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INVESTIGATION OF SILICA AEROGEL AS A HIGH VOLTAGE INSULATOR

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Abstract: Silica aerogel is a unique open porous material that is 90% air and less than 10% solid silica existing in a highly cross linked network structure. It is therefore a very light weight material with nanosized pores. One of the most dominant causes of electrical insulation deterioration is the existence of cavities. Therefore minimizing them is desirable. In this research, the objective was to investigate the possibility of using silica aerogel, being a light weight material with nanosized pores, as a lighter, higher dielectric strength high voltage insulator as compared to those currently used. This investigation has involved simulations representative of silica aerogel subjected to electrical stress between electrodes of flat, curved and pointed configuration. The results of preparation of silica aerogel samples are also presented. The results suggest a more emphatic breakdown of the solid dielectric between nanopores than within the nanopores thereby suggesting progression of electrical trees. The pattern of the electric field distribution during discharge suggests that the combination of several nanopores in proximity behave like one apparent micropore encapsulating the space that they occupy. This diminishes the advantage of having nanosized pores as opposed to solitary micropores in a dielectric.

1. INTRODUCTION

Dielectric breakdown in insulation materials is usually initiated by localized partial discharge occurring within voids in insulators or at the conductor-insulator interface. Therefore, minimizing voids increases the dielectric strength of insulation material thereby enabling reduction of safety clearance. Silica aerogel has voids that have extremely fine pore sizes. Due to the nanosize of the pores and pore channels it can be postulated that silica aerogel should be an excellent high voltage insulation material.

2. PARTIAL DISCHARGE

A Partial Discharge (PD) is that which occurs within only a portion of an insulating material placed between two electrodes without bridging them [1].

Various researches have shown that voids within insulation material exacerbate the progress of electrical treeing in insulation which consequently causes geometric deformation of the void's inner surface, deposition of charge along it and therefore deterioration of the material. [1][2]

In addition to external factors such as applied voltage, the extent of PD activity within a cavity/void is also dependent on internal factors which include the size and shape of the cavity as well as the humidity level and initial pressure within the cavity. [1][3][5][6] For purposes of simplicity, the model applied for this contribution shall assume the shape of a nanopore as a spherical cavity.

2.1 Influence of cavity size

Research has shown that during discharge, the electric field in the cavity is nearly zero. However, it takes a shorter time for small cavities to recover their inception voltage and electric field such that the next PD activity is less delayed than in larger cavities. [4][5]. Consequently, for small cavities such as is the case with the nanopores in Silica Aerogel, there are more PDs per cycle though the maximum PD amplitudes are lower than is the case for larger cavities. Furthermore, since for a nanopore, there is a smaller propagation distance for formation of an avalanche than for cavities of larger diameter, its avalanche size is smaller resulting in lower PD magnitude than for the larger cavities. [4][5]

The electric field prior to PD is higher inside the cavity than in the surrounding solid dielectric because the latter has a higher relative permittivity. Also, the electric field is lowest on the cavity surfaces within the solid dielectric that are closest to the electrodes due to the higher concentration of charge at these areas considering that the electric field at these parts of the cavity surface is nearly perpendicular to it. [3]

3. SILICA AEROGEL

Aerogel has been characterized as being 90% air and 10% solid, mean pore diameter 20nm, primary particle size is 2 – 5 nm and dielectric constant of 1.1 – 2.2.

Silica Aerogel was first prepared in 1931 by Steven S. Kistler of the College of the Pacific in Stockton, California. Since then significant improvements have been made to Kistler's process by Nicholaon and Teichner, Brinker and Schertfeiger. More recent research developments have been focused on optimal production of silica aerogel with characteristics biased to suit a specific application.

In this contribution, the desirable characteristic was to minimize the pore size of the aerogel. Consequently, based on previous research, silica aerogel samples were prepared by applying the procedures known to provide the smallest pore size. The process that was adopted for this contribution is described in the next section.

3.1 Sample preparation

The initiating stage for preparation of silica aerogel is called a "Sol gel" process. This involves the formation of a gel from a solution consisting of a silica base undergoing acid or base catalyzed hydrolysis and condensation reactions. Acid catalysis produces aerogel of smaller pore size and therefore was the preferred approach for high voltage insulation [11].

In this study, the target was to produce silica aerogel of diameter 5cm and 4mm thick. Sol A was prepared by mixing solvents as follows;

7.62ml of TEOS, 23ml of absolute ethanol, 0.23ml of 1M Hydrochloric acid and 31ml of deionized water were mixed in a mold of 5cm diameter to form a Sol A. This was then placed in an oven at 40°C for 1 hour.

1.6ml of Ammonium Hydroxide, 1.5ml of TEOS and 2ml of absolute ethanol were then added to Sol A while stirring to form Sol B.

Sol B was then left in an oven at 40°C to attain gelation. A gel about 4mm thick and 5cm in diameter was formed after about 10 hours.

Figure 3.1: Silica gel

The next step was to increase the structural strength of the gel and also replace by way of diffusion the water and any other unreacted chemicals within the pores with ethanol. This is called "aging". Increasing the aging time increases the mechanical strength of the aerogel. Also, aging at room temperature enables formation of gels with a smaller average pore diameter [7]. Furthermore, aging the gel in a solvent of shorter alkyl chain produces aerogel of smaller pore size [9]. For this reason, ethanol would be the preferred solvent for aging of the gel for high voltage insulation. Therefore, to achieve this, 33ml of absolute ethanol were added to allow for aging at room temperature. This was done twice over a 24 hour period.

The gel at this stage has unreacted silanol groups along its surface that make the gel hydrophilic. In this state, allowing the gel to dry would cause collapse of the aerogel's skeletal structure due to surface tension as the pore liquid evaporates. [11] To avoid this, the silanol (Si-OH) groups had to be replaced with silyl ($Si\text{-}(CH_3)_3$) groups by using a silylating agent. The most commonly used silylating agent is Tetramethylchlorosilane (TMCS) [8]. TMCS is chemically unstable in ethanol and therefore a solvent exchange is necessary prior to its application to the gel for surface modification to occur [10]. Therefore, in preparation for drying, the residual ethanol within the pores was replaced by solvent exchange using diffusion whereby the gel was soaked in 33ml of n-Hexane. This was done twice in a 24 hour period.

The surface modification was carried out by soaking the gel in a solution comprising of 1ml of TMCS, 1ml of ethanol and 25ml of n-Hexane. This was done twice in a period of 48 hours. It was observed that using this approach to the sample preparation, it was a challenge maintaining the monolithicity of the gel up to the drying process. In a lot of attempts, the gel fragmented especially during the surface modification process leaving only pieces.

One of the products of surface modification is hydrochloric acid which if left within the pores can cause cracking of the gel during drying. Therefore it, as well as any other unreacted chemicals, needs to be extracted using diffusion prior to drying. By using a shorter chain inert solvent for this, the pore size of the gel is minimized. This justified n-Hexane as the preferred solvent for this purpose. Therefore, the gel was soaked in 33ml of n-Hexane. This was done twice in 24 hours.

The gel pieces were then left to dry at ambient temperature and pressure while covered. Significant volume shrinkage was observed. The thickness after 3 days was about 2.5mm indicating 37% shrinkage. Furthermore, although the pieces retained monolithicity, there was significant segmentation observed along the surface (Figure 3.2). The process thus described enabled the formation of silica aerogel by evaporation of the n-Hexane from the gel at ambient temperature and pressure. This is a method called "Ambient Pressure Drying". [8][9][10]

Figure 3.2: Silica Aerogel after drying

Ongoing research is focused on improving the process elaborated above so as to produce crack free monolithic aerogel with minimum possible pore size and thereafter dielectric testing.

4. PD ACTIVITY IN SILICA AEROGEL

For this study we have considered a hypothetical case of aerogel whose structure comprises of pores of diameter 20nm each of which is surrounded by primary particles of diameter 5nm hereafter referred to as the “solid dielectric”. This presents as an elemental area of aerogel that is 30nm thick and 30nm wide. It is also assumed that the pore is composed of air and therefore has a relative permittivity of 1 while the solid part has a relative permittivity of 2.2.

In this contribution, simulations were carried out for a 30nm thick elemental area of silica aerogel containing a single pore of diameter 20nm subjected to an electric field that would be produced by an applied voltage of 11kV on a 3mm thick sample of silica aerogel. The results are displayed below.

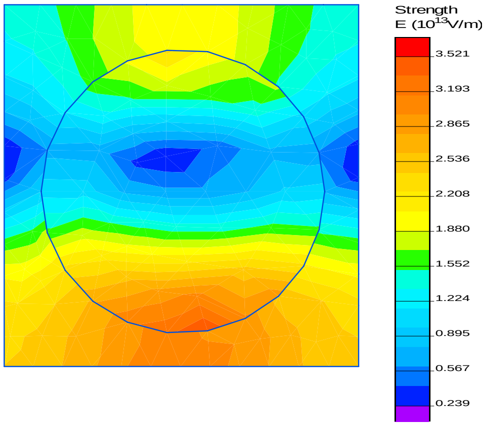


Figure 4: Electric field for a single isolated nanopore after Discharge

Due to PD, there is a dynamic movement of charge across the cavity and consequently, the electric field within the cavity is significantly reduced. This is because the accumulation of charge at the cavity surface creates an opposing electric field which reduces the electric field strength within the cavity. [3] Since more charge accumulates on the lower and upper surfaces than on the cavity wall that is quasi-parallel to the applied field, the electric field in the solid dielectric at the lower and upper surfaces is enhanced. However, notably the electric field in the nanopore does not “collapse” to nearly zero everywhere. This suggests that the streamer formed in a solitary nanosized cavity is unable to develop into a total discharge across the cavity.

The ABC model is considered to be more applicable than Pedersen’s model in describing PD in a solid dielectric with a cavity. [6] Based on the ABC model, for two closely coupled cavities in a solid dielectric, previous research has postulated that the occurrence of PD activity (i.e. breakdown) in one cavity causes transient overvoltage across the other cavity. This may in turn cause breakdown in the adjacent cavity thereby triggering a “knock on” effect such that repetitive partial discharges occur in the rest of the insulation material. The transient over voltages also stress neighboring parts of the solid dielectric greatly increasing the electric field strength. This ultimately causes breakdown of the entire dielectric material. [6] This model can be extended to investigation of PD activity in three or more cavities. [2]

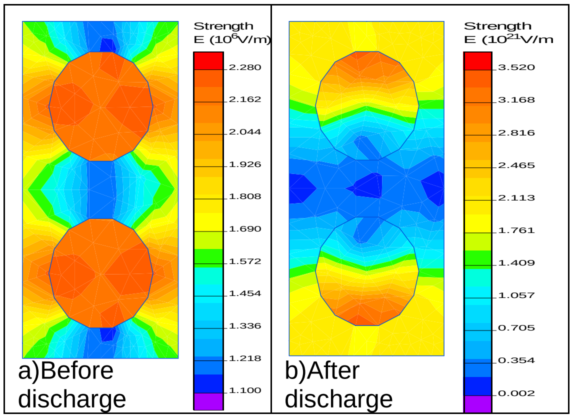
In this contribution, a simulation was carried out for a 60nm thick elemental area of silica aerogel comprising of 2 pores of diameter 20nm. This was considered to be part of a sample of 3mm thick aerogel subjected to an electric field due to an applied voltage of 11kV. The assumption is that the voltage profile varies uniformly from the top of the elemental area to the HV electrode.

The results are indicated below;

[NB: For all graphs, L –axis refers to heights measured from ground electrode (at the base of the solid dielectric below the lower nanopore) through the diameters of the pores to the HV electrode (over the solid dielectric above the upper nanopore). Therefore, 0-0.005µm – solid dielectric, 0.005-0.025µm – lower nanopore, 0.025-0.035µm- solid dielectric, 0.035 – 0.055µm – upper nanopore, 0.055-0.06µm – solid dielectric]

4.1 Aerogel between flat electrodes

A sample was simulated placed between a flat HV electrode (upper surface) and a flat ground electrode (lower surface). The results are displayed figure below.


a)Before discharge

b)After discharge

Figure 4.1-1: Electric field in Aerogel between flat electrodes before and after Discharge

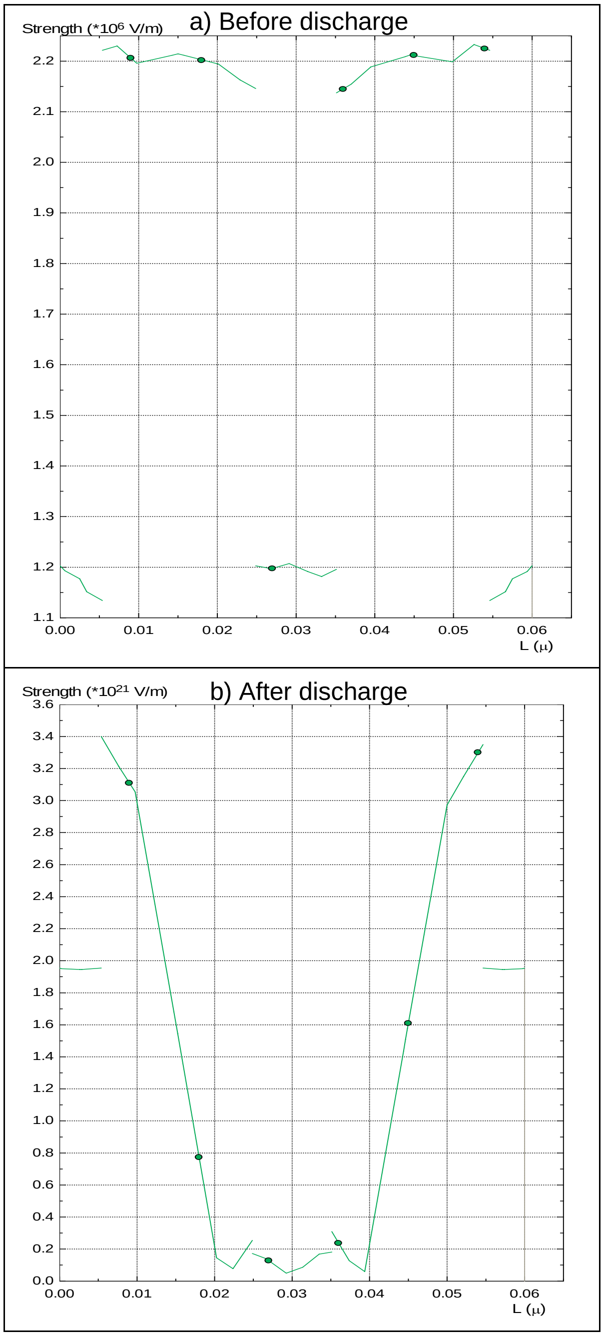


Figure 4.1-2: Electric field in Aerogel between flat electrodes before and after Discharge

From the shape of the "channel" of minimum electric field strength in the solid dielectric between the nanopores, it appears that the shape of the electrical tree as a result of breakdown is wide. This could be because the electric field radiating from a flat surface is fairly uniform. Consequently, a wide streamer shape is formed. This results in a wide breakdown channel through the solid dielectric.

4.2 Aerogel between flat & pointed electrodes

A sample was simulated placed between a pointed HV electrode and a flat ground electrode. The results are displayed below;

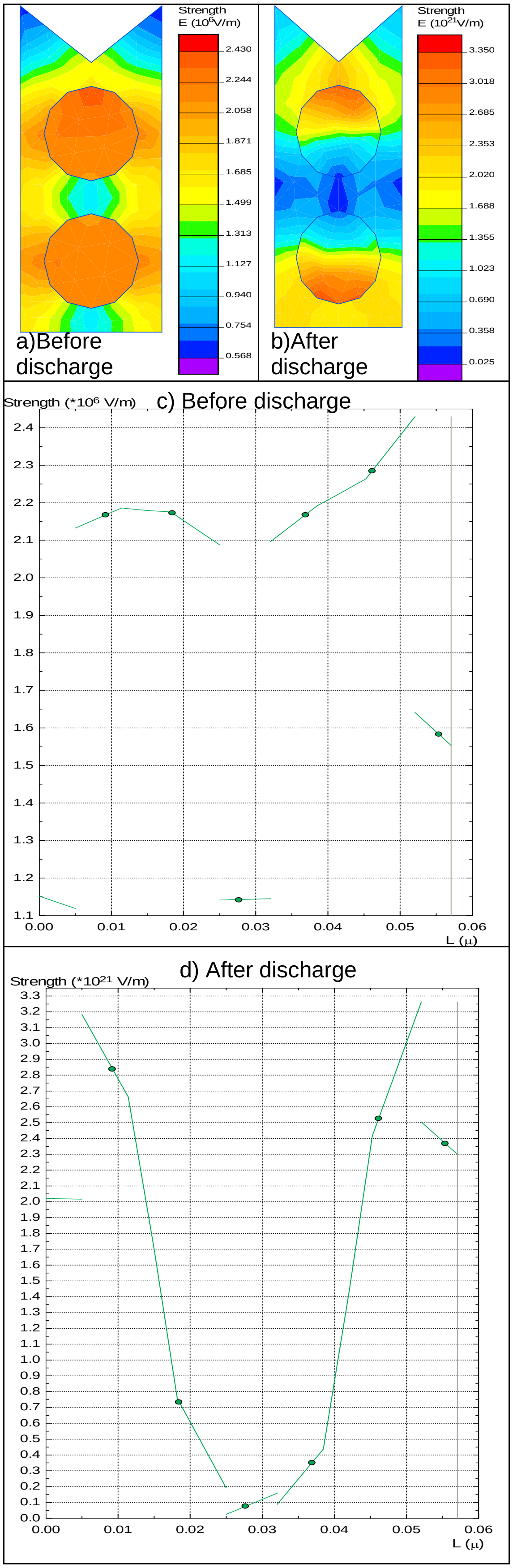


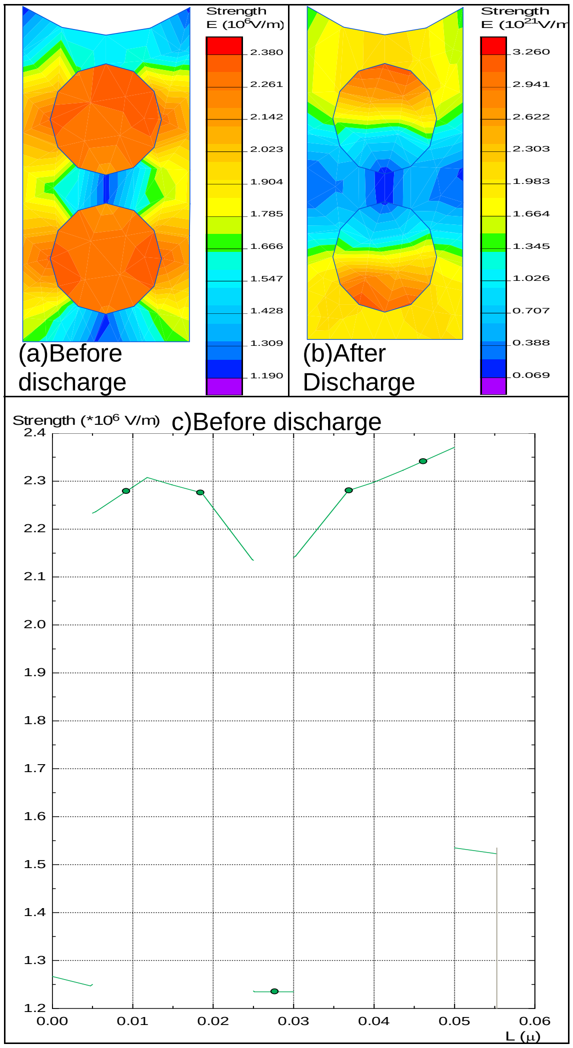
Figure 4.2: Electric field in Aerogel with pointed electrode before and after Discharge

From Figure 4.2(a) and (b), the appearance of the “channel” of minimum electric field strength in the solid dielectric between the nanopores suggests that the shape of the electrical tree as a result of breakdown is narrow. This could be because the electric field intensity is greater for pointed sources than those with a larger radius of curvature. This creates a more pointed streamer shape and consequently a narrower breakdown channel through the solid dielectric.

4.3 Aerogel between flat & curved electrodes

A sample was simulated placed between a pointed electrode and a flat one.

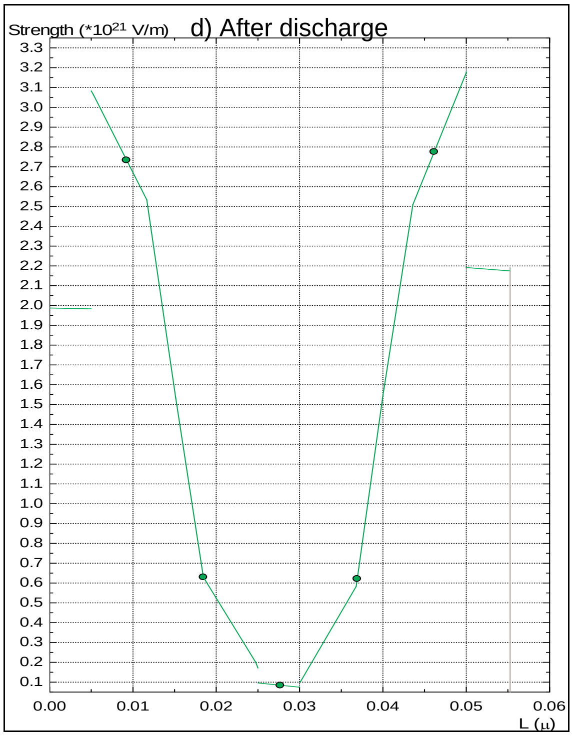
The results are displayed below;



(a)Before discharge

(b)After Discharge

c)Before discharge



d) After discharge

Figure 4.3: Electric field in Aerogel with curved electrode before and after Discharge

From Figure 4.3(a) and (b), the shape of the “channel” of minimum electric field strength in the solid dielectric between the nanopores suggests that the shape of the electrical tree as a result of breakdown is broad and uniformly directed. This could be because the electric field intensity is perpendicular to the wall of the nanopore at a broad surface area. Consequently, the broad shape of the streamer bombarding this area causes a broad breakdown channel through the solid dielectric.

5. DISCUSSION

The Figures 4.1-1(a) and 4.1-2(a), 4.2(a) and (c), 4.3(a) and (c) show the status of the electric field strength before discharge. It can be seen that there is a fairly uniform electric field strength pattern within the nanopores. This suggests that prior to discharge, within each nanopore, the electric field intensity is nearly the same. Furthermore, the electric field strength for both nanopores for all three electrode configurations seems to have nearly the same mean value. This suggests the possibility that the electric field in nanopore’s is enhanced by nearly the same factor regardless of their geometric location within aerogel. Consequently, the rate of streamer development and therefore partial discharge activity could be the same all over a sample. Therefore, as is the case for larger cavities, the diameter of the nanopore is likely to be a more dominant factor than its geometric location within the sample in determining the size of the streamer.

Figures 4.1-2(a) and (b), 4.2(c) and (d), 4.3(c) and (d), show the electric field strength after discharge activity. On these, a sudden "collapse" of the electric field is displayed from the centre of one nanopore to another. It appears that electrical breakdown occurs linking one nanopore to the other. The region of near zero electric field strength also seems to broaden. This implies that, there could be rapid lateral progression of electrical trees in the solid dielectric.

Figure 4 shows the electric field distribution for a single nanopore in isolation undergoing discharge. Comparing this with Figures 4.1-1(b), 4.2(b) and 4.3(b), shows a similarity in the electric field pattern which suggests that after discharge, the combination of both nanopores acts as an apparent single pore encircling both nanopores that is undergoing discharge. This suggests that a new apparent charge is formed that is a conglomerate of that which was in the nanopores before discharge and is therefore higher in amplitude. This increases the possibility of occurrence of partial discharge event of larger amplitude though fewer per cycle for an applied AC voltage. Based on previous researchers, this is a typical behavioral pattern for larger cavities. [3] Therefore, the net effect could be the progressive disintegration of nanopores to form new cavities of larger diameter until puncture of the material occurs.

Figures 4.1-1(b), 4.2(b) and 4.3(b) indicate that during discharge, the electric field is enhanced within the upper nanopore on the side closest to the HV electrode and within the lower nanopore on the side closest to the ground electrode. This suggests that the nanopores appear as oppositely charged capacitances. It is also noticeable that the near zero electric field between the nanopores has a similitude to that in a conductor. This tends to digress from the ABC model that assumes the solid dielectric around a cavity as a capacitance.

6. CONCLUSION

The results of simulations in this contribution indicate that due to nanopores being in close proximity to each other, the occurrence of partial discharge enables a rapid progression of electrical treeing. The shape of the electrodes will only serve to modify the shape of the tree. Therefore, there is likely to be fast deterioration of silica aerogel when subjected to electrical stress. Nonetheless, it is not clear from the simulations how maximizing the extent of cross linking in the aerogel structure and thereby minimizing the pore size could increase the electrical stress limits.

Ongoing research on this is focused on preparing an aerogel sample that satisfies this requirement while maintaining its monolithicity and thereafter carrying out the appropriate electrical tests. Possibly, this shall provide clearer insight to establish limits within which silica aerogel can be applied to high voltage insulation applications. Progress in this regard shall be presented in future contributions.

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