and the point electrode has with several different radii. In the whole system, the authors also used a spacer, which is made of epoxy. In some experiments the spacer is placed on the top surface of the plane electrode to act as barrier insulation. The bottom electrode is connected to ground through a resistance. Then the flow of corona current can be detected through the transient voltage across the resistor. The charge deposited on the plane electrode is also detected through the probe. To get the corona inception voltage, 50% of the inception voltage V_i will be first applied and maintained for 10 s. If no discharge happens then the voltage will gradually increase until the first discharge is observed. The voltage at this instance is the corona inception voltage. Then the voltage raises about 10% and then gradually decreases until there are no corona pulses. This voltage is denoted as the discharge extinction voltage V_e. The experiments are first conducted without the insulation spacer. The corona inception always takes place in the negative half cycles, with several equal magnitude pulses. When the spacer is mounted, the corona can appear at both positive and negative half cycles depending on the residual charges on the plane electrode. In this case the magnitude of the pulses is not equal because the discharge sites migrate on the insulation surface. The pulse discharge is not able to distort the voltage waveform due to low density. With the increase of the gap distance d, V_i and the breakdown voltage V_b tend to increase and saturate. Both V_i and V_b are highly dependent on the radius of the point electrode. With larger radius, both V_i and V_b will increase. With certain point electrode radius, V_i is dependent on the air-gap length *g*. For different *d* values, when *g* is about 20 mm, V_i reaches the peak. With increasing of *d*, this peak value also increases. With a certain value of *d*, V_b decreases with *g* increases. With *d* increases, the V_b also increases. With *r* increases, V_b decreases. The results demonstrated that the spacer surface charging can also has great impact on the generation of corona and creepage characteristics. The corona is initiated from the point electrode. When $g = 0$, the presence of the spacer increases the breakdown voltage but decreases the corona inception voltage. The sudden change from the electrode to the spacer could enhance the electric field and thus reduce the corona discharge. When the density of corona is low, this would not result in the flashover. With the increase of voltage, there will be more corona pulses and glow would develop around the point electrode. If there is no spacer, the corona inception voltage increases very rapidly with larger point electrode radius. With spacer, the saturation voltage for V_i is greatly reduced. The reason is that before breakdown, the electric field concentration caused by the charge deposited on the spacer surface has more influence on the breakdown than the homogenous electric field induced by bigger point electrode diameter. When $g > 0$, Townsend discharge pattern will appear first at the highly stressed cathode, providing enough electrons for breakdown. If a pulse appears, pulses will sustain during the half-cycle regardless of the polarity. The reason is that the accumulated charge from the previous corona activities enhances the electric field distribution. Corona on either polarity is different. The duration of the pulses is strongly dependent on the length of the air gap. For higher value of *g*, the effect of the charge deposit can be neglected. Only the qualitative discussions can be made at this time since it is difficult to detect the deposited charge.

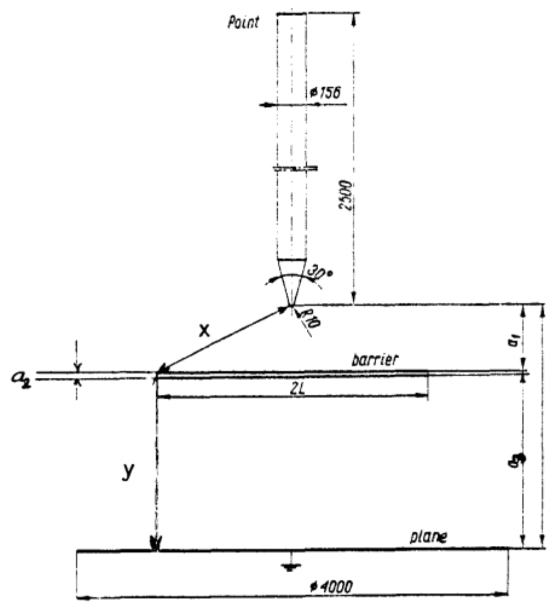


Figure 1.10 Arrangement of the electrodes and barrier in Reference [17]

A. Beroual and A. Boubakeur [17] investigated the influence of barriers on the impulse dielectric strength in point-plane electrode arrangement. A steel needle point is used as the high voltage electrode. The ground electrode is a circular steel plate. The gaps between the two electrodes can vary. A very thin cuboid bakelized paper barrier is used as the insulation. The paper barrier is thick enough to avoid inside breakdown. The surface is clean or contaminated using a uniform semiconductor film to simulate the situation that the barrier is polluted. The authors use the "up and down" method to find out the impulse breakdown voltage. The time between two tests is at least 60 s to avoid the impact of surface charge. For the clean barrier test, if the distance from the point electrode to the barrier is about 0.2 of the total gap distance, the breakdown voltage reaches the maximum value. With longer gap distance, the influence of the barrier is smaller. For the shortest gap distance in the experiment, the maximum increment of the breakdown voltage is 130% while for the longest gap distance, the maximum increment is only 20%. The reason is that the barrier is an obstacle to the discharge. The barrier elongates the creepage length. Additionally, the surface charge on the barrier forms an electromagnetic obstacle. Both two factors contribute to higher breakdown voltage. When the barrier surface is contaminated, the effect of the barrier can vary from a clean barrier to a metal barrier. When the surface conductivity is more than 1.6 μS, the results are the same with a metal barrier. In this case, the discharge develops from the point electrode to the center of the barrier first and then from the edge of barrier to the plane electrode. When the conductivity is less than 0.4 μS, the results are like a clean barrier. With a polluted barrier, at low voltage some streamers can grow from the edge of the barrier, which makes the barrier act as an electrode. When the gap distance is large enough the polluted barrier can even make the breakdown voltage lower than without barrier. Some other papers have concluded that metal barrier with large curvature can increase the breakdown voltage. So for polluted barrier it is important to improve the shape of the barrier. Additionally, if the barrier surface facing the point electrode is clean then however condition the other surface is the breakdown voltage can be improved. It is found that while the electric field is non-uniform at the space between the point electrode and the barrier, the electric field inside the barrier and at the space between the barrier and the plate electrode is uniform. The authors then developed some equations to find out the relationship between the parameters. From the equations, using the hyperboloidal approximation for the point electrode, the best position of the barrier depends on the radius of the point conductor. The optimal distance from the point electrode to the barrier is about half of the radius of the point electrode. Moreover, using spherical approximation for the point electrode, the optimal position is just clinging to the point electrode. Both two calculated values are confirmed to be effective for clean and polluted barrier.

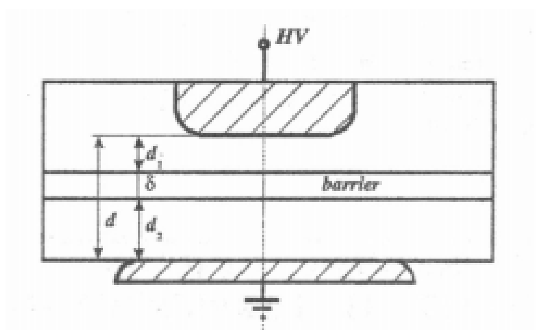


Figure 1.11 Electrode configuration in Reference [18]

In literature [18], the authors investigated the impact of barrier on solid insulation flashover characteristics in a homogeneous or nearly homogeneous electric field. In the experiment, the experiment samples are parallel-plane single- and three-layer disks. The single- layer barrier is made of LDPE (Low-density polyethylene), which has a high permittivity. For three-layer barrier, a LDPE piece is placed between two insulating materials. The ratio of the permittivity of the three-layer barrier material and the insulation material is denoted as Ψ. Ψ can vary from 1 to 6 with different barrier material. The electrodes are rounded-edge electrodes with radii of 12.5 and 22.5 mm respectively. The smaller electrode is used as the high voltage electrode while the other electrode is connected to ground. The gap distance from the high voltage electrode to ground electrode is defined as d and the distance from the boundary of the barrier to the high voltage electrode is defined as d_1. Then the position of the barrier can be defined as $\xi = d_1/d$. The test is conducted under 50 Hz AC voltage using the step-by-step method. The voltage step is 2.5 kV and the step duration is 1 min. Measurements are performed for without and with the insulation barrier. The results indicate that for different Ψ value, the breakdown voltage always reaches maximum at $\xi = 0.25\pm0.1$. With higher barrier permittivity, the breakdown voltage can also reach higher and tends to saturate. Typically, when partial discharge is less than 10 pC the insulation material will not be damaged. For all test groups, the discharge is less than 10 pC when the applied voltage is less than 7.5 kV. However, the discharge pattern starts to change significantly when the voltage is higher. The critical partial discharge, which is the discharge that can destruct the barrier dielectrics, varies from 10 to 100 pC. These partial discharges will form incomplete discharge channels inside the barrier dielectric. The change of discharge mechanism may be due to the increased corona activities at the electrode edge induced by higher voltage. For samples with different Ψ, the ignition voltage of PD will be higher if Ψ is higher. For different ξ value, the PD inception voltage is highest at the optimal position. Additionally, the possibility of the barrier can be destructed is lowest at the optimal position. A possible explanation to this phenomenon is that the electric field distortion induced by the barrier causes the electric field to be non-uniform. The electric field will concentrate in the area near the barrier. Barrier at the optimal position can reduce the non-uniformity of the electric field, thus reduce the partial discharge activities.

1.3 Summary

Solid insulation is commonly used in power apparatus such as insulator, transformer and switchgear. Many researchers have conducted researches concerning on the creepage characteristics of solid insulation. Since some insulation device is working in the oil, reference [1]-[4] investigated the creepage discharge of solid insulation material on the liquid/solid, or oil/solid interface. In [1], both AC and DC creepage breakdown are studied using point-plane electrode arrangement. With the DC source voltage, the breakdown characteristics are relevant to the polarity. More discharge branches and luminous are observed in negative polarity. With AC source voltage, then in each AC cycle, both positive and negative DC breakdown will appear. When the pressure of the oil increases, the branches and emitted light will decrease. Reference [2] dealt with the oil-paper interface. The experimental results in [2] indicate that the breakdown not only can occur in the interface, it can also occur at the oil near the interface. When the paper surface is not clean or has gaseous voids, breakdown is more likely to happen in the interface. The authors also point out that it should be feasible to develop a two-component system by possibility distribution function factor to calculate the breakdown voltage. The authors of [3] discussed the breakdown process when the applied voltage stress is parallel with the flat side of the solid insulation. Breakdown in such insulation system is relevant to the solid insulation material's dielectric constant and physical surface structure. With smooth surface of the solid insulation, the possibility of breakdown will be lower. Reference [4] investigated the creepage discharge of the insulation barrier in power transformer with needle-plane electrode configuration. The relationship between breakdown voltage of oil gap E with gap distance d is $E = Ad^{-B}$. The authors also find out that if the insulation is dry and clean, breakdown voltage is dependent on the oil quality. With wet insulation board, the flashover voltage is not influenced by the moisture while the moisture greatly reduces the partial discharge voltage.

Typically the high voltage insulation equipment are very easy contaminated by different pollutant. Reference [5]-[7] discussed the influence of the climate, pollution and humidity on the creepage characteristics. The results in [5] have shown that the impulse withstand voltage is not much influenced by the climate, although the climate can lower the breakdown voltage a little bit. The pollution has no much influence on the breakdown either except the humidity is very high. The authors thus concluded that it may be permissible to reduce the creepage clearance distance. Reference [6] discussed the breakdown properties of the printed wiring board with back electrode. Results show that in normal condition or under low pollution, the breakdown voltage is reduced by the back electrode, which means the back electrode dominates the breakdown. However, in the environment with high humidity and high pollution, the breakdown voltage is dominant by the environment. Similar results are obtained in [7]. With uniform electric field, with increasing volume of the water the partial discharge inception voltage decreases. The partial discharge impulse can react with the water droplets.

Solid insulation with back electrode is a common type of insulation which has been adopted in many high voltage insulation equipment. Reference [9]-[13] discussed the influence of back electrode on the creepage discharge characteristics of several solid insulation. In literature [9], the authors studied the breakdown at the interface between silicon rubber and epoxy. The electric field is parallel with the interface. Without back electrode, the field is almost uniform and the measured partial discharge inception field is 10 kV/mm. With the back electrode, the electric field will turn to perpendicular to the interface at some places. The breakdown voltage is lower than without back electrode. The breakdown characteristics are highly dependent on how thick the air layer is at the interface. With increasing of the layer thickness, the AC breakdown voltage decreases. Reference [10] and [11] discussed the breakdown properties of solid insulation under impulse voltage in transformer oil. In the test, it is found that if the back electrode can cover the whole gap length from the high voltage electrode to the ground electrode, there is big difference between with and without discharge happening at the high voltage electrode. When the gap distance is short, all the discharges will lead to breakdown. But if the gap distance is longer, discharge can occur before the breakdown happens. If the back electrode cannot cover the whole gap distance, then almost all the electric field will concentrate in the region from the high voltage electrode to the tip of the back electrode. The breakdown voltage also depends on the length of this region. If the high voltage electrode is covered by paper, then the breakdown voltage will be higher and there will be no partial discharge. Literature [12] investigated the creepage breakdown on the solid-oil interface with back electrode. With pulse applied voltage the positive streamers exhibit a tree-like shape while negative streamers exhibit fuzzy aspects like a bush. The distance from the side electrode to board surface has impact on electric field distribution on the partial discharge streamer. The potential at solid-liquid interface increases with increasing of the distance from the side electrode to board surface and it is also relevant to the permittivity of the solid dielectric. On the contrary, the positive charges will prevent such energy injection. when positive streamer is travelling along the surface of the insulation, the electric field in the streamer will be raised by the negative surface charge, which results in the more energy is injected to the streamer and the propagation distance of the streamer will be longer. The impact of back electrode on DC breakdown characteristics is investigated in [13]. In the experiment, for the rod-plate arrangement, the influence of grounded back electrode is obvious when the gap distance is large. The field distribution is more inhomogeneous and corona onset voltage is lower with back electrode. With higher corona current, the corresponding breakdown voltage will also be higher.

Reference [14]-[18] discussed the influence of insulation barrier. All of the literatures have found that the optimal position is that the distance between the barrier and the high voltage electrode is about 20% to 30% of the gap distance. At that position the breakdown voltage will be highest, typically 60% to 80% higher than without barrier. Literature [14] and [16] have stated that at some extreme cases, for example the permittivity of the barrier is very low or the distance from the barrier to the ground electrode is very small, the breakdown voltage with barrier even can be lower than without barrier. The dimensions of the barrier can also affect the breakdown voltage. With larger barrier, the breakdown voltage will be higher. The breakdown voltage and the corona inception voltage are dependent on the electric field distribution. With more uniform field distribution these voltages will be higher. Literature [17] investigated the influence of insulation barrier on impulse breakdown. The authors found two reasons to explain why the breakdown voltage is higher with barrier. First is that the barrier elongates the creepage length. The second is the charges deposited on the barrier form an electromagnetic obstacle. When the barrier surface is contaminated, the effect of the barrier can vary from a clean barrier to a metal barrier, depending on the conductivity of the barrier. While the electric field is non-uniform at the space, the electric field inside the barrier is uniform. The calculated best location of the barrier is relevant to geometry of the electrodes. In literature [18], the influence of the barrier in uniform field is discussed. With higher barrier permittivity, the breakdown voltage can also reach higher and tends to saturate. The change of discharge mechanism may be due to the increased corona activities at the electrode edge induced by higher voltage. The electric field distortion induced by the barrier causes the electric field to be non-uniform. The electric field will concentrate in the area near the barrier. Barrier at the optimal position can reduce the non-uniformity of the electric field, thus reduce the partial discharge activities.

1.4 Objectives of this research project

Although solid insulation with back electrode is often used in power equipment, the influence of the back electrode on the creepage discharge characteristics is not fully discussed. The influence of the back electrode has been investigated in some papers. However, the mechanism is still unknown. Moreover, while a lot of high voltage equipment operate under AC, the previous researches seem to be more concerned on the creepage discharge under DC than AC. In addition, the electrode configurations adopted in most of these studies (such as needle-plane, rod-plane) differ from the electrode configurations used in actual electrical devices [10]. Therefore, it is of practical significance to study the influence of back electrode on solid insulation under AC voltage stress.

The main objective of this research project is to find out the impact of the back electrode on the AC creepage discharge characteristics. The breakdown voltage is obtained through the experiments first. Then we use the Coulomb software to calculate the electric field distribution. Previous researchers have proposed that the back electrode can lower the breakdown voltage and electric field distribution is distorted by the back electrode. However, none of the papers have established a relationship between the electric field and the breakdown characteristics. So we compare the electric field distribution between with and without back electrode to find the explanation to solve all these phenomena. Additionally, we will also study the influence of the insulation barrier. The results will be compared with normal system to see how the barrier affects the breakdown characteristics.

1.5 Organization of thesis

The thesis is organized in six chapters. Chapter 1 presents the details of researches and achievements made by other researchers. At the end of this chapter, the objects of this project are also summarized.

Chapter 2 introduces the setup and the procedures of the experiments.

Chapter 3 lists the results of every experiment in detail. This chapter also summarized the average breakdown voltage for different experiment case.

Chapter 4 presents the analysis for the experiment without barrier. The electric field distribution at breakdown is calculated using Coulomb. Through analyzing the electric field, the internal relationship between breakdown voltage and electric field distribution is established in the analysis.

Chapter 5 analyzed the influence of barrier on the breakdown characteristics. This chapter focuses on how discharge pattern changes with different position and different height of the barrier.

Chapter 6 concludes all the progress made in this research program. Some suggestions for future work are also proposed in this chapter.

Chapter 2. EXPERIMENTAL SETUP AND PROCEDURES

The main target of this research project is investigating the influence of grounded back electrode on the breakdown properties on solid insulation system. To fully understand the behavior of breakdown with back electrode, the experiment is divided into two phases: The first is the experiment without barrier while the second is the experiment with barrier. The details of experimental setup and procedures for both two tests are listed in this chapter.

2.1 Experimental setup

2.1.1 Without barrier

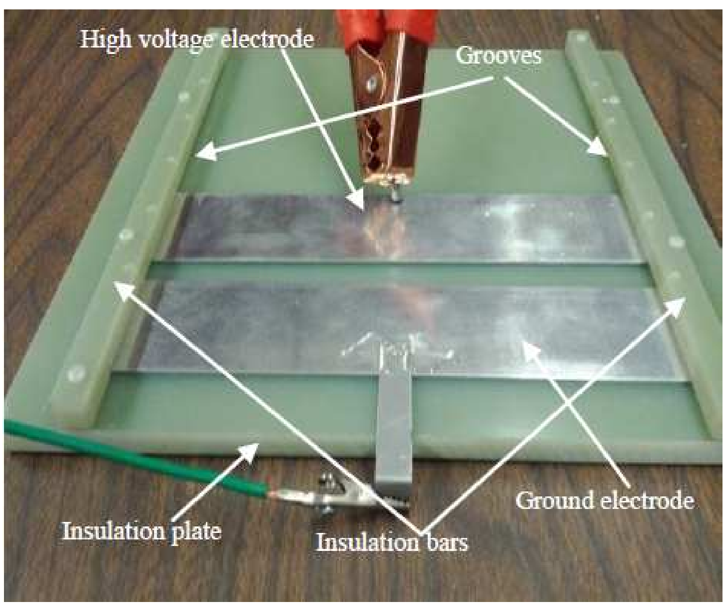


Figure 2.1 The experiment setup for the test without barrier

The test setup is shown in Figure 2.1. The material for the insulation board is epoxy resin. Both of the length and width of the epoxy board are 12 inches (30.48 cm). The thickness of the board is 0.50 inch (1.27 cm). On upper surface there are two aluminum electrodes and two epoxy bars. The bars are placed in symmetrical. The length of the bars is the same as the board while the width and thickness of the bars are both 0.50 inch (1.27 cm). The distance between two bars is 9 inches (22.86 cm). At the bottom of either bar, there is one groove on the inner surface. The depth of the groove is about a quarter of an inch (0.64 cm) and the width of the groove is the same with the height of the electrode. The electrodes can change their positions easily through siding in the grooves. Some researchers have pointed out that if there is a gap between the groove and electrode, the experimental results would be influenced. Therefore, when an electrode is inside the groove, we make sure that the surface of the electrode is close to the groove so the experiment results are not influenced by the groove.

In the experiment, there are three aluminum electrodes in total. On the upper surface, there are two electrodes. One is the high voltage electrode, which is connected to the high voltage source. The other is the ground electrode, which is connected to the ground. The dimensions for both high voltage electrode and ground electrode are exactly the same. The dimensions are 9.50*2.00*0.06 $inch^3$ (24.13*5.08*0.15 cm^3). The ground electrode is fixed while the high voltage electrode can move through siding in the grooves. Since there are no gaps between the electrode and the grooves, the two electrodes can be kept parallel with the high voltage electrode by moving in the groove. The radius of the electrode edges is controlled between 20 to 50 micrometers. With a so small radius, the impact of the edges on the experiment can be avoided.

The third electrode used in the experiment is the back electrode. The figure of back electrode is shown in Figure 2.2. The dimensions of the back electrode are 8.50*7.00*0.03 inch^3 (21.59*17.78*0.08 cm^3). When we do the experiment with back electrode, the back electrode will attached at the center at back side of the epoxy plate so that it can cover the whole area between the high voltage electrode and ground electrode.

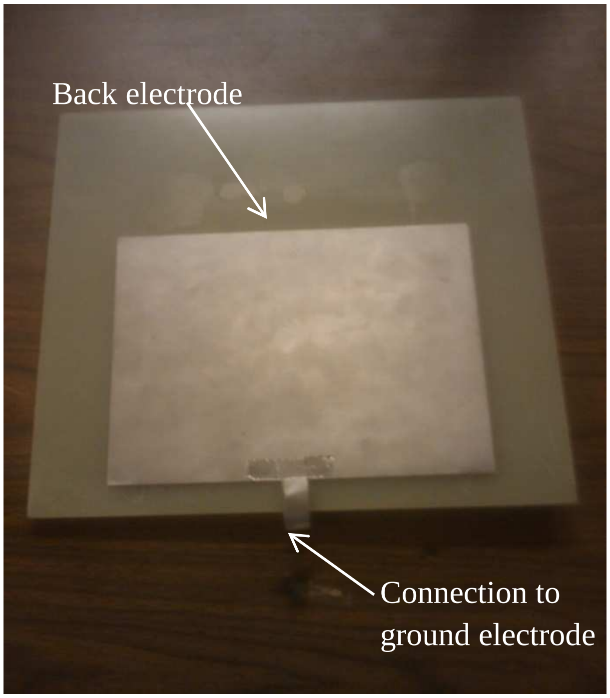


Figure 2.2 The picture of back electrode for experiment without barrier

The connection between the epoxy boar and the high voltage generating capacitor is shown in Figure 2.3. The maximum AC voltage limit of the lab is 100 kV. The primary side of the CT is connected to the high voltage generating capacitor. Then the applied voltage can be read from the voltage meter connected to the secondary side of the transformer.

Figure 2.3 The connection diagram of the experiment setup

2.1.2 With barrier

The setup for the test with barrier is shown in Figure 2.4. To avoid breakdown high voltage electrode to the back electrode, the dimensions of the electrodes and the epoxy board are changed. The thickness of the epoxy board is still 0.5 inch (1.27 cm) while the length and width are much larger. The length is 21 inches (53.34 cm) and the width is 24 inches (60.96 cm). On the epoxy board there are no epoxy bars, instead, there is a barrier across the whole board, which is also made of epoxy. The barrier is fixed on the board with epoxy glue. The distance from the bar edge to board edge is about 8 inches (20.32 cm). The length of the barrier is 24 inches (60.96 cm) and the width is 0.50 inch (1.27 cm). To investigate the effect of the barrier height, two different barriers are used: One with height of 1 inch (2.54 cm) while the other with height of 2 inches (5.08 cm).

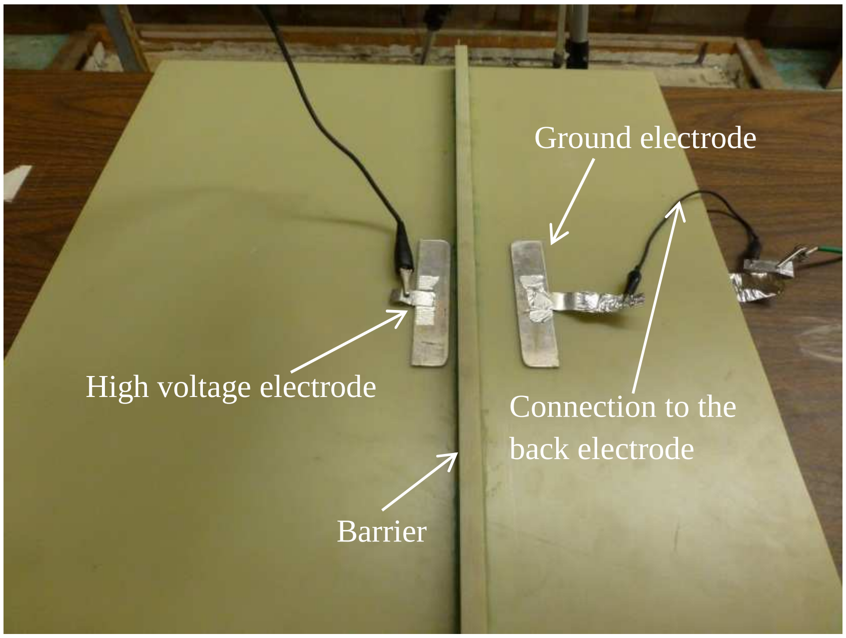


Figure 2.4 The experiment setup for the test with barrier of 1 inch (2.54 cm) high

The high voltage electrode and ground electrode are still made of aluminum with dimensions of 4.75*1.00*0.06 inch^3 (12.07*2.54*0.15 cm^3). They are placed on different sides of the barrier. To eliminate the tip effect of the electrode corners, the corners which face the barrier are polished into a smooth circular arc. The radii of the arcs are between 4 to 5 mm. Both high voltage electrode and ground electrode are movable. The electrodes are fixed on the surface of the epoxy board using thin double sided tapes.

The size of the back electrode is the same. The dimensions are 8.50*7.00*0.03 inch^3 (21.59*17.78*0.08 cm^3). The back electrode is fixed using double sided tape and the position of the back electrode can be adjusted to cover the whole gap between the high voltage electrode and ground electrode in every experiment. The picture of back electrode is shown in Figure 2.5.

Figure 2.5 The picture of back electrode for experiment with barrier

2.2 Experimental Procedures

In the experiment without barrier, since the ground electrode is not movable, the gap distance between the high voltage electrode and ground electrode, which is referred to as *L*, is determined by the position of the high voltage electrode. Every time when we want to do the experiment with different *L*, we will move the high voltage electrode slowly to the desired position so the surface of the board will not be damaged. After sliding the high voltage electrode, the gap distance *L* will be measured at several different points to make sure the distance is correct and both electrodes are parallel with each other.

In the experiment with barrier, besides the gap distance *L*, the distance between the high voltage electrode and the barrier, which is referred to as *a*, is also a variable which needs to be controlled. So in the experiment with barrier, besides measuring gap distance *L*, *a* is also measured at several points to ensure that the relative distance between the electrodes and the barrier is correct and they are in parallel with the barrier. Additionally, since there are no bars on the board, the movement of both electrodes is not restricted. Then the distances from the side edges of the board to both electrodes also have to be measured before experiments. The distances from the side edge of the board to both the high voltage electrode and ground electrode must be exactly the same to make sure that both electrodes are directly facing each other.

For both tests with and without barrier, the experiments are conducted both with and without back electrode. The experiment procedures strictly follow the instructions in the IEEE standard [19]. During experiment, rise rate of the applied voltage is controlled to be continuous and less than 2% of the estimated breakdown voltage. For every test case, we will repeat the experiments for at least 8-10 times. All the experiments will be recorded by camera. In the experiments, we must avoid the impact of other factors, such as the edge effect of the electrodes and the effect of the insulation bars. Therefore, to ensure the validity of the test data, the captured videos for all the experiments will be reviewed. If the breakdown occurs near the corners of the electrodes or it is too close to the insulation bars, the result corresponding to that experiment will be thrown out. For each test case, there are at least 8-10 valid data. Then the breakdown voltage of that test case would be the average of all the valid data.

To avoid the impact of residential charge on the electrodes, the high voltage will be grounded before each experiment starts. The time interval between two experiments is more than one minute so the insulation strength of air can recover during that period.

Chapter 3. EXPERIMENTAL RESULTS

In the experiments, the average breakdown voltages for different experimental cases are obtained. The detailed results for both with and without barrier are listed in the following content.

3.1 Without barrier

To investigate the influence of the back electrode, the experiments are conducted for both with back electrode and without back electrode. For the experiment with back electrode, the chosen gap distance *L* values are 1 cm, 2 cm, 3cm, 4 cm, 5cm, 10 cm and 15 cm. To make a direct comparison between these two test cases, the test results are listed in the seven tables below:

Table 3.1 Breakdown voltage for gap distance of 1 cm without barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	10.5	9.2
2	10.4	9.1
3	10.0	9.1
4	10.0	9.0
5	10.1	9.1
6	10.3	9.1
7	10.1	9.2
8	10.2	9.1
Average	10.2	9.1
Standard deviation	0.2	0.1

Table 3.2 Breakdown voltage for gap distance of 2 cm without barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	15.5	N/A
2	15.9	
3	15.8	
4	15.5	
5	16.0	
6	15.3	
7	15.7	
8	15.9	
9	15.7	
Average	15.7	
Standard deviation	0.2	

Table 3.3 Breakdown voltage for gap distance of 3 cm without barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	18.9	18.5
2	18.8	18.9
3	17.8	18.9
4	17.9	19.0
5	18.6	19.1
6	18.4	19.1
7	18.1	18.9
8	18.5	18.9
9	18.9	18.6
10	18.1	19.2
Average	18.4	18.9
Standard deviation	0.4	0.2

Table 3.4 Breakdown voltage for gap distance of 4 cm without barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	22.2	N/A
2	22.5	
3	22.4	
4	22.7	
5	23.0	
6	23.1	
7	23.2	
8	22.6	
9	23.3	
Average	22.8	
Standard deviation	0.4	

Table 3.5 Breakdown voltage for gap distance of 5 cm without barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	26.9	26.9
2	27.0	27.4
3	26.5	27.0
4	26.3	27.2
5	26.0	27.4
6	27.0	27.3
7	27.2	27.2
8	26.5	26.9
9	26.3	27.5
10	26.2	27.0
Average	26.6	27.2
Standard deviation	0.4	0.2

Table 3.6 Breakdown voltage for gap distance of 10 cm without barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	35.4	46.8
2	35.9	47.8
3	34.9	47.8
4	35.1	46.0
5	36.3	45.8
6	35.6	47.5
7	34.8	45.1
8	34.5	45.8
9	36.0	46.8
10	34.6	47.9
Average	35.3	46.7
Standard deviation	0.6	1.0

Table 3.7 Breakdown voltage for gap distance of 15 cm without barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	40.8	58.2
2	40.8	58.6
3	40.7	58.7
4	43.7	59.0
5	43.3	57.7
6	40.8	58.1
7	42.1	58.5
8	41.9	58.1
9	43.6	58.6
10	41.2	58.8
Average	41.9	58.4
Standard deviation	1.2	0.4

Table 3.8   Average breakdown voltage and standard deviations for different *L* values without barrier

Gap distance (cm)	**With back electrode**		**Without back electrode**		
	Breakdown voltage (kV)	**Standard deviation (kV)**	**Breakdown voltage (kV)**	**Standard deviation (kV)**	**Predicted breakdown Voltage (kV)**
1	10.2	0.2	9.1	0.1	8.6
2	15.7	0.2	-	-	-
3	18.4	0.4	18.9	0.2	19.3
4	22.8	0.4	-	-	-
5	26.6	0.4	27.2	0.2	28.1
10	35.3	0.6	46.7	1.0	47.7
15	41.9	1.2	58.4	0.4	64.5

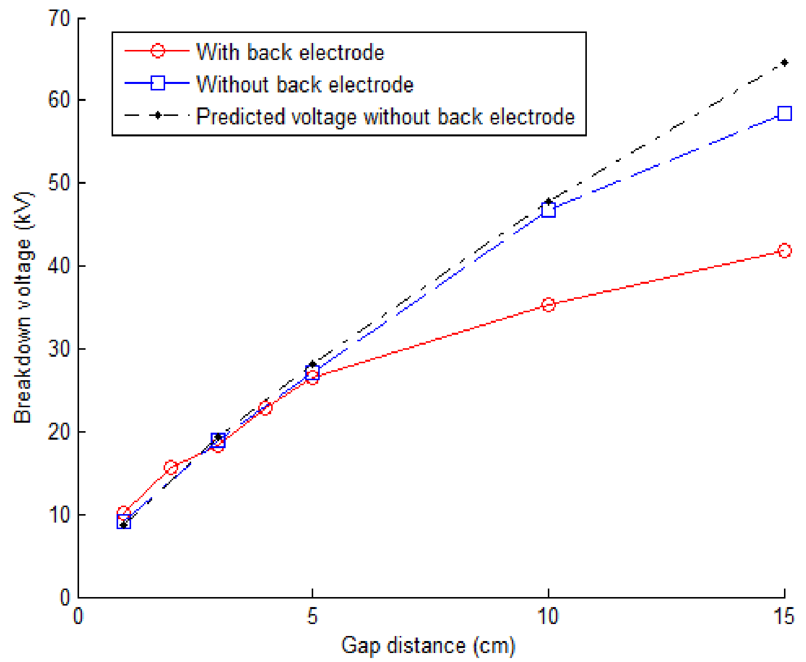


Figure 3.1 The relationship between breakdown voltage and gap distance without barrier

The breakdown voltages obtained through the experiments are shown in the tables above. Using these data we calculated the average breakdown voltage and the standard deviations. The results are shown in Table 3.8. In Table 3.8, for the case without back electrode, the predicted breakdown voltage is also calculated using Coulomb.

The curve of breakdown voltage versus gap distance L is shown in Figure 3.1. The red solid line represents the breakdown voltage of experiments with back electrode while the blue dashed line represents the results of experiments without back electrode. The black dash-dot line is the predicted breakdown voltage for the case without back electrode. Without back electrode, the curve-fitting function for the blue curve is $V_B = 9.09 \times L^{0.693}$ while for the black curve the function is $V_B = 8.47 \times L^{0.750}$. With back electrode, the curve-fitting function for the blue curve is $V_B = 11.27 \times L^{0.492}$. In all these functions V_B is in kV and L is in cm. From Figure 3.1, without back electrode, the difference between the measured breakdown voltage and predicted breakdown voltage is less than 10 %. Therefore, it is valid to use Coulomb in further analysis.

From Figure 3.1 it is very clear that the back electrode has impact on the breakdown voltage. Generally, with gap distance increases, the breakdown voltage of both with and without back electrode also increases. When the gap distance L is less than 5 cm, both two curves almost overlap. So in that case, the back electrode almost has no influence on the breakdown voltage. However, when L gets larger, the two curves start to diverge. The breakdown voltage of with back electrode becomes less than without back electrode. This phenomenon indicates that when back electrode is attached, there exists a critical gap distance, which is referred to as L_C. When L is less than L_C, the influence of back electrode on breakdown voltage can be ignored. The breakdown voltage is nearly the same as without back electrode. When L is larger than L_C, the influence of back electrode turns noticeable. The back electrode will lower the breakdown voltage. With increasing L, the difference between the breakdown voltage of with back electrode and without back electrode becomes more significant.

3.2 With barrier

From the experiments without barrier, with back electrode, when the gap distance L exceeds the critical gap distance L_C, the breakdown voltage would be lower than without back electrode. From Literature [16], [17] and [18], the researchers have pointed out that a barrier inserted into the gap would increase the breakdown voltage. Therefore, we will further investigate the influence of barrier, especially in the condition that with back electrode.

For the barrier test, three gap distances are chosen, which are 5cm, 10 cm and 15 cm. Since the position of the barrier would also affect the breakdown voltage [17][18], in the experiments, three different positions are selected. The position is defined by the ratio a/L, in which a denotes the distance from the high voltage electrode to the barrier, while L represents the total gap distance. The selected a/L ratios are 0.1, 0.2 and 0.5 respectively. The barrier height, which is referred to as *H*, also has two different values. The *H* values are 1 inch (2.54 cm) and 2 inches (5.07 cm). The detail experimental results with barrier are listed in the tables from Table 3.9 to Table 3.26.

Table 3.9 Breakdown voltage for *L* = 5 cm, *a* = 0.1, *H* = 1 inch (2.54 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	40.6	44.5
2	40.9	44.8
3	40.0	45.6
4	41.2	45.4
5	40.0	45.5
6	40.4	44.7
7	41.1	45.0
8	40.9	45.3
9	40.1	45.7
10	40.6	44.9
Average	40.6	45.1
Standard deviations	0.4	0.4

Table 3.10 Breakdown voltage for *L* = 5 cm, *a* = 0.1, *H* = 2 inches (5.08 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	53.5	56.0
2	54.7	56.4
3	53.6	56.9
4	53.7	58.1
5	53.2	55.4
6	54.8	58.1
7	53.6	56.8
8	53.2	55.9
9	53.8	58.6
10	52.9	58.3
Average	53.7	57.0
Standard deviation	0.6	1.1

Table 3.11 Breakdown voltage for *L* = 5 cm, *a* = 0.2, *H* = 1 inch (2.54 cm) with barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	42.1	44.8
2	41.9	44.6
3	41.2	44.6
4	41.8	45.3
5	41.4	46.7
6	42.1	45.4
7	41.5	46.1
8	40.9	45.2
9	41.7	46.6
10	42.2	45.9
Average	41.7	45.5
Standard deviation	0.4	0.7

Table 3.12 Breakdown voltage for *L* = 5 cm, *a* = 0.2, *H* = 2 inches (5.08 cm) with barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	56.2	59.0
2	58.4	57.9
3	55.3	57.2
4	58.4	56.9
5	55.9	57.7
6	54.7	56.8
7	54.3	58.3
8	54.5	56.6
9	55.4	57.2
10	55.0	56.7
Average	55.8	57.4
Standard deviation	1.5	0.8

Table 3.13 Breakdown voltage for L = 5 cm, a = 0.5, H = 1 inch (2.54 cm) with barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	42.2	44.2
2	41.1	44.5
3	41.9	45.4
4	42.1	44.9
5	41.6	44.1
6	43.1	44.4
7	42.7	45.2
8	41.8	44.8
9	42.4	45.2
10	41.8	44.9
Average	42.1	44.8
Standard deviation	0.6	0.4

Table 3.14 Breakdown voltage for L = 5 cm, a = 0.5, H = 2 inches (5.08 cm) with barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	55.9	55.9
2	55.4	56.2
3	56.3	58.6
4	55.5	57.1
5	55.3	55.3
6	55.8	55.6
7	55.0	56.3
8	55.4	55.3
9	56.9	57.1
10	55.4	56.6
Average	55.7	56.4
Standard deviation	0.6	1.0

Table 3.15 Breakdown voltage for *L* = 10 cm, *a* = 0.1, *H* = 1 inch (2.54 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	53.2	61.0
2	52.8	59.5
3	55.8	60.7
4	54.8	60.5
5	52.6	59.9
6	55.3	60.8
7	53.3	60.5
8	54.2	60.1
9	54.7	60.9
10	53.9	60.5
Average	54.1	60.4
Standard deviation	1.1	0.5

Table 3.16 Breakdown voltage for *L* = 10 cm, *a* = 0.1, *H* = 2 inches (5.08 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	63.4	65.6
2	62.7	66.3
3	62.3	65.9
4	62.9	66.6
5	63.8	64.7
6	63.5	66.1
7	62.3	66.4
8	62.6	66.7
9	63.1	66.4
10	65.3	65.4
Average	63.2	66.0
Standard deviation	0.9	0.6

Table 3.17 Breakdown voltage for L = 10 cm, a = 0.2, H = 1 inch (2.54 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	54.6	60.4
2	55.1	59.2
3	55.0	59.3
4	55.0	60.1
5	55.1	59.1
6	55.1	58.1
7	55.0	58.5
8	54.9	59.6
9	55.7	59.2
10	55.1	59.1
Average	55.1	59.3
Standard deviation	0.3	0.7

Table 3.18 Breakdown voltage for L = 10 cm, a = 0.2, H = 2 inches (5.08 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	64.0	65.6
2	64.3	66.4
3	64.6	64.9
4	65.6	63.9
5	65.1	64.0
6	65.3	65.9
7	64.3	66.2
8	64.5	66.1
9	63.9	67.5
10	63.9	67.3
Average	64.5	65.8
Standard deviation	0.6	1.2

Table 3.19 Breakdown voltage for L = 10 cm, a = 0.5, H = 1 inch (2.54 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	50.7	58.2
2	48.8	58.1
3	52.0	57.6
4	50.0	57.8
5	51.5	57.7
6	52.3	57.7
7	49.6	57.0
8	49.9	57.1
9	49.4	57.1
10	51.7	57.7
Average	50.6	57.5
Standard deviation	1.2	0.5

Table 3.20 Breakdown voltage for L = 10 cm, a = 0.5, H = 2 inches (5.08 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	59.1	64.9
2	59.0	64.3
3	59.2	68.1
4	58.4	64.4
5	59.0	65.8
6	57.8	65.2
7	58.4	65.5
8	58.4	65.5
9	58.8	65.3
10	59.1	66.2
Average	58.7	65.5
Standard deviation	0.4	1.1

Table 3.21 Breakdown voltage for *L* = 15 cm, *a* = 0.1, *H* = 1 inch (2.54 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	55.7	70.3
2	55.4	70.1
3	53.5	70.9
4	53.6	71.3
5	53.8	72.5
6	55.1	70.6
7	56.4	69.5
8	55.9	70.6
9	53.6	71.7
10	56.0	70.0
Average	54.9	70.8
Standard deviation	1.2	0.9

Table 3.22 Breakdown voltage for *L* = 15 cm, *a* = 0.1, *H* = 2 inches (5.08 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	66.5	74.3
2	67.4	74.1
3	65.6	76.8
4	66.2	75.2
5	67.5	74.2
6	65.8	76.6
7	65.9	76.1
8	67.3	76.4
9	68.3	73.6
10	67.1	75.1
Average	66.8	75.2
Standard deviation	0.9	1.2

Table 3.23 Breakdown voltage for L = 15 cm, a = 0.2, H = 1 inch (2.54 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	54.5	69.2
2	54.9	70.1
3	55.3	71.0
4	55.9	70.5
5	54.1	71.6
6	55.8	71.5
7	54.4	71.3
8	54.8	72.1
9	55.4	70.9
10	55.0	71.3
Average	55.0	71.0
Standard deviation	0.6	0.8

Table 3.24 Breakdown voltage for L = 15 cm, a = 0.2, H = 2 inches (5.08 cm) with barrier

Test #	**Breakdown Voltage with Back Electrode (kV)**	**Breakdown Voltage without Back Electrode (kV)**
1	67.9	75.0
2	66.7	73.5
3	67.8	73.2
4	67.3	72.4
5	68.7	74.7
6	67.0	74.2
7	68.9	75.4
8	67.3	72.4
9	66.2	72.8
10	67.8	73.4
Average	67.6	73.7
Standard deviation	0.8	1.1

Table 3.25 Breakdown voltage for *L* = 15 cm, *a* = 0.5, *H* = 1 inch (2.54 cm) with barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	59.5	69.4
2	58.9	70.5
3	61.7	68.7
4	61.5	68.6
5	60.2	70.4
6	61.6	70.3
7	61.0	70.1
8	60.1	70.3
9	61.6	69.4
10	59.9	69.2
Average	60.6	69.7
Standard deviation	1.0	0.7

Table 3.26 Breakdown voltage for *L* = 15 cm, *a* = 0.5, *H* = 2 inches (5.08 cm) with barrier

Test #	Breakdown Voltage with Back Electrode (kV)	Breakdown Voltage without Back Electrode (kV)
1	68.3	72.3
2	67.7	72.3
3	69.2	72.8
4	69.5	72.9
5	69.4	12.5
6	67.4	73.4
7	68.9	71.6
8	66.7	72.2
9	69.6	73.0
10	68.6	71.2
Average	68.5	72.4
Standard deviation	1.0	0.7

Table 3.27 Average breakdown voltage and standard deviations for L = 5 cm with barrier

Barrier Height	***a*/*L* ratio**	**With back electrode**		**Without back electrode**	
		Breakdown voltage (kV)	**Standard deviation (kV)**	**Breakdown voltage (kV)**	**Standard deviation (kV)**
No barrier	-	26.6	0.4	27.2	0.2
1 inch (2.54 cm)	0.1	40.6	0.4	45.1	0.4
	0.2	41.7	0.4	45.5	0.7
	0.5	42.1	0.6	44.8	0.4
2 inches (5.08 cm)	0.1	53.7	0.6	57.0	1.1
	0.2	55.8	1.5	57.4	0.8
	0.5	55.7	0.6	56.4	1.0

Table 3.28 Average breakdown voltage and standard deviations for L = 10 cm with and without barrier

Barrier Height	***a*/*L* ratio**	**With back electrode**		**Without back electrode**	
		Breakdown voltage (kV)	**Standard deviation (kV)**	**Breakdown voltage (kV)**	**Standard deviation (kV)**
No barrier	-	35.3	0.6	46.7	1.0
1 inch (2.54 cm)	0.1	54.1	1.1	60.4	0.5
	0.2	55.1	0.3	59.3	0.7
	0.5	50.6	1.2	57.5	0.5
2 inches (5.08 cm)	0.1	63.2	0.9	66.0	0.6
	0.2	64.5	0.6	65.8	1.2
	0.5	58.7	0.4	65.5	1.1

Table 3.29 Average breakdown voltage and standard deviations for L = 15 cm with and without barrier

Barrier Height	***a/L* ratio**	**With back electrode**		**Without back electrode**	
		Breakdown voltage (kV)	**Standard deviation (kV)**	**Breakdown voltage (kV)**	**Standard deviation (kV)**
No barrier	-	41.9	1.2	58.4	0.4
1 inch (2.54 cm)	0.1	54.9	1.2	70.8	0.9
	0.2	55.0	0.6	71.0	0.8
	0.5	60.6	1.0	69.7	0.7
2 inches (5.08 cm)	0.1	66.8	0.9	75.2	1.2
	0.2	67.6	0.8	73.7	1.1
	0.5	68.5	1.0	72.4	0.7

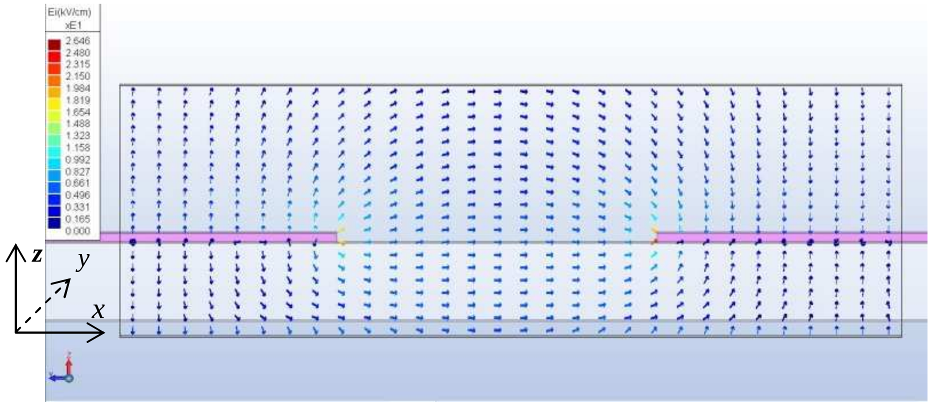
The summary of the experimental results with barrier is listed in Table 3.27, Table 3.28 and Table 3.29. In these three summary tables, the breakdown voltages of different test conditions for one gap distance are listed in one table. It is very obvious that with barrier, the breakdown voltage increases significantly. Generally, the breakdown voltage with a barrier of 2 inches is higher than barrier of 1 inch. However, the impact of barrier height on different gap distances L is not the same. When increasing the barrier height for a certain value, which in our experiment is 1 inch, the percentage of increase of breakdown voltage for smaller gap distance is larger than longer gap distance. With barrier, in every experiment case, the breakdown voltage with back electrode is still lower than without back electrode. However, the difference is smaller if there is barrier. Additionally, that difference will get even smaller when the height of the barrier increases from 1 inch to 2 inch. Therefore, we can conclude from the data that inserting a barrier into the gap can efficiently increase the breakdown voltage, especially when in the case with back electrode.

Another factor we should pay attention to is the position of the barrier. For the case without back electrode, the maximum breakdown voltage is at a = 0.1 or a = 0.2. The breakdown voltage at a = 0.5 is always the lower than the other two a values. This is consistent with the results in other papers [26],[27]. But in this case the impact of the barrier position is quite small. The differences of breakdown voltages at different gap distances without back electrode are usually less than 2-3 % of the total breakdown voltage. In the case with back electrode, the results are a little more complicated. At L = 5 cm and L = 15 cm, the breakdown voltage increases with increasing of a value. However, at L = 10 cm, the breakdown voltage decreases increasing of a value. Moreover, at L = 5 cm, the difference of breakdown voltages for different a values is small, just like the case without back electrode. However, at L = 10 cm and L = 15 cm, the difference of breakdown voltage between a = 0.5 and a = 0.1/0.2 can be as high as10%. Since the influence of barrier is so different between the experiment cases, it is not feasible to generalize a function or specific relationship between the gap distance and breakdown voltage. In addition, we have to investigate why the impact of barrier position is so big at large gap distance.

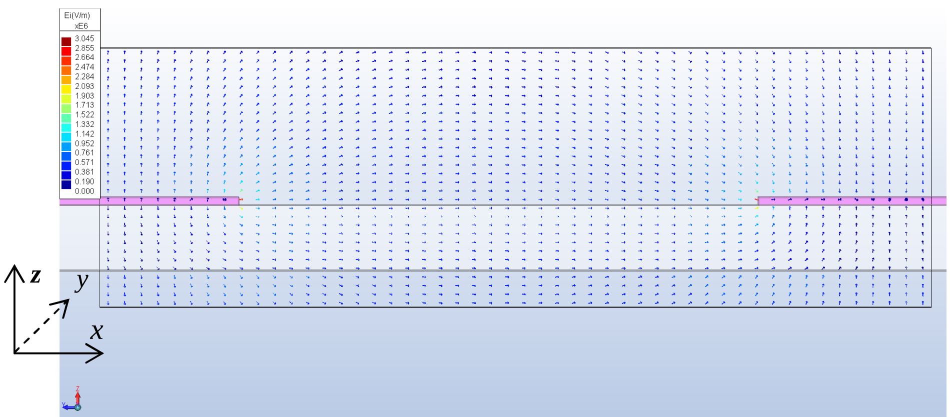
Chapter 4. ELECTRIC FIELD ANALYSIS AND DISCUSSION FOR EXPERIMENTS WITHOUT BARRIER

4.1 Influence of back electrode on electric field distribution

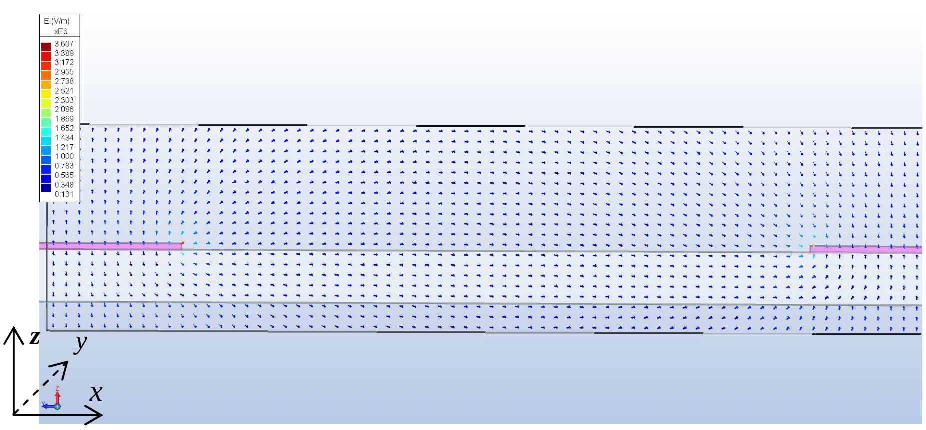
The electric field distribution is computed using commercial software named “Coulomb”. Based on the given model, the software uses Finite Element Method (FEM) to solve the equations and calculate the electric field. The 3-Dimensional model used in the simulation is built based upon real dimensions of the epoxy board and electrodes. The voltage of the high voltage electrode is the average breakdown voltage for that gap distance. From the results presented in [22], in the experiments with AC applied voltage, the residential charge is far less that experiments with DC. In their experiments, after applying high AC electric field on the cable for one hour, the quantity of residential charge is very small. In our experiment, typically we get breakdown after only one minute. Therefore, the impact of residential charge on experiments is very small. Additionally, from [21], due to the nature of AC voltage, the polarity and quantity of the residential charge is totally random. That means the residential charge can randomly increase or decrease the electric field. In brief, since the quantity of residential charge is very small and the impact of residential charge is random, we do not consider the influence of residential charge in the simulation. After solving the model, the cross-sectional electric field distributions along the central line at *y* axis of the board for different gap distances are shown in Figure 4.1 and Figure 4.2. The pink sections are electrodes while the white sections are denoted as epoxy board.



(a) *L* = 5cm

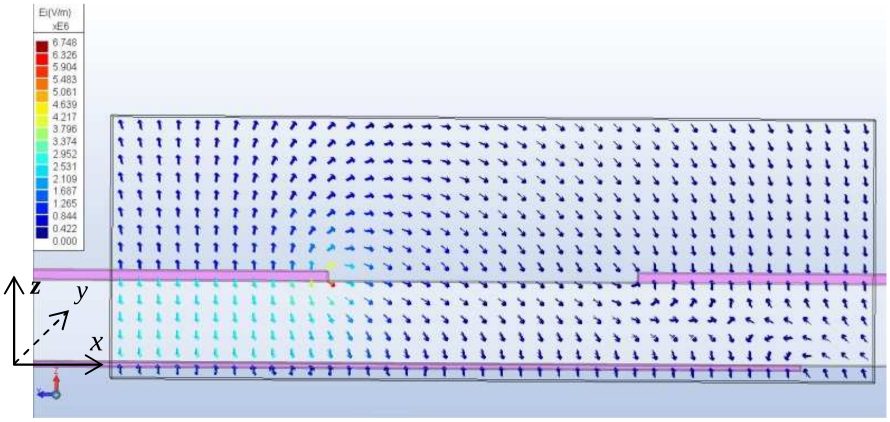


(b) *L* = 10 cm

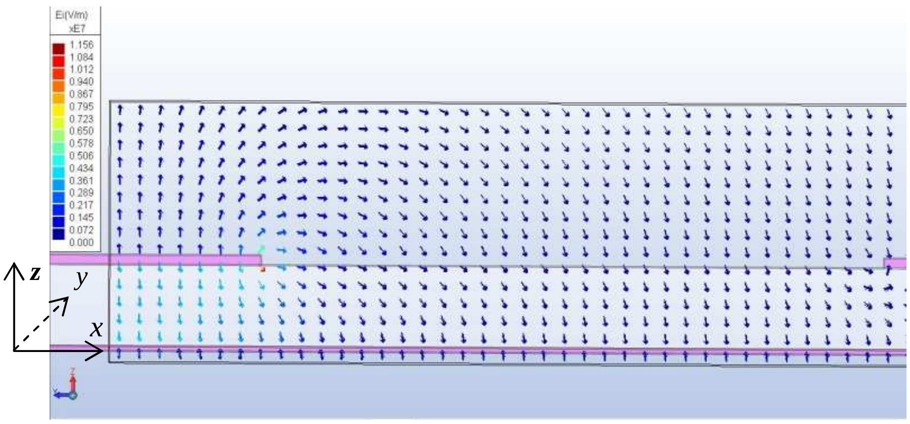


(c) *L* = 15 cm

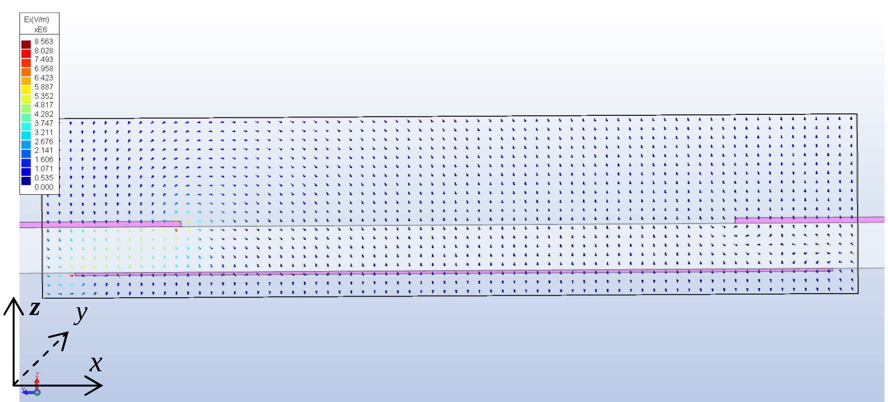
Figure 4.1 The cross-sectional view of the electric field distribution without back electrode for different gap distances



(a) L = 5cm



(b) L = 10 cm



(c) L = 15 cm

Figure 4.2 The cross-sectional view of the electric field distribution with back electrode for different gap distances

The figures in Figure 4.1 show the electric field distribution without back electrode while the figures in Figure 4.2 demonstrate the electric field distribution with back electrode. Since the breakdown always happens on the board surface, we concentrate our discussion on the electric field near the board surface. In Figure 4.1, without back electrode, the electric field around the gap surface is almost parallel with the surface. All the electric field lines start from the high voltage electrode and end up in the ground electrode. However, with back electrode, the situation is different. The electric field lines are no longer parallel with the surface. When *L* is small, along the whole gap the electric field lines are only in a small angle with the surface, just like the situation shown in Figure 4.2 (a). When *L* is larger, the angle between the electric field lines and the gap surface varies. In the region near the high voltage electrode, the angle is pretty small. With the distance to the high voltage electrode getting larger, the angle is also increasing. When the distance to the high voltage electrode is bigger than 4-5 cm, the electric field lines are almost vertical to the board surface, just like Figure 4.2 (b) and Figure 4.2 (c). The value of electric field strength in that area, which is less than 5 kV/cm, is also much less than in the area near the high voltage electrode. This phenomenon shows that the electric field distribution is distorted by the back electrode. With back electrode, some electric field lines will travel to the ground electrode while others will travel to the back electrode. This results in a “competition” between those two electrodes. When gap distance is small, the electric field near the surface is influenced by both electrodes. However, when the gap distance is longer, the influence of ground electrode becomes weak and thus the back electrode dominates the electric field distribution. In this case, almost all electric field lines near the gap surface will travel from the high voltage electrode directly to the back electrode.

4.2 Maximum electric field strength for with and without back electrode

The presence of back electrode not only changes the cross-sectional electric field distribution, but also changes the value of maximum electric field. The maximum electric field strength on the surface for different gap distances L, which is referred to as E_m, is listed in Table 4.1. The curve of maximum electric field strength versus gap distance L is shown in Figure 4.3. The red solid line represents the maximum electric field with back electrode while the blue dashed line represents the maximum electric field without back electrode.

Table 4.1 Maximum electric field strength for different gap distances without barrier

Gap distance *L* (cm)	**Maximum electric field strength E_m (kV/cm)**	
	With back electrode	**Without back electrode**
1	123	64.7
2	177	-
3	197	67
4	241	-
5	273	67
10	328	71.8
15	366	68.2

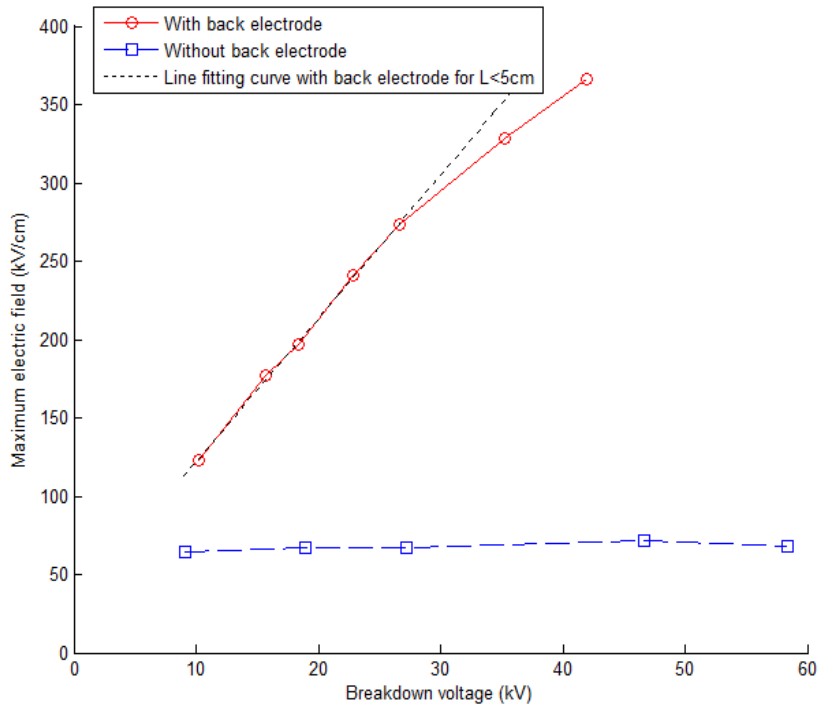


Figure 4.3 The relationship between maximum electric field strength and breakdown voltage without barrier

From Figure 4.3 we can see that without back electrode, E_m is a constant irrespective of the L. For every L value ranging from 1 cm to 15 cm, E_m stays the same about 70 kV/cm. However, the back electrode changes this characteristic. With back electrode, E_m is dependent on L. Generally, with larger L, E_m would also be bigger. But the dependence of E_m on breakdown voltage, which is referred to as V_B, is not uniform for all the V_B values. When the breakdown voltage is small, which is less than 26 kV in our experiment, the maximum electric field is almost linear with the breakdown voltage. We plot this linear function as a straight line in Figure 4.3 in a black dotted line. The function of this line is $E_m = 9.15 \times V_B + 30.62$, where E_m is in kV/cm and V_B is in kV. For the upper part of the red curve, the function is $E_{Sm} = 6.09 \times V_B + 111.58$. When V_B is above 26 kV, the real curve for E_m, which is shown in red solid line, starts to diverge from the black dotted line. The slope of the curve for $V_B > 26$ kV is less than the slope of the dotted line. This phenomenon shows that the impact of back electrode is different between $V_B > 26$ kV and $V_B < 26$ kV. Recall the experiment data in Table 3.8, $V_B = 26$ kV corresponds to the breakdown voltage of $L = 5$ cm. Additionally, the critical gap distance L_C discussed in Chapter 3 is also 5 cm. This illustrates that there may be some internal relationship between the electrical field and breakdown voltage. The breakdown mechanism changes at $L = L_C$, which is 5 cm in our experiment.

4.3 The internal relationship between the tangential electric field component and breakdown voltage

It is very likely that there is a mechanism difference at $L = L_C$ when there is back electrode. According to Townsend Discharge Theory [23],[24], the charged particles in the electric field will accelerate and travel all the way to the electrodes. During that process, the speed and kinetic energy will also increase. The kinetic energy which a charged particle can obtain is proportional to the electric field strength. If the charged particle has sufficient kinetic energy, then before it hits the electrodes, it can liberate free electrons from the molecule through colliding with these molecules. The freed electron can repeat this process to free more electrons. This will result in an electron avalanche and eventually breakdown. From Figure 4.4, it is very clear the breakdown occurs only at the surface. This means that in spite of the high total electric field strength, the tangential component of the total electric field, which is also the component that is parallel to the board surface from the high voltage electrode to the ground electrode, is the key that dominates the breakdown characteristics. Therefore, we will use the tangential component of the total electric field, which is denoted as E_S, in our discussion. The maximum value of E_S, which is referred to as E_{Sm}, with respect to gap distance L are listed in Table 4.2.

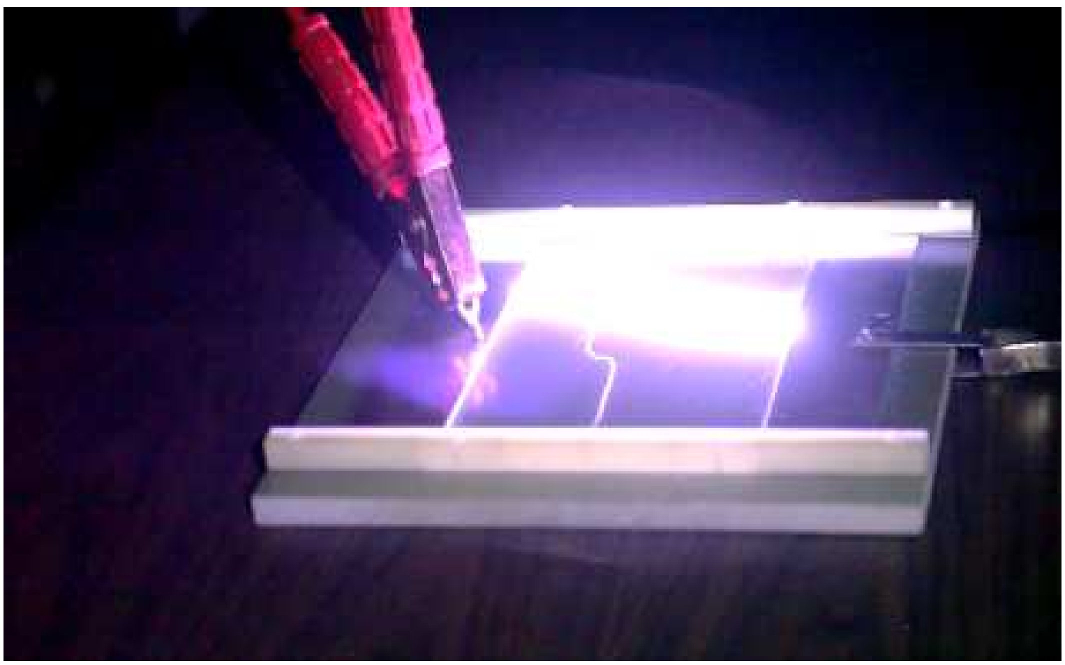


Figure 4.4 The snapshot of breakdown without barrier

Table 4.2 Maximum tangential electric field for different gap distances without barrier

Gap distance *L* (cm)	**Maximum tangential electric field strength E_{Sm} (kV/cm)**	
	With back electrode	**Without back electrode**
1	80.5	42.1
2	116	-
3	132	44.0
4	162	-
5	183	44.0
10	223	47.3
15	252	46.2

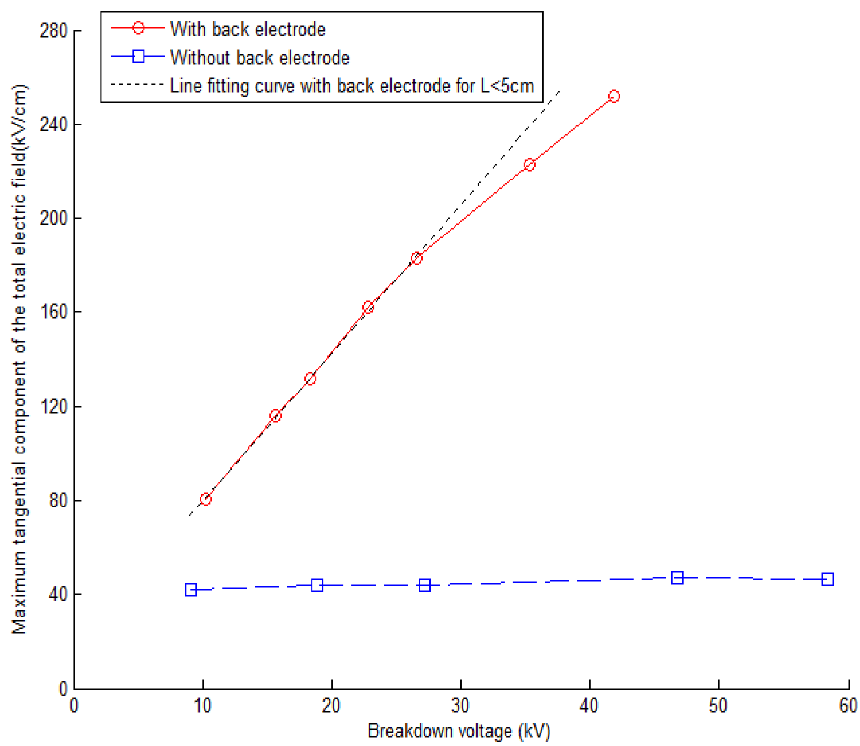
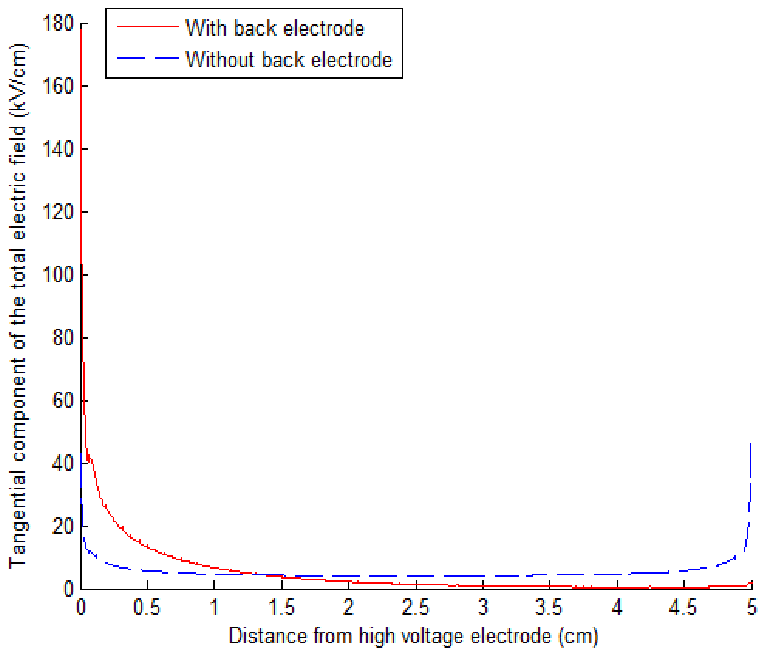
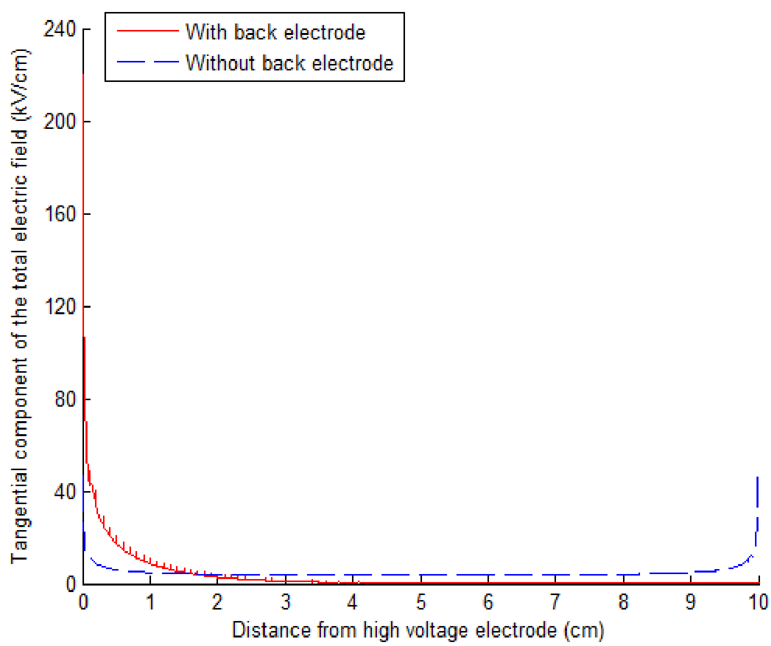


Figure 4.5 The relationship between maximum tangential electric field strength and breakdown voltage without barrier



(a) *L* = 5cm



(b) *L* = 10 cm

Figure 4.6 The distribution of the tangential component of the total electric field strength for different gap distances

The curve of maximum tangential electric field strength E_{Sm} versus gap distance L along the central line of the board is shown in Figure 4.5. The shape of the curves of E_{Sm} for both with and without back is almost the same with E_m in Figure 4.3 except the values are different. So the discussions and properties about E_m in Part 4.2 also apply to E_{Sm}. In Figure 4.5, the function of the black dotted line is $E_{Sm} = 6.30 \times V_B + 16.68$, where E_{Sm} is in kV/cm and V_B is in kV. For the upper part of the red curve, the function is $E_{Sm} = 4.51 \times V_B + 63.14$.

From Figure 4.5, it is very obvious that the back electrode has elevated E_{Sm} several times higher than without back electrode. To further investigate the influence of back electrode on the electric field. The distribution of E_S along the surface gap for different gap distance L along the central line of the board is plotted in Figure 4.6.

The shapes of curves in both figures in Figure 4.6 are very similar. When there is no back electrode, E_S starts from the maximum value, which is 40-50 kV/cm at the region very close to the high voltage electrode. Then E_S drops to 4-5 kV/cm and keeps that value for most region in the gap. In the area very close to the ground electrode, E_S raises again back to 40-50 kV/cm. in brief, despite the high electric field in the area near the electrodes, the electric field is evenly distributed for most area of the gap. No matter what gap distance L is, the minimum value of E_S can be always above 3-4 kV/cm.

However, with back electrode, the story is totally different. At the region near the high voltage electrode, E_S can be as high as 100-200 kV/cm. From Figure 4.6 we can see that in the region near high voltage electrode the red solid line is much above the blue dashed line. But later the value of E_S falls very rapidly with the distance to the high voltage electrode getting a little bit larger. When the distance to the high voltage electrode is about 1.5-2 cm, two lines intersect. After that, E_S is still getting lower. When the distance to the high voltage electrode is greater than 3-4 cm, the value of E_S gets so low that it almost can be ignored.

The curves in Figure 4.6 can be used to explain why back electrode increases E_{Sm} several times higher than without back electrode. From Townsend Discharge Theory, the electrons must have enough kinetic energy to generate electron avalanche and eventually to generate breakdown. Assume for a certain gap distance L, the kinetic energy needed to generate breakdown is a constant value. Then without back electrode, since the E_S value is always beyond 3-4 kV/cm, then the electrons can accelerate in the whole gap. However, with back electrode, the distribution of E_S along the gap is quite uneven. When the distance to the high voltage electrode is larger than 3-4 cm, E_S will be too low to accelerate the electrons. Therefore, the electrons can only be accelerated near the high voltage electrode. To provide enough energy for the electrons to get a breakdown, with back electrode the electric field in the region near the high voltage electrode should be much higher than without back electrode. So this explains why the back electrode makes E_{Sm} bigger.

The electrodes are placed in parallel on the surface. Then from equation $V_B = \int E\,dl$ we can get that at breakdown, the relationship between breakdown voltage V_B and E_S should be $V_B = \int E_S\,dl$, where l is the whole gap distance L. From Figure 4.6 we also found that with back electrode, for different L values, the effective distance for electrons to accelerate remains almost the same, which is about 2-2.5 cm. So this explains why with back electrode, E_{Sm} is proportional to the gap distance L. Then with back electrode, in the equation $V_B = \int E_S\,dl,\ l$ also can be expressed as the effective distance. So if our explanation is correct, with back electrode, the integration result of $\int E_S\,dl$ for both l = 2.5 cm and l equals to gap distance L should be the same with the breakdown voltage V_B. Without back electrode, there should be a big difference between those two results. The integration result is in Table 4.3.

Table 4.3 Comparison between integration results and measured voltage

	Gap distance L (cm)	**Measured breakdown voltage (kV)**	**$\int E_S\,dl$ (kV)**	
			Integral upper limit is L	**Integral upper limit is 2.5 cm**
With back electrode	5	26.6	25.7	24.0
	10	35.3	34.5	32.1
	15	41.9	41.2	38.4
Without back electrode	5	27.2	26.7	13.4
	10	46.7	46.2	14.0
	15	58.4	57.8	15.1

The results in Table 4.3 confirm the discussions we made previously. The required kinetic energy W for breakdown can be considered as a constant for both with and without back electrode. Then from equation $W = \int F\,dl = \int (E_S * q)\,dl = E_{S\_ave} * q * L$, for a certain gap distance, the average of E_S, which is referred to as E_{S_ave}, is the same for both with and without back electrode. Therefore, from equation $V_B = \int E_S\,dl = E_{S\_ave} * L$ we can conclude that the breakdown voltage V_B is the same for both with and without back electrode for any gap distance. From Figure 3.1, this conclusion is correct only when $L < L_C$, the reason why L_C occurs and why the breakdown characteristics change at $L = L_C$ is still unknown. We have to further investigate this phenomenon.

4.4 The influence of streamers on breakdown characteristics

From the recorded videos we find that with back electrode, the breakdown process is different between $L < L_C$ and $L > L_C$. With back electrode, when $L < L_C$, during the experiment process, nothing would happen on the epoxy board surface until breakdown occurs. However, when $L > L_C$, before breakdown occurs, when the applied voltage reaches some certain value, there will be partial discharge streamers on the surface coming out from the high voltage electrode. The streamer will cover a certain portion of the gap area. After these streamers are generated, with higher applied voltage value, the length and covered area of these streamers will also increase. It should be noted that even the applied voltage is close to breakdown voltage, the streamer covered area is still much less than the whole gap area. Figure 4.7 shows an example of streamers when L = 15 cm.

However, when there is no back electrode, there will be no streamers like that whether $L < L_C$ or $L > L_C$.

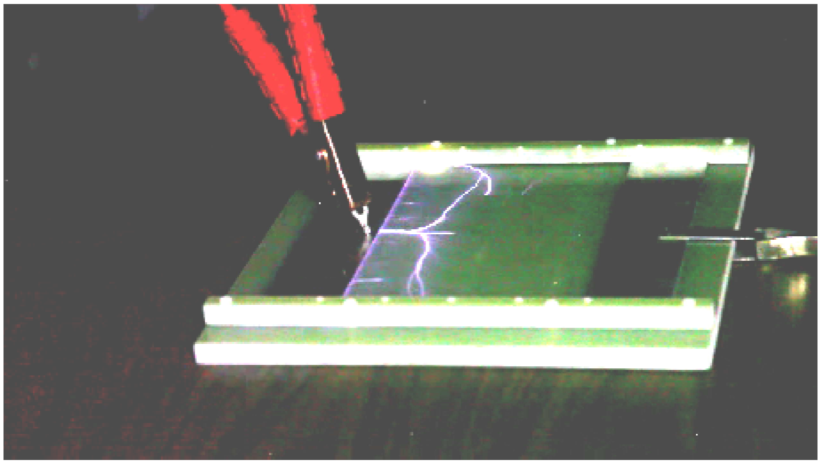


Figure 4.7 The snapshot of partial discharge streamers at L = 15 cm

The streamers can explain why the breakdown mechanism changes at $L = L_C$. From streamer discharge theory [23],[24], while the streamers travelling and propagating to the ground electrode, the electric field distribution around the streamers will be influenced and distorted. When there is no back electrode, the maximum electric field is only 40-50 kV/cm, it is too low to generate streamers. Even when there is back electrode, at $L < L_C$ the electric field is still not high enough. In this case, once a discharge occurs, it would lead to breakdown immediately [10]. When $L > L_C$ with back electrode, the maximum electric field is high enough to generate partial discharge streamers. Since the tangential electric field strength will decrease with the distance to the high voltage electrode increases, after the streamers propagate a certain distance, the tangential electric field at the streamer tip would be too low to let streamers continue propagating. In that case, the travelling direction of the streamers will suddenly turn to the bars and then vanish.

From the Streamer Theory, with the streamers travelling towards the ground electrode, they will further distort the electric field and enhance the electric field concentration near the streamers. That means the actual tangential electric field strength is even higher than the calculated value. Recall in Part 4.3, we have discussed and confirmed that the average tangential electric field E_{S_ave} for a certain gap distance is a constant, whether there is back electrode or not. Without streamers, the actual E_{S_ave} is equal to the calculated E_{S_ave}. However, with streamers, the actual E_{S_ave} is higher than calculated E_{S_ave}. This explains why in Figure 4.3 with back electrode, when $L > L_C$, the calculated E_{Sm} is less than the predicted value. Then the required electric field strength for breakdown can be also achieved with a lower applied voltage. This is why in Figure 3.1, the actual breakdown voltage is less than the predicted value when $L > L_C$ with back electrode.

The existence of streamers solves the problem why L_C exists. But it is still not clear why the partial discharge streamers occur at a so high electric field. The typical value of partial discharge inception field is about 20-30 kV/cm. However, from the calculated electric field value, the streamer inception field strength is more than 180-200 kV/cm. Therefore, the reason why the partial discharge occurs at so high field also needs to be analyzed.

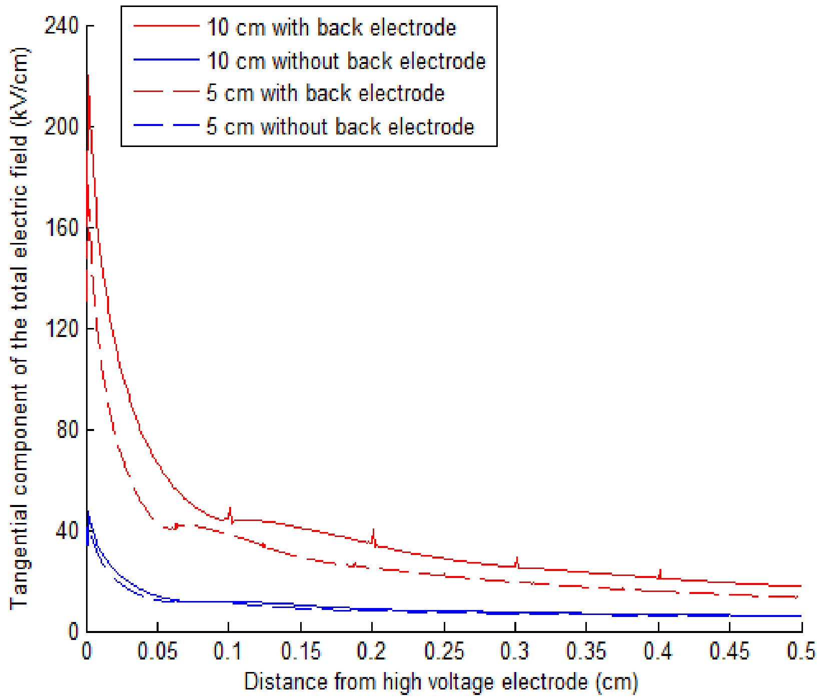


Figure 4.8 The distribution of E_S near high voltage electrode for different L

Figure 4.8 is the distribution of E_S along the central line of the board around the high voltage electrode. From Figure 4.8 we know that although with back electrode, the maximum of E_S is very high, E_S drops very rapid in the first 0.05-0.1 cm. From [25], partial discharge streamers will occur when the applied electrical stress exceeds a certain value. 20-30 kV/cm is enough to generate corona, however, it is not enough to generate partial discharge streamers. From the experimental and simulation results, compared to the partial discharge streamers, the impact of corona is much less. To generate streamers which can influence breakdown properties, the streamers have to cover a portion of the whole gap. That means the electric stress for that portion should be high enough. With back electrode, when $L < L_C$, although the maximum E_S is much higher than

20-30 kV/cm, the total electrical stress around the high voltage electrode is not high enough because E_S drops too quickly. Additionally, many other factors like the electrode shape, insulation material and experimental setup, all those things also impact the streamer inception. So all these factors combine together and result in a so high partial discharge inception field. Without back electrode, from Figure 4.8, the electrical stress near the high voltage electrode is almost the same for every gap distance, which is far less than with back electrode. So that is why streamers are not observed without back electrode.

Chapter 5. THE IMPACT OF BARRIER ON BREAKDOWN CHARACTERISTICS

5.1 Without back electrode

5.1.1 Influence of barrier on breakdown voltage

As discussed in Part 3.2, without back electrode, the barrier can increase the breakdown voltage. The breakdown voltage reaches maximum value when *a*/*L* is between 0.1 and 0.2. To study the influence of barrier position, the results for different cases are listed in Table 5.1. The percentage of increase denotes to the percentage of increase of breakdown voltage compared to without barrier.

Table 5.1 Breakdown voltages for different experiment cases without back electrode

Gap distance *L* (cm)	***a*/*L* ratio**	**1 inch (2.54 cm) barrier**		**2 inch (5.08 cm) barrier**	
		Breakdown voltage (kV)	**Percentage of increase**	**Breakdown voltage (kV)**	**Percentage of increase**
5 cm	0.1	45.1	65.8%	57.0	109.6%
	0.2	45.5	67.3%	57.4	110.3%
	0.5	44.8	64.7%	56.4	107.4%
10 cm	0.1	60.4	29.3%	66.0	41.3%
	0.2	59.3	27.0%	65.8	40.9%
	0.5	57.5	23.1%	65.5	40.3%
15 cm	0.1	70.8	21.2%	75.2	28.8%
	0.2	71.0	21.6%	73.7	26.2%
	0.5	69.7	19.3%	72.4	24.0%

From Table 5.1, the influence of barrier position is small when there is no back electrode. For a certain gap distance, the difference of percentage of increase between different *a*/*L* values is less than 5% of the breakdown voltage without barrier. This is smaller than the results in some other papers [27],[28]. The reason may be that in those papers, most of the researchers focus on the point-point or point-plane electrode configuration. These electrode configurations will generate extremely inhomogeneous field. Then if the position of barrier changes a little, the electric field around the barrier may change greatly. However, in our case without back electrode, the electric field is homogeneous except in the area very close to the electrodes, like Figure 4.6. So the electric filed around the barrier will not change much when the position of the barrier varies. That may be the reason why without back electrode, the influence of barrier position is small.

For different gap distances, the influence of barrier is not the same. When only considering the percentage of increase, for the same barrier height, with larger gap distance, the influence of barrier is smaller. In our case, when L = 5 cm, with 1 inch barrier the breakdown voltage is 65% higher than without barrier. However, when L = 10 cm and 15, this percentage drops to only 20-30%. When considering the increased breakdown voltage, when L = 5 cm, with 1 inch barrier the breakdown voltage increases about 18 kV, while for L = 10 cm and 15, the increased voltage drops to about 10 to 12 kV. However, when we consider the ratio of barrier height/gap distance, we found some interesting phenomena. For example, the ratio of barrier height/gap distance is identical for L = 5cm with 1 inch barrier, and L = 10 cm with 2 inch barrier. The percentage of increase is more than 60% for L = 5cm with 1 inch barrier while that percentage is only about 40% for L = 10 cm with 2 inch barrier. If we compare the increased voltage, for L

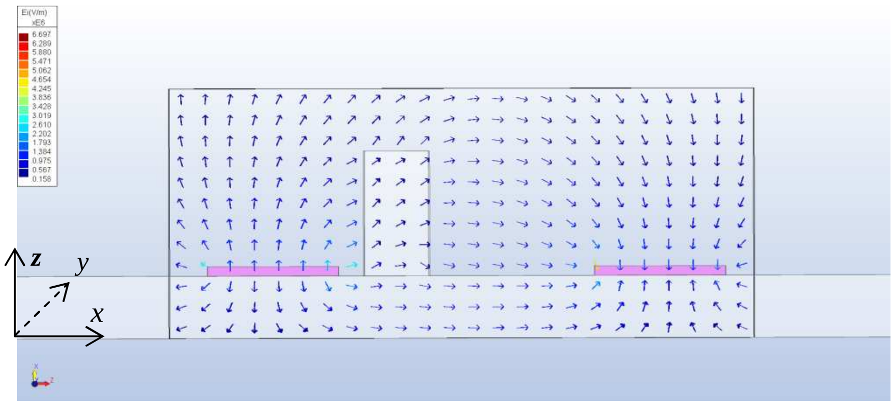
= 5cm with 1 inch barrier the increased breakdown voltage is about 18 kV and the increased voltage is around 19 kV for L = 10 cm with 2 inch barrier. This phenomenon reveals that for a certain barrier height/gap distance ratio, the increased breakdown voltage will be almost the same for different gap distances.

Another factor which we should pay attention to is the influence of barrier height. Generally speaking, when increase the barrier height, the breakdown voltage will increase. However, the influence of the barrier is not linear. When the barrier height increases to 2 inch from 1 inch, both the percentage of increase and increased breakdown voltage are smaller than from no barrier to 1 inch. That may be due to that the increased discharge length from 1 inch to 2 inch is smaller than from no barrier to 1 inch.

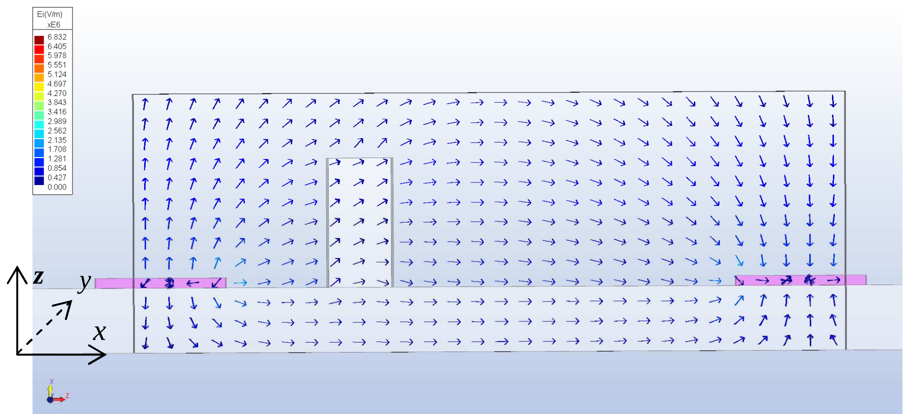
In brief, for long gap distance like L = 10 or 15 cm, inserting barrier into the gap does not seem to be a very effective way to increase breakdown voltage. In our experiment results, even we increase the barrier height to 2 inch (5.08 cm), which is equal to 50% of L when L = 10 cm and 33% of L when L = 15 cm, the breakdown voltage only increases 30% to 40% of its original value.

5.1.2 Electric field analysis

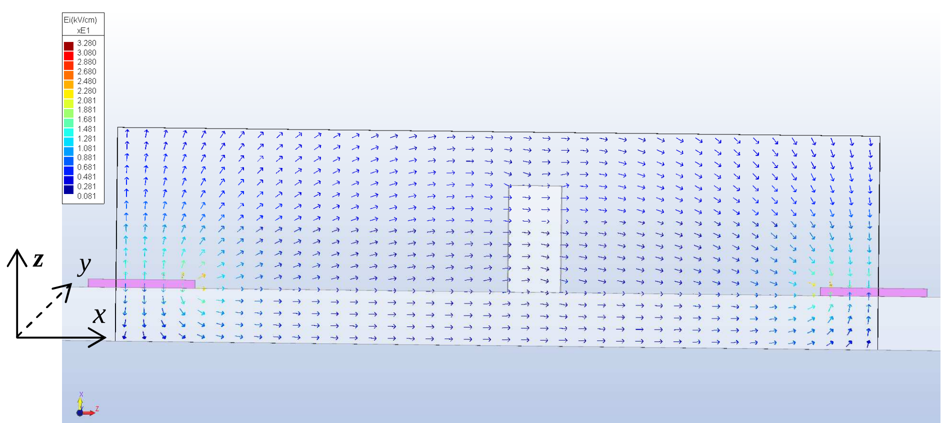
The electric field distribution for breakdown along the central line at y axis of the board without back electrode is shown in Figure 5.1 and Figure 5.2. In the simulation the breakdown voltage is the boundary condition and we do not consider the influence of residential charge.



(a) L = 5cm, a/L = 0.1

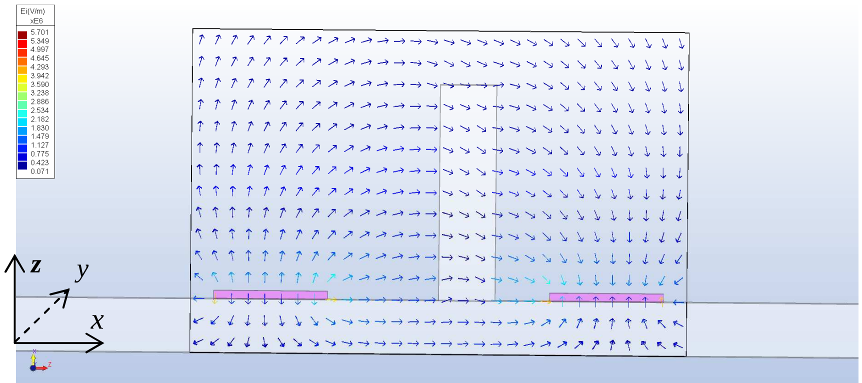


(b) L = 10 cm, a/L = 0.2

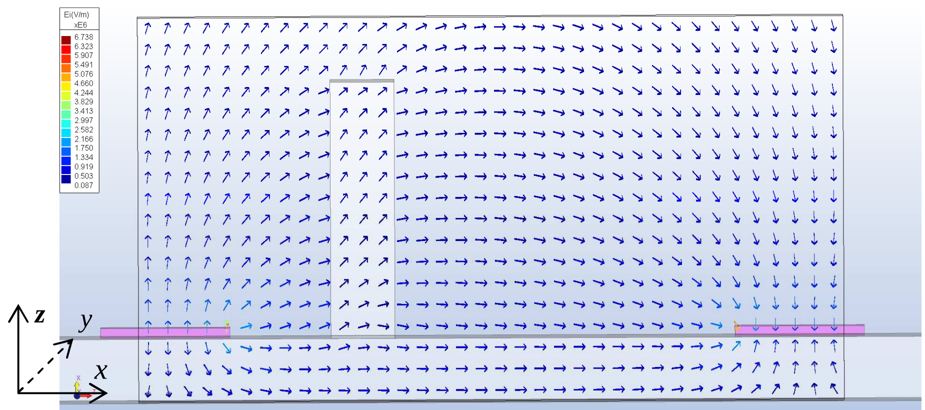


(c) L = 15 cm, a/L = 0.5

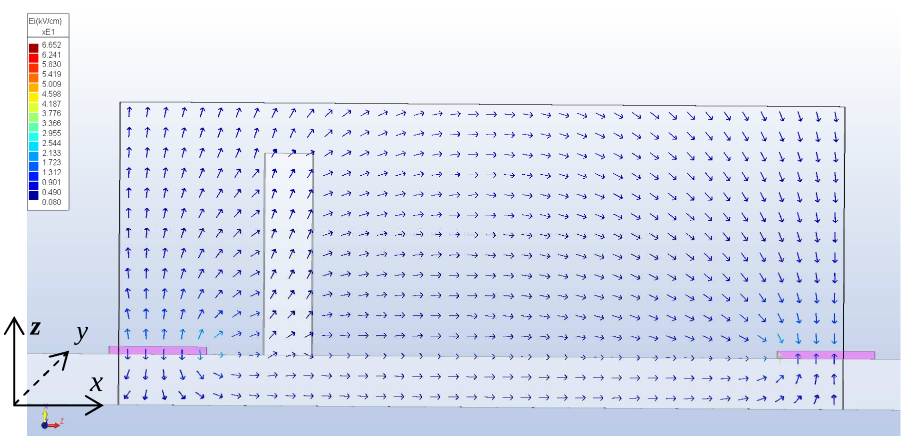
Figure 5.1 The cross-sectional view of the electric field distribution without back electrode with 1 inch (2.54 cm) barrier



(a) L = 5cm, a/L = 0.5



(b) L = 10 cm, a/L =0.2

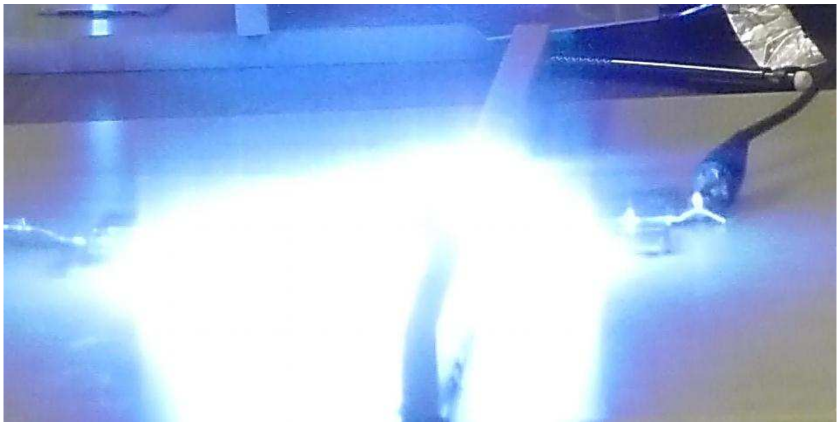


(c) L = 15 cm, a/L = 0.1

Figure 5.2 The cross-sectional view of the electric field distribution without back electrode with 2 inch (5.08 cm) barrier

In Figure 5.1 and Figure 5.2, the pink sections are referred to electrodes while the white sections are denoted as epoxy board and the barrier. From Figure 5.1 and Figure 5.2, without back electrode, the simulation result shows that for the space outside the barrier, the insertion of a barrier does not change the electrical field distribution. That means the improvement of breakdown voltage is due to the increase of creepage length induced by the barrier. In Chapter 4 we have discussed that to generate breakdown, the electrons must accelerate in the electric field and get enough kinetic energy. With barrier, the electrons can no longer accelerate along the surface because the presence of barrier blocks that route. Therefore, the electrons must find another route to cross the barrier and get breakdown. Most probably the electrons will take the route from the high voltage, then go up along the electric field lines to jump over the barrier, and finally go down to the ground electrode. Obviously this proposed breakdown route is much longer than directly from the high voltage electrode to ground electrode. That is why in the case without back electrode, the breakdown voltage with barrier is higher than without barrier. To confirm this hypothesis and to find out more information about the relationship between breakdown characteristics and electric field distribution, we must know how the breakdown trajectory looks like with barrier. The snapshots of breakdown for different gap distances are extracted from experiment videos and they are shown in Figure 5.3.

(a) *L* = 10cm, *a*/*L* = 0.5, 1 inch barrier



(b) *L* = 15 cm, *a*/*L* =0.2, 1 inch barrier

(c) *L* = 15 cm, *a*/*L* = 0.1, 2 inch barrier

Figure 5.3 The snapshot of breakdown for different experiment cases without back electrode

From Figure 5.3, we can see that without back electrode, the breakdown trajectory follows the same way for different gap distances. The discharge route initiates from the high voltage electrode, goes up to the barrier upper surface, cross the barrier along the upper surface and finally go down to the ground electrode. Then for different barrier position, this route should be different. To simplify the analysis, we assume that the breakdown route from electrodes to the barrier is almost a straight line, just like Figure 5.3. Then the breakdown routes for different barrier positions are shown in Figure 5.4.

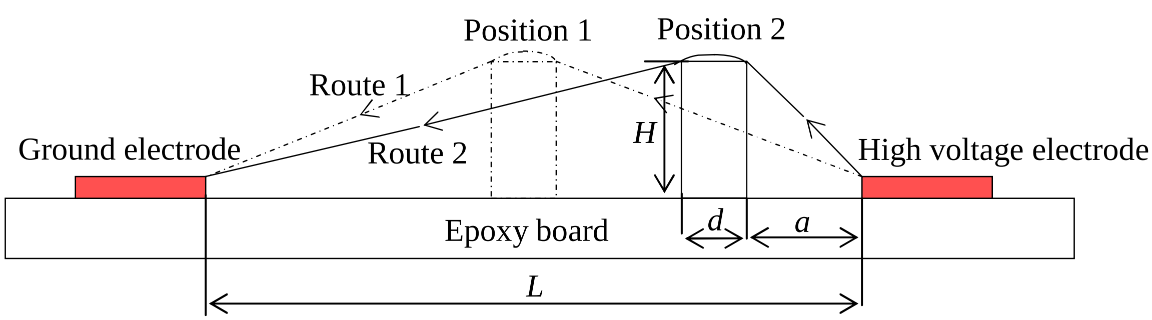


Figure 5.4 The proposed breakdown routes for different barrier positions without back electrode

In Figure 5.4, the barrier has two different positions. Position 1 is the case that *a*/*L* = 0.5 while position 2 corresponds to the case that *a*/*L* = 0.1 or 0.2. From geometry, the discharge length is $\sqrt{(L-a-d)^2+H^2}+\sqrt{a^2+H^2}+d$, in which *a* is the distance from barrier to high voltage electrode, *H* is the barrier height and *d* is the barrier thickness. From the differential result of this equation, when the barrier is exactly in the middle between two electrodes, which is near position 1, the total length of the breakdown route, which is route 1, reaches the minimum. That means the length of breakdown route for *a*/*L* = 0.5 is always less than *a*/*L* = 0.1 or 0.2. This explains why without back electrode breakdown voltage is minimum when *a*/*L* = 0.5.

From Figure 5.4, the length of breakdown route increases as *a*/*L* decreases all the way from 0.5 to 0.1. The length will reach maximum at *a*/*L* = 0.1. That means that breakdown voltage will always be maximum at *a*/*L* = 0.1, with *a*/*L* increasing, the breakdown voltage will drop and the breakdown voltage reaches minimum at *a*/*L* = 0.5. However, the experiment results do not meet this projection. Sometimes breakdown voltage reaches maximum at *a*/*L* = 0.2 rather than 0.1. This is because the charge accumulation effect near the barrier. From Figure 5.3 (c), when *a*/*L* = 0.1, the breakdown route is very close to the barrier surface. From [16], when the electric field is not strong, due to the nature of AC voltage, when the applied voltage alters from one half-cycle to another, there will be charge neutralization process for the residential charge. Thus the quantity of residential charge is small. However, when the local electric field is higher, like the case *a*/*L* = 0.1, in each half cycle, the charges which have the same polarity with the high voltage electrode, are more likely to accumulate near the barrier surface. Since the charges with same polarity will repel each other, the electromagnetic force from residential charge then acts as an “elevator”, which pushes the ionized particles in the air to jump over the barrier [28], thus enhance the breakdown process. That explains why at *a*/*L* = 0.1 the breakdown voltage is lower than expected. When *a*/*L* gets larger, since the breakdown trajectory starts to get away from the barrier surface and the electric field around the barrier is lower, in this case the residential charge will have almost no impact on the breakdown characteristics and the breakdown voltage follows the theoretical analysis.

Generally, without back electrode, the length of breakdown route for different barrier position does not have too much difference. Although the residential charge has impact on breakdown when *a*/*L* = 0.1, from the experiment results, the influence of residential charge is small. Therefore, the influence of barrier position on breakdown voltage is small.

Table 5.2 Maximum electric field strength for different experiment cases without back electrode

Gap distance *L* (cm)	***a*/*L* ratio**	**1 inch (2.54 cm) barrier**		**2 inch (5.08 cm) barrier**	
		Maximum electric field E_m (kV/cm)	**Maximum tangential electric field E_{Sm} (kV/cm)**	**Maximum electric field E_m (kV/cm)**	**Maximum tangential electric field E_{Sm} (kV/cm)**
5 cm	0.1	98.1	88.0	125	113
	0.2	96.1	83.7	121	106
	0.5	96.0	85.1	121	107
10 cm	0.1	85.8	76.3	96.2	84.8
	0.2	81.2	70.9	90.2	79.5
	0.5	80.8	70.7	90.6	80.6
15 cm	0.1	82.0	72.5	88.9	78.3
	0.2	80.0	69.7	83.8	73.0
	0.5	80.2	70.4	85.2	73.2

The maximum electric field for different experiment cases without back electrode is shown in Table 5.2. Compared with the experiment results without barrier in Table 4.1 and Table 4.2, both E_m and E_{Sm} increase. Both gap distance and a/L ratio have influence on maximum electric field. With larger L, both E_m and E_{Sm} decrease and they will approach to a constant value. For each gap distance, E_m and E_{Sm} for the experiment case of a/L = 0.2 are almost equal to the case of a/L = 0.5. However, when a/L = 0.1, both E_m and E_{Sm} are higher than a/L = 0.2 and a/L = 0.5, although the difference is not very large, which is in the range of 3-7 %. This is different from the relationship between breakdown voltage and a/L position. The breakdown voltage is almost the same for a/L = 0.1 and a/L = 0.2 while the breakdown voltage is lower for a/L = 0.5. The reason is that the maximum electric field occurs at the region very close to the high voltage electrode. From Figure 5.1 and Figure 5.2, when barrier is at a/L = 0.1, the electric field around the barrier is just like "climbing up", which is in an angle with the board. Then we can determine that the position of a/L = 0.1 in the region "close to electrode" and thus the barrier at a/L = 0.1 will have impact on the maximum electric field. However, when barrier is at a/L = 0.2 or 0.5, the electric field around the barrier is almost parallel to the board surface. Then the positions of a/L = 0.2 and a/L = 0.5 are not "close to electrode". Therefore, the influence of barrier at a/L = 0.1 on maximum field is higher than a/L = 0.2 and a/L = 0.5.

5.2 With back electrode

5.2.1 Influence of barrier on breakdown voltage

The results for different cases with back electrode are listed in Table 5.3. The percentage of increase denotes to the percentage of increase of breakdown voltage compared to without barrier.

Table 5.3 Breakdown voltages for different experiment cases with back electrode

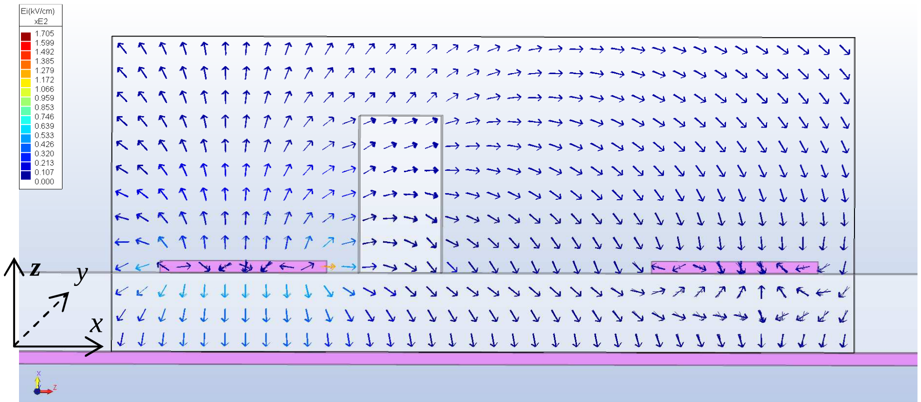
Gap distance *L* (cm)	***a*/*L* ratio**	**1 inch (2.54 cm) barrier**		**2 inch (5.08 cm) barrier**	
		Breakdown voltage (kV)	**Percentage of increase**	**Breakdown voltage (kV)**	**Percentage of increase**
5 cm	0.1	40.6	52.6%	53.7	101.9%
	0.2	41.7	56.8%	55.8	109.8%
	0.5	42.1	58.3%	55.7	109.4%
10 cm	0.1	54.1	53.3%	63.2	79.4%
	0.2	55.1	56.1%	64.5	82.7%
	0.5	50.6	43.3%	58.7	66.3%
15 cm	0.1	54.9	31.0%	66.8	59.4%
	0.2	55.0	31.3%	67.6	61.3%
	0.5	60.6	44.6%	68.5	63.5%

Compared with breakdown voltages without back electrode in Table 5.1, for a certain gap distance, the breakdown voltage with back electrode is 10-20 % lower than without back electrode. That means even with barrier, the back electrode will still lower the breakdown voltages. However, if we look at the percentage of increase, for gap distances longer than 10 cm, the percentage of increase with back electrode is much higher than without back electrode. For instance, with 1 inch barrier, the average percentage of increase with back electrode is about 50%, while without back electrode is only less than 30%. Therefore, with back electrode, the barrier has stronger effect on the breakdown voltage.

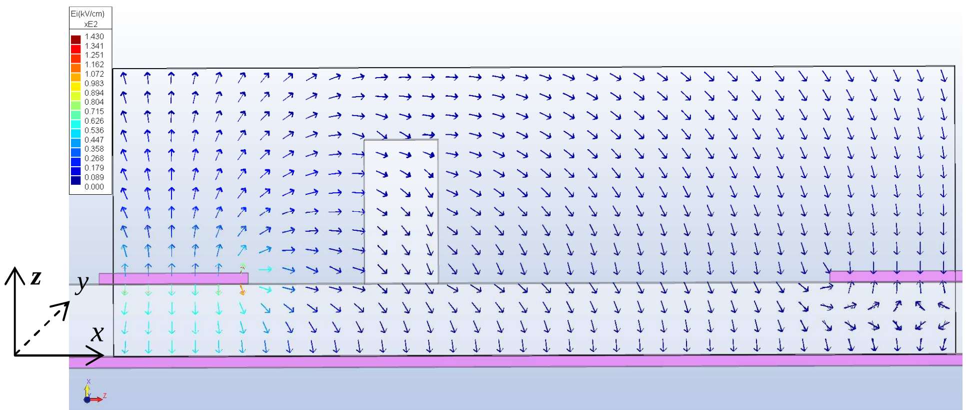
From Table 5.3, with back electrode, the breakdown voltage for 2 inch barrier is higher than 1 inch barrier, which is the same with the case without back electrode. However, the influence of barrier position on the breakdown voltage is different for different gap distances. From the analysis in Part 5.1, without back electrode, the influence of barrier position on breakdown voltage is very small, which is less than 5% of total breakdown voltage. For every gap distance, the breakdown voltage reaches maximum at a/L = 0.1 to 0.2. With back electrode, it seems that there is no consistency in the breakdown voltage. When L = 5 cm, for different barrier positions, the breakdown voltage is almost the same. When L = 10 cm, the breakdown voltage at a/L = 0.5 is about 10 % less than a/L = 0.1 and a/L = 0.2. At L = 15 cm, with 1 inch barrier, the breakdown voltage at a/L = 0.5 is about 10 % higher than a/L = 0.1 and a/L = 0.2, while with 2 inch barrier the breakdown voltage is almost the same for all the barrier positions. To investigate why this phenomenon happens, we have to take a look at the electric field distribution result.

5.2.2 Electric field simulation result

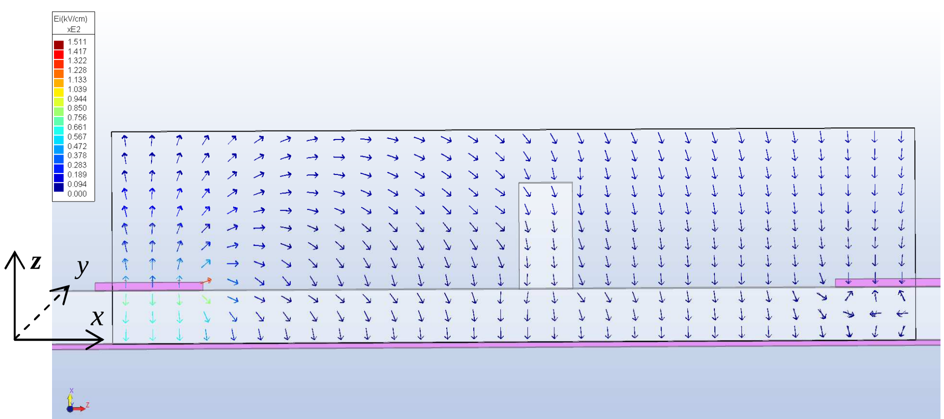
The electric field distribution for different gap distances and different barrier positions along the central line at y axis of the board are shown in Figure 5.5 and Figure 5.6. The model is build based on real dimensions. The boundary condition is the breakdown voltage for the experiment case. Like the previous simulations, we do not consider the influence of the residential charge.



(a) L = 5cm, a/L = 0.1

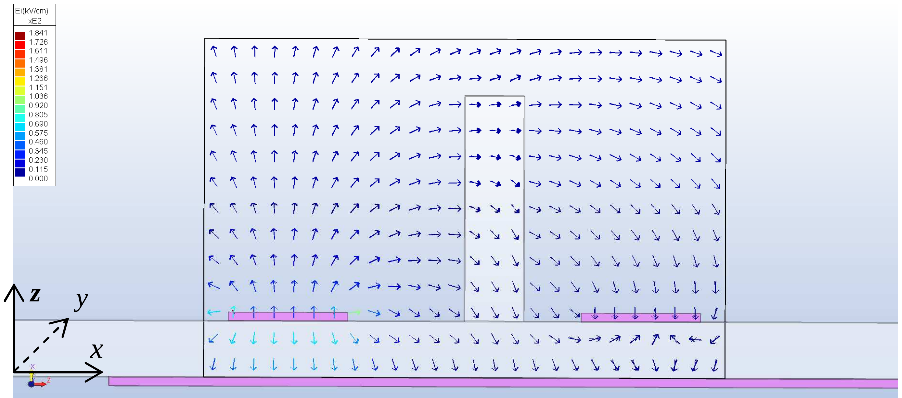


(b) L = 10 cm, a/L = 0.2

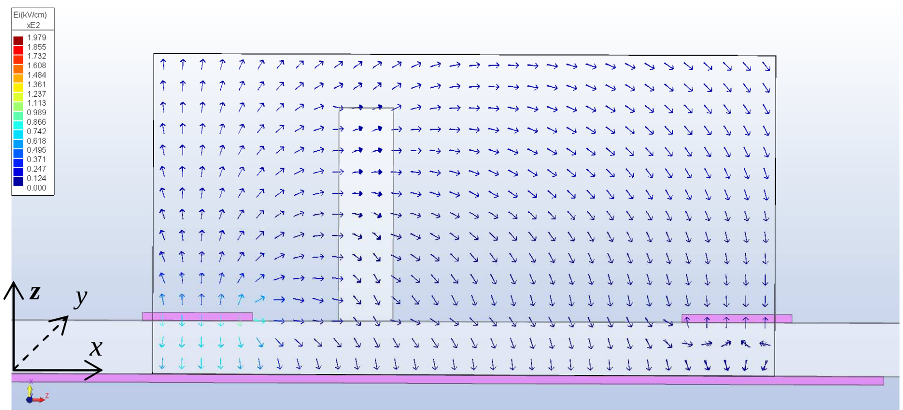


(c) L = 15 cm, a/L = 0.5

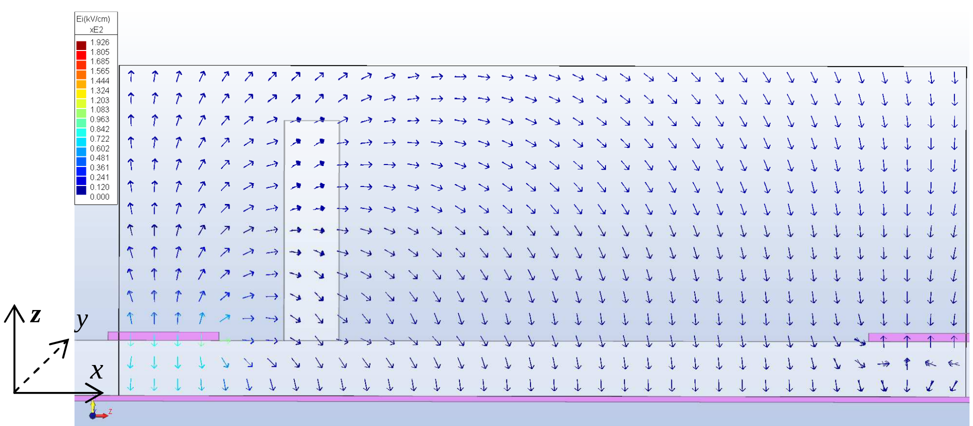
Figure 5.5 The cross-sectional view of the electric field distribution with back electrode with 1 inch (2.54 cm) barrier



(a) L = 5cm, a/L = 0.5



(b) L = 10 cm, a/L =0.2



(c) L = 15 cm, a/L = 0.1

Figure 5.6 The cross-sectional view of the electric field distribution with back electrode with 2 inch (5.08 cm) barrier

In Figure 5.5 and Figure 5.6, the pink sections are electrodes while the white sections are epoxy board and the barrier. Compared with the electric field distribution shown in Figure 4.2, with back electrode, the barrier still does not have much influence on the electric field distribution.

Table 5.4 Maximum electric field strength for different experiment cases with back electrode

Gap distance *L* (cm)	***a*/*L* ratio**	**1 inch (2.54 cm) barrier**		**2 inch (5.08 cm) barrier**	
		Maximum electric field E_m (kV/cm)	**Maximum tangential electric field E_{Sm} (kV/cm)**	**Maximum electric field E_m (kV/cm)**	**Maximum tangential electric field E_{Sm} (kV/cm)**
5 cm	0.1	324	292	430	387
	0.2	322	287	432	384
	0.5	341	303	452	402
10 cm	0.1	418	372	489	435
	0.2	415	366	486	429
	0.5	392	351	455	407
15 cm	0.1	443	379	540	461
	0.2	413	363	496	434
	0.5	453	388	512	439

The maximum electric field strength for different experiment cases with back electrode is shown in Table 5.4. Compared with the results in Table 4.1 and Table 4.2, the barrier has greatly increased the value of maximum electric field and maximum tangential electric field, especially at small gap distance. From our discussions in Chapter 4, when E_{Sm} values are over 180-200 kV/cm, there should be partial discharge streamers coming from the high voltage electrode. From Table 5.4, the E_{Sm} values for every experiment case are much over that threshold.

So we can predict that there would be partial discharge streamers generated in all the experiment cases. With larger gap distance or higher barrier height, both E_m and E_{Sm} values will increase. This is different from the experiments without back electrode. The influence of barrier height will become less with larger gap distance. For a certain gap distance, the barrier position has more significant influence on the maximum electric field than without back electrode, and the influence of barrier position is not consistent for different gap distances. The reason is probably that the breakdown voltage changes greatly for different barrier positions, thus influences the maximum electric field. Therefore, the key to solving this question is to investigate why breakdown voltage changes greatly for different experiment cases.

Since the electric field does not change too much with barrier, only the electric field distribution cannot explain how the barrier position impacts breakdown voltage. Additionally, from Chapter 4, it is known that the partial discharge streamers also have impact on breakdown. Therefore, we have to examine the videos again to find out the how breakdown mechanism changes with the presence of barrier.

5.2.3 Influence of partial discharge and residential charge

From the videos, it is found that for every experiment case with barrier, even L is only 5 cm, there are partial discharge streamers coming out of the high voltage electrode, which is consistent with the prediction in Part 5.2.2. The partial discharge streamers are shown in Figure 5.7. The partial discharge starts from the high voltage electrode, and ends at the barrier.

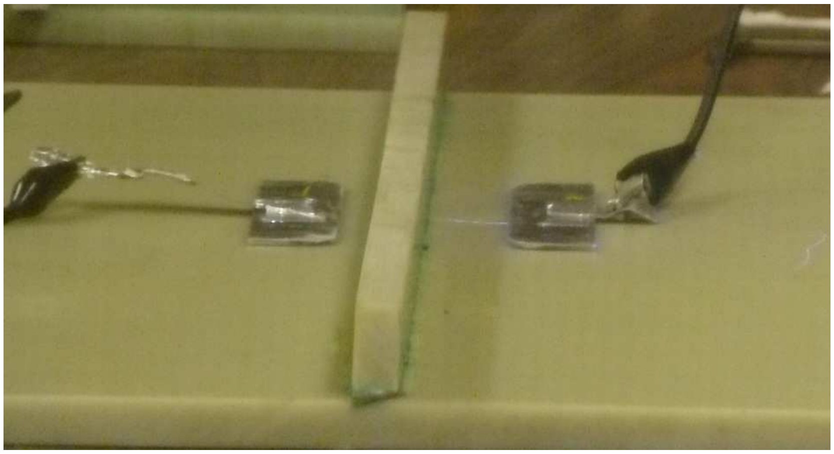


Figure 5.7 The snapshot of partial discharge streamers at L = 5 cm, a/L = 0.5

As discussed in Chapter 4, the partial discharge would enhance the electric field distribution and lower breakdown voltage. This is why with barrier, the breakdown voltage with back electrode is lower than without back electrode. The other factor we should focus is the breakdown trajectory. From the analysis in Part 5.1, without back electrode, the breakdown only has one discharge pattern. For different barrier positions, the difference in the discharge length results in the difference in breakdown voltage. However, with back electrode, the breakdown trajectory is not the same. With different barrier positions and gap distances, the discharge pattern would change. There are totally three different kinds of breakdown patterns. The details of these breakdown patterns are demonstrated in the following discussion

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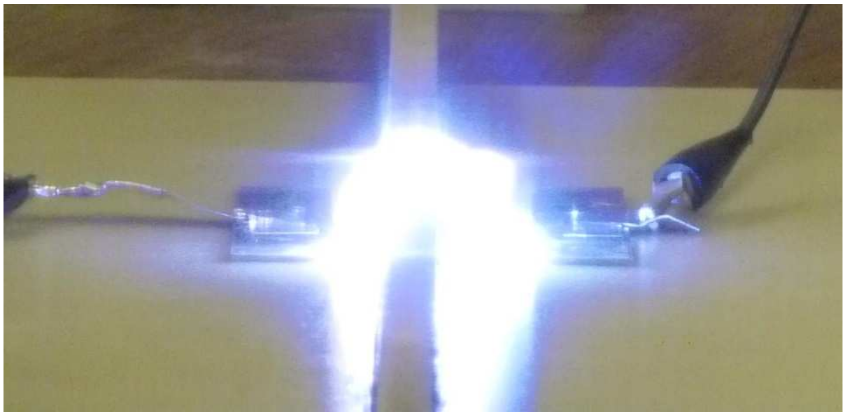
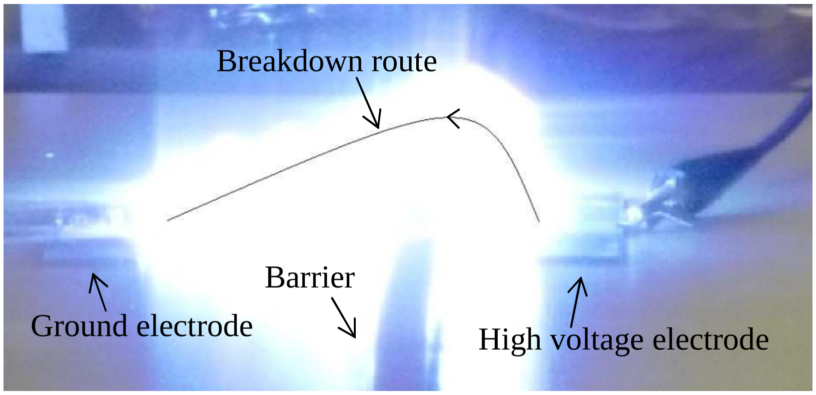
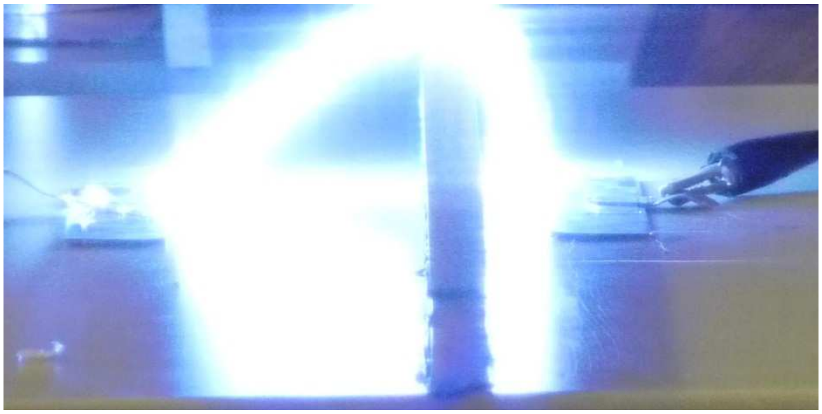
Breakdown pattern 1



(a) *L* = 5cm, *a*/*L* = 0.5, 1 inch barrier



(b) *L* = 5 cm, *a*/*L* =0.2, 1 inch barrier



(c) *L* = 10 cm, *a*/*L* = 0.2, 2 inch barrier

Figure 5.8 The snapshot of breakdown pattern 1 with back electrode

The figures for breakdown pattern 1 are shown in Figure 5.8. This breakdown pattern is the same as discussed in the case without back electrode in Part 5.1. The discharge starts from the high voltage electrode, jumps over the barrier and then goes to the ground electrode. This discharge pattern happens at small gap distance like L = 5 cm, or longer gap distance with small a/L value like L = 10 cm with a/L = 0.1 and 0.2. With this breakdown pattern, the barrier position does not make too much difference in breakdown voltage. From [22], in AC system, the quantity of deposited charge is dependent on the electric field strength. With higher field, there would be more residential charge. In our experiment case with back electrode, the maximum field is several times higher than without back electrode. Therefore, we can predict the residential charge would have more impact on the breakdown characteristics. With this breakdown pattern, the breakdown voltages for a/L = 0.5 and a/L = 0.2 are always higher than a/L = 0.1. For the maximum electric field, it's almost the same for a/L = 0.1 and a/L = 0.2, while the value for a/L = 0.5 is always higher than a/L = 0.1 and 0.2. The reason may be the influence of the residential charge. The residential charge changes the electric field distribution and thus changes the breakdown voltage. However, even though the influence of residential charge is higher for the case with back electrode, we still do not see a significant difference with larger quantity of residential charge. So, for breakdown pattern 1, the influence of residential charge can be ignored.

In the discussion of Chapter 4, we have discussed that when there is partial discharge streamer generated, these streamers dominate the breakdown properties. However, this does not apply to this breakdown pattern. Since the breakdown trajectory is far from the board surface, the impact of these streamers is limited. With 1 inch barrier, the breakdown voltage with back electrode is about 10-15 % lower than without back electrode. With 2 inch barrier, the breakdown voltages for both with and without back electrode are almost equal. Compared with the results without barrier in Table 3.8, we can see that the barrier can effectively reduce the impact of partial discharge streamers. With higher barrier, the influence of partial discharge streamers would be less.

Breakdown pattern 2

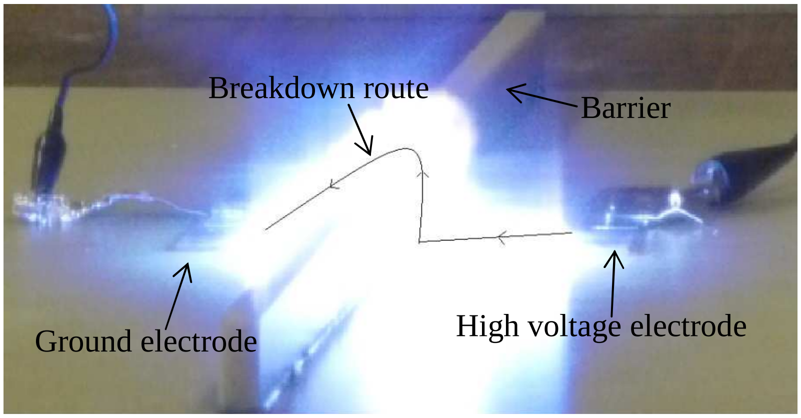
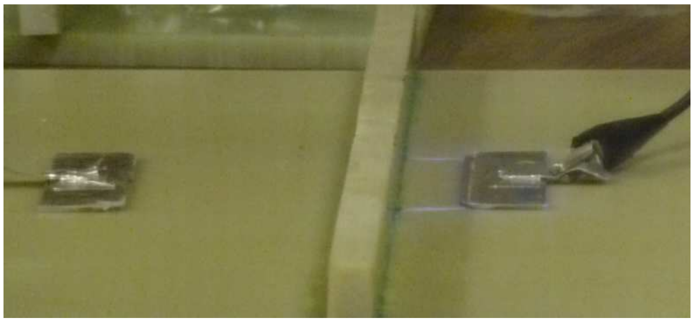
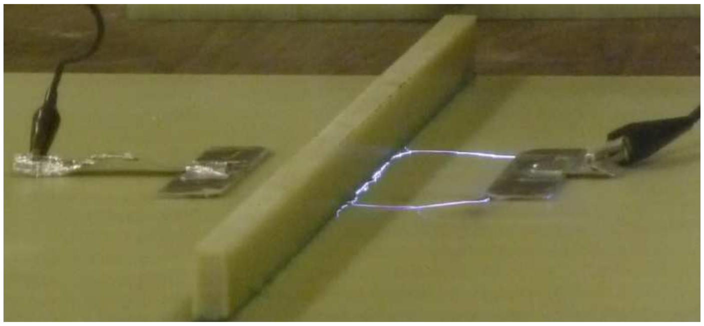


Figure 5.9 The snapshot of breakdown pattern 2 with back electrode at *L* = 10cm, *a*/*L* = 0.5, 1 inch barrier

The snapshot of breakdown pattern 2 is shown in Figure 5.9. In this breakdown pattern, the discharge starts from the high voltage electrode, travels to the barrier along the board surface first, then it would go along the barrier surface to the barrier top, and finally it crosses over the barrier and goes directly to the ground electrode. This kind of discharge happens at a long gap distance with a large a/L value, such as a/L = 0.5, 1 inch barrier with L = 10 cm and L = 15 cm, and 2 inch barrier with L = 10 cm. However, when we investigate the electric field distribution in Figure 5.5 and Figure 5.6, we find that this kind of breakdown is theoretically impossible. In the cases which a/L = 0.5 and L = 10 or 15 cm, the electric field near the intersection of the board and barrier is going downward to the back electrode. That means if the discharge propagates to the barrier along the board surface, it is not able to climb over the barrier since the force from the electric field will always push the discharge to the board surface. Therefore, to find out the reason, we have to focus on other factors that influence breakdown.



(a) L = 10cm, a/L = 0.2, 1 inch barrier



(b) L = 10 cm, a/L =0.5, 1 inch barrier

Figure 5.10 The snapshots of partial discharge streamers with barrier

The snapshots of partial discharge streamers are shown in Figure 5.10. From Table 5.4 we know that the maximum field strength is much higher than the threshold of generating partial discharge streamers. For all the experiments with barrier, the partial discharge streamers initiate from the high voltage electrode and travel along the board surface. However, due to the existence of the barrier, when the streamers hit the barrier, the streamers would divert and finally vanish since the streamers cannot penetrate through the barrier. Therefore, the barrier would limit the area under influence of the streamers to the space between the barrier and the high voltage electrode. As discussed in Chapter 4, the electrons would get extra kinetic energy from the streamers thus the breakdown voltage is lower. Therefore, with larger a/L value, the breakdown process would be influenced more by the partial discharge, and the breakdown voltage would be further lowered. That is probably why the breakdown voltage for breakdown pattern 2 is lower than breakdown pattern 1.

Although partial discharge streamers can explain why breakdown voltage is lower, it is still unknown how the discharge can jump over the barrier and lead to breakdown. To solve this question, we have to look at both the partial discharge and the residential charge. For a certain gap distance, the partial discharge characteristics are different for different a/L values. Like the pictures shown in Figure 5.10, when a/L is small, the partial discharge has a higher discharging frequency but the discharge current is small. When a/L is larger, the discharging frequency is lower but the discharge current is much higher. From discussions in

[16], in AC system, as applied voltage goes up, the residential charge is likely to accumulate, and the polarity of the residential charge is the same as the polarity of high voltage electrode. In our experiment system, since the discharge streamers would always vanish under the barrier, then the charges carrier by the partial discharge current would accumulate under the barrier. From the equation $Q = \int I\, dt$, the charge accumulated with large *a*/*L* value is much more than small *a*/*L* value. This can explain why such kind of breakdown happens. The electrons first get a lot extra kinetic energy from the partial discharge streamers while they travel to the barrier. When the electrons get near to the barrier, since there is a large quantity of residential charge near the barrier, the residential charge would repel with the electrons. So the force from the residential charge would push the electrons upward, help electrons cross the barrier and finally lead to breakdown.

When breakdown pattern 2 happens, typically the breakdown voltage is about 10-15% lower than breakdown pattern 1. The maximum electric field is also lower than pattern 1 due to the strong effect of partial discharge. In this breakdown pattern, both residential charge and partial discharge streamers play an important role in the breakdown process and they are no longer negligible.

Breakdown pattern 3

The last kind of breakdown pattern, which is breakdown pattern 3, is shown in Figure 5.11. This pattern happens when gap distance is long, *a*/*L* value is small with low barrier, such as *L* = 15 cm, *a*/*L* = 0.1/0.2 with 1 inch barrier.

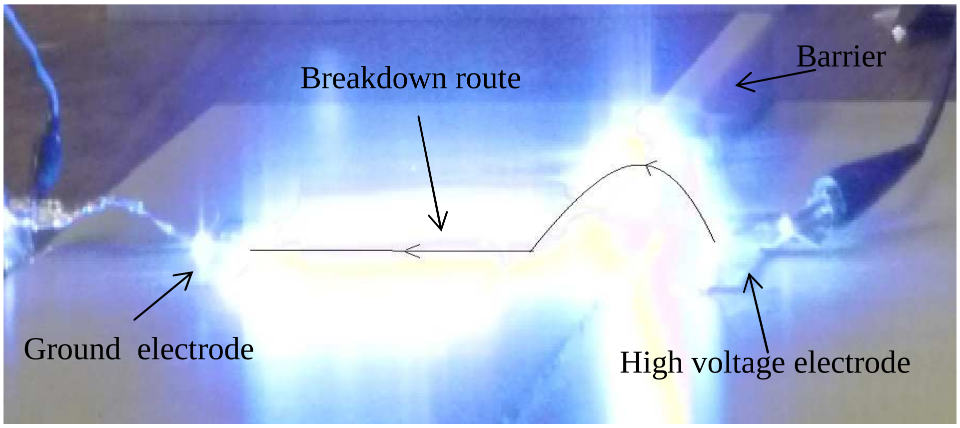


Figure 5.11 The snapshot of breakdown pattern 3 with back electrode at *L* = 15cm, *a*/*L* = 0.2, 1 inch barrier

As we can see from Figure 5.11, in this kind of breakdown pattern, the discharge starts from the high voltage electrode, then directly goes up and crosses the barrier, then goes down to the board surface and finally travels to the ground electrode. This type of breakdown happens when the ratio of barrier height/gap distance is small. As discussed previously, with the same barrier height and position, when *L* is smaller, breakdown pattern 1 happens. The explanation of why breakdown pattern 1 transfers to breakdown pattern 3 is that when *L* is small, compared with the energy needed to get breakdown, the electrons also need a relatively larger value of kinetic energy to jump over the barrier. Then once it has enough energy to cross the barrier, it can go all the way directly to the ground electrode and leads to breakdown. However, when *L* is large, the electrons only need a smaller value of energy to cross the barrier. Then once the electrons cross over the barrier, they do not have enough energy to lead to breakdown. So the electrons have to go down to the board and get more energy from the electric field. That is why this breakdown pattern happens only at L = 15cm and barrier height is 1 inch. Actually when the barrier height changes from 1 inch to 2 inches, the breakdown pattern would change to breakdown pattern 1, just like the picture shown in Figure 5.12.

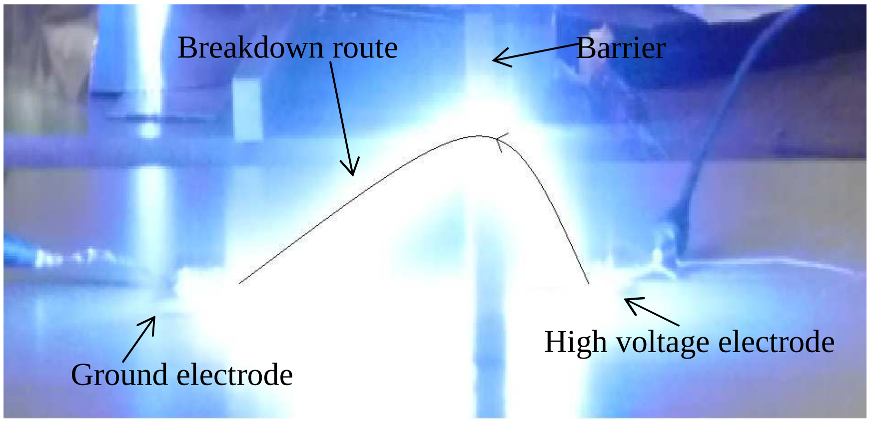


Figure 5.12 The snapshot of breakdown at L = 15cm, a/L = 0.2, 1 inch barrier with back electrode

The breakdown voltage of this breakdown pattern is lowest among all three kinds of breakdown patterns. As we can see from Table 5.3, this kind of breakdown is 10-20 % lower than others. This is because for other breakdown patterns, the energy needed for crossing the barrier is larger than the energy needed for getting breakdown, while for breakdown pattern 3 the energy needed for crossing the barrier is smaller than the energy needed for getting breakdown.

5.2.4 Summary of the breakdown characteristics with back electrode

The simulation result shows that the barrier does not have too much impact on the electric field distribution for both with and without back electrode. Compared with the case without back electrode, the breakdown for the case with back electrode is pretty complicated. Depending on different barrier height, barrier position and gap distance, the breakdown pattern would be different. For most of the cases, the percentage of increase is much higher than without back electrode. So adding a barrier is an effective way to improve breakdown voltage. The maximum electric field is several times higher than without barrier. Another factor we should point out is that we are unable to do integration like we did in Chapter 4. The first reason is that the breakdown trajectory is different for different breakdown patterns, and it is hard to accurately get the exact breakdown route. The second reason is that both partial discharge and residential charge play an important role in the breakdown process. The result would be inaccurate if we do not consider these factors.

Chapter 6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

This thesis deals with the influence of grounded back electrode on the AC breakdown characteristics. The research establishes a relationship between the breakdown properties and electric field distribution.

6.1.1 Without barrier

The back electrode has a great impact on breakdown. When there are partial discharge streamers generated from high voltage electrode, the streamers can enhance the breakdown process, thus reduce both the breakdown voltage and maximum electric field.

The back electrode also influences the electric field distribution. When there is no back electrode, the maximum electric field for different gap distances is a constant. When there is back electrode, the maximum electric field is much higher than without back electrode, and it is proportional to the gap distance value. The back electrode also has an effect of concentrating the electric field on the area near the high voltage electrode. The impact of back electrode would be more distinct with longer gap distance.

When the tangential electric field exceeds a certain critical value, there will be partial discharge streamers generated. The streamer initiation field strength is higher than typical corona inception value. We can also get breakdown voltage through integration of the tangential electric field along board surface.

6.1.2 With barrier

The presence of barrier will not change the electric field distribution. This is valid for both with and without back electrode.

The presence of barrier can improve the breakdown voltage, especially for the case with back electrode. So adding barrier can be an effective way to increase breakdown voltage for the case with back electrode. However, adding barrier for the case without back electrode does not seem to be a good idea since the influence of barrier on the breakdown voltage is small.

Both the barrier position and barrier height have influence on the breakdown voltage and electric field distribution. Generally, both the breakdown voltage and maximum electric field are higher for higher barrier, but the effectiveness of barrier is different for different experiment cases.

For the case without back electrode, there is only one breakdown pattern. The barrier position does not make too much difference on breakdown voltage and maximum field.

For the case with back electrode, there are three breakdown patterns observed. The effect of barrier on breakdown voltage changes greatly on different breakdown patterns. All the factors like gap distance, barrier position and barrier height contribute together to determine which breakdown pattern would take place.

For the case with back electrode, both partial discharge streamers and residential charge have impact on breakdown characteristics. Depending on different breakdown patterns, the influence is different. It is not feasible to do integration since the breakdown trajectory and influence of residential charge are hard to measure accurately.

6.2 Future work

In the present work, the impact of grounded back electrode is studied. I n this article, we mainly focus on the impact of back electrode on both with and without barrier. To more thoroughly investigate the influence of back electrode, more factors can be taken into consideration, such as different board width, barrier width, electrode configuration, board material, and so on.

Another factor can be improved is to precisely study the influence of partial discharge streamer and residential charge. In our research, due to the limitation on the tools, we are unable to measure the discharge current and residential charge accurately. If these can be precisely measured, then we can get a more precise electric field distribution through the simulation and we can analyze the impact of these factors more easily.

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APPENDIX A

The research work done in this thesis has contributed to the papers listed below:

[1] J. Liu, G. G. Karady, H. Alamer, A. Alhabib and Q. Yan, “Influence of grounded back electrode on the AC creepage breakdown,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no.5, pp.1887-1894, October 2013.

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