

The Role of various types of plasma treatments to improve and enhance the various insulation and dielectric properties of the materials-A Review

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Abstract: *Enhancing the insulation and dielectric properties may be regarded as one of the major research topics that can be undertaken for study and analysis. When any insulating material is exposed to extreme weather conditions, the degradation of such insulating materials is a very common phenomenon due to variations in temperatures, external weather extremities, wind, dust, and many other naturally occurring phenomena. Thus, the protection of insulating materials has become a vital area of study for researchers and scholars to enhance the lifespan, insulation, and dielectric properties and also to prevent the degradation of such insulating materials due to extreme weather conditions when exposed to an open environment. The various withstanding properties of the materials like breakdown strength, flashover voltage, contact angle, thermal conductivity and various dielectric properties are being studied in this paper. Also, the applications of various non-thermal plasma treatments generated by using various discharge methods like Dielectric Barrier Discharge (DBD), Corona discharge, Microwave discharge and Radiofrequency discharges and the effects of those non-thermal plasma treatments in improving and enhancing the insulation and dielectric properties of the insulators have been extensively studied and reviewed.*

Keywords: Non-Thermal Plasma (NTP); Dielectric Barrier Discharge (DBD); Atmospheric Pressure Plasma (APP); Aramid Fiber Reinforced Epoxy Composites (AFRC); Low Density Polyethylene (LDPE) Nanocomposites; Atmospheric Pressure Plasma Jet (APPJ) treatment; High temperature vulcanized (HTV) Silicon Rubber Composites; Polyethylene Terephthalate (PET); Polydimethylsiloxane (PDMS).

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1. Introduction

Non-thermal plasma (NTP) is a state of matter that consists of charged particles such as electrons, ions, and neutral molecules, which have significantly different temperatures. In a traditional thermal plasma, all the particles are in thermal equilibrium, which means they have similar kinetic energies and temperatures. However, in a non-thermal plasma, the electrons are at a much higher temperature than the heavier particles (ions and neutrals). This difference in temperature between electrons and ions/molecules is the phenomenon that characterizes non-thermal plasmas. Typically, the electrons are at a high energy state, while the ions and neutral particles remain at room temperature. This leads to a situation where the overall temperature of the plasma is not in thermal equilibrium.

Due to their special and unique characteristics and wide range of applications in

various fields, ranging from material science and surface treatment to medicine and environmental protection, the application of Non-Thermal Plasma (NTP) can be used for enhancing the insulation and dielectric properties of outdoor insulators which is exposed to varying harsh weather conditions. Non-thermal plasma is generated and produced by creating a partially ionized gas containing a mixture of charged particles (electrons and ions) and neutral molecules. This unique state of matter (i.e., the plasma state) is achieved by applying energy to a gas, causing some of its atoms or molecules to become ionized (i.e., the loss or gain of electrons). There are several methods to generate Non-Thermal Plasma some of them are Dielectric Barrier Discharge (DBD), corona discharge, Microwave, and Radio Frequency (RF) discharges. The production of non-thermal plasma (NTP) also involves the development of a plasma generation system.

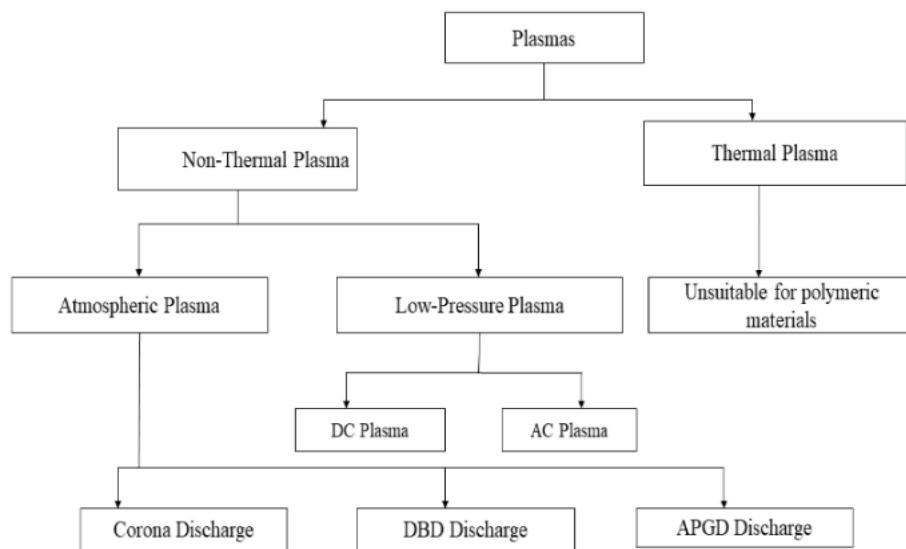


Figure 1: Classification of Plasmas based on various properties.

2. Plasma Treatments to Improve Insulation Properties

2.1 Breakdown Strength

The breakdown voltage of an insulator refers to the maximum electric field that an insulating material can withstand before it begins to conduct electricity. It is the voltage above which the insulator starts losing its properties and starts behaving like a conductor. The breakdown voltage is an important electrical phenomenon specially in the case of materials selection during high voltage applications where the insulation is the key component to prevent accidental currents and to maintain the safety of the workforce involved in the process.

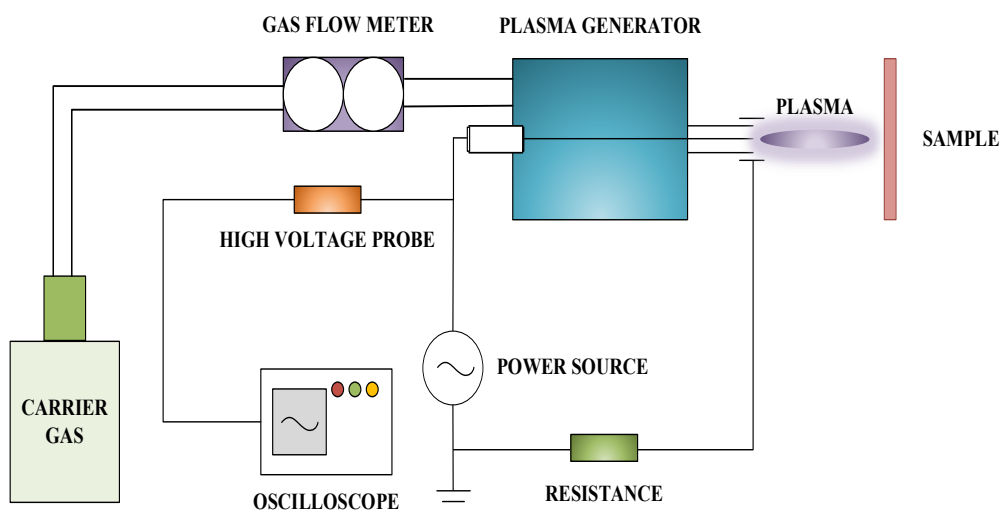


Figure 2: Generalized Plasma generating setup

Studies were conducted to understand the implementation of the plasma treatment on various base materials to enhance the breakdown strength of the insulator. In the experimental work performed by B. X. Du *et al.* [1], on GIS (Gas Insulated Substation) switchgear insulation, the insulation rod had to bear a high electric field and large mechanical

loads, and due to this reason, proper insulation of the outer surface is a much-needed step that is to be achieved and taken care off during the manufacturing process. The insulation rod comprises fiber-reinforced epoxy composites, primarily classified into glass fiber and aramid fiber-reinforced insulation rods.

The main disadvantage of aramid fiber is its high crystalline properties. Due to this property's presence, the aramid fiber's surface becomes chemically inert, making it difficult for the polymer matrix to react with the base surface material. To overcome the shortcomings caused due to chemical inertness and to improve the interaction and bonding property between the outer surface of the aramid fiber and the polymer matrix appropriate Dielectric Barrier Discharge (DBD) plasma treatment is applied. After the DBD plasma treatment, it has been found that there is a significant enhancement in interfacial bonding properties between the fiber and the polymer matrix.

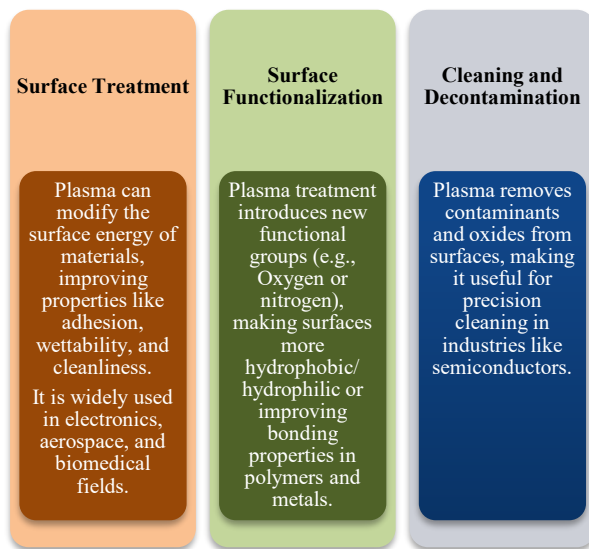


Figure 3: Various applications of Plasma treatment on the external surface.

Also, there is a significant enhancement in the breakdown strength that is the breakdown strength increases from 29.2 to 32.6 KV/mm, and shear strength is increased from 29.38 to 58.93 Mpa. The improvement in both breakdown strength and shear strength directly improves the dielectric and mechanical properties of Aramid Fiber Reinforced Epoxy Composites (AFRC).

The effect of Atmospheric Pressure Plasma (APP) treatment has been studied by N. M. Saman *et al.* [2], A. Yudhana *et al.* [3] and R. F. Kurnia *et al.* [4]. Silicon dioxide nanoparticles are the base material used to improve and enhance the partial discharge and breakdown strength characteristics of low-density polyethylene (LDPE) nanocomposites. The partial discharge resistance and breakdown strength characteristics increased to 70 in the unfilled samples, as the SiO₂ nanoparticles were treated using the application of atmospheric pressure plasma (APP). In another experimental analysis conducted by Y. Mi *et al.* [5], the main objective is

to improve and enhance the breakdown strength and thermal conductivity of Boron Nitride and epoxy resin nanosheets. The accumulation of Boron Nitride Nanosheets (BNNS) can significantly reduce the AC breakdown strength of the composites. The improvement of the AC breakdown strength can be done by Atmospheric pressure bipolar nanosecond pulse dielectric barrier discharge (Ar+H₂O) low-temperature plasma to introduce hydroxyl group to Boron Nitride epoxy resin nanosheets to improve the AC breakdown strength as well as the thermal conductivity of the composites.

In the experiment performed by Z. Li *et al.* [6] the setup used to improve the breakdown mechanism of IGBT (Insulated Gate Bipolar Transistor) was conducted by using a Metal-based printed wiring board (MB-PWB). Due to the repetitive partial discharge phenomenon, the insulation breaks down and simultaneously the breakdown strength becomes lower when there is a high content of micro-fillers. The addition of the nano-micro-composite increases both the breakdown strength and partial discharge resistance as compared to that of the micro-composite that is the addition of the nano-fillers to the existing micro-composite material provides an excellent approach that can increase the dielectric breakdown strength and partial discharge properties. The addition of micro-Al₂O₃ fillers increases the thermal conductivity of epoxy composites which is considered to be one of the major advantages, whereas the addition of micro fillers/micro-composites is regarded as one of the major disadvantages since they lower the breakdown strength as studied by Z. Li *et al.* [6].

Studies also have been made to enhance and improve the AC breakdown strength of transformer oil by using the applications of nanofluids, through the application of the Atmospheric Pressure Plasma (APP) treatment to treat the SiO₂ nanoparticles to enhance the AC breakdown strength of nanofluids by using Helium gas as discharge working gas [7]. The Atmospheric Pressure Plasma (APP) treatment is used to modify the nanosilica surface [7] to enhance the interaction with the base material and thus enhance and improve the insulation properties.

In the experimental work performed by I. H. Zakaria *et al.* [8], the surface of the silica nanoparticles was treated using atmospheric pressure plasma (APP) discharge in order to enhance interfacial interaction. From the experimental work, it has been found that the plasma-treated nanoparticles possess strong interaction properties with the liquid molecules. The same phenomenon was also observed in other literature [5, 6, 9]. It has also been observed in another literature [8] that the

AC breakdown voltage of the oil is also enhanced after treating the oil with Atmospheric Pressure Plasma (APP). The enhanced breakdown voltage of the oil has a wide range of applications for increasing the dielectric strength as well as the efficiency and performance of the transformers.

Table 1: For Untreated Nanofluid (UNF) samples at different concentration of SiO₂

Percentage Concentration of SiO ₂ in the untreated Nanofluid sample	Percentage enhancement of breakdown voltage strength.
0.1 weight % of SiO ₂ untreated Nanofluid sample	21.90%
0.5 weight % of SiO ₂ untreated Nanofluid sample	8.43%
0.01 weight % of SiO ₂ untreated Nanofluid sample	8.10%

The addition of the silica nanoparticles enhances the AC breakdown voltage of the mineral oil used in the transformer significantly. The untreated Nanofluid (UNF) samples and plasma-treated Nanofluid samples (PTNF) samples are studied and analyzed for different concentrations of silica nanoparticles traces added as an additive to enhance the AC breakdown strength. Through Weibull's analysis, the AC breakdown voltage estimation can be done for the mineral oil significantly in the experimental work conducted by I. H. Zakaria *et al.* [8].

Table 2: For Plasma Treated Nanofluid (PTNF) samples at different concentration of SiO₂

Percentage Concentration of SiO ₂ in the plasma treated Nanofluid sample	Percentage enhancement of breakdown voltage strength
0.1 weight % of SiO ₂ plasma treated nanofluid sample	45.45%
0.5 weight % of SiO ₂ plasma treated nanofluid sample	40.94%
0.01 weight % of SiO ₂ plasma treated nanofluid sample	25.25%

The plasma treatment on SiO₂/LDPE nanocomposite samples for 15 minutes, increases the AC breakdown voltage. The comparison between the existing and improved breakdown strength for 5 different samples is shown in Table 3 below:-

Table 3: Comparison table for AC breakdown strength of SiO₂ nanoparticles

Samples	Existing AC Breakdown Strength	Improved AC Breakdown Strength	Percentage weight of SiO ₂ added
Sample-1	155.47 KV/mm	167.80 KV/mm	1 weight %
Sample-2	155.47 KV/mm	168.99 KV/mm	3 weight %
Sample-3	155.47 KV/mm	173.65 KV/mm	5 weight %
Sample-4	155.47 KV/mm	174.70 KV/mm	7 weight %
Sample-5	155.47 KV/mm	176.44 KV/mm	9 weight %

The addition of 1 weight %, 3 weight %, and 5 weight % of untreated and treated Nano silica results in the increment of the AC breakdown strength. The AC breakdown strength of pure LDPE samples are 160.15 KV/mm, 159.78 KV/mm, and 170.71 KV/mm, whereas, after the plasma treatment, the AC breakdown strength increases up to 173.01 KV/mm, 174.70 KV/mm and 176.44 KV/mm respectively.

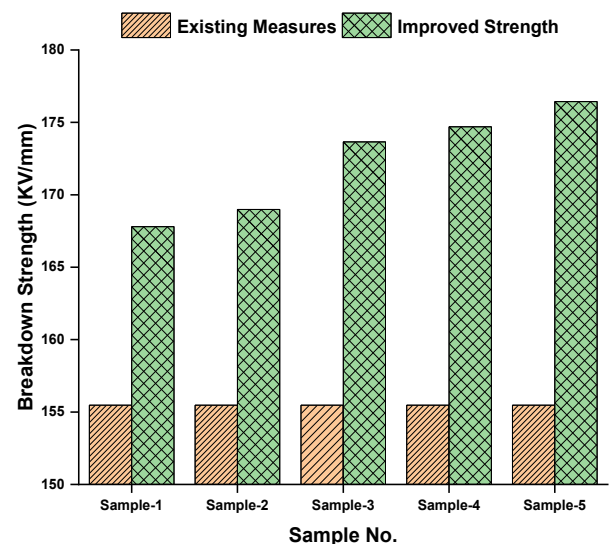


Figure 4: Representation of existing and improved AC breakdown strength of various samples for SiO₂ nanoparticles.

2.2 Flashover Voltage

The flashover voltage refers to the minimum voltage required for dielectric breakdown across the surface of the insulator which results in disruptive discharge or arc. The phenomenon of flashover voltage is of utmost importance for ensuring the reliability and safety of the overall power system. During flashover voltage, the insulation materials fail and allow a spark on electric discharge to jump across the surface of the insulator.

In the study conducted by T. Shao *et al.* [10], it has been observed that the flashover voltage increases with the increase in the plasma treatment when the plasma treatment is being applied for a specific time period, but it has also been found that as soon as the plasma treatment time increases to 5 minutes and 10 minutes, the flashover voltage decreases significantly. The experimental study by T. Shao *et al.* [10] also explored the relation between the flashover voltage and the corona charging voltage that is the flashover voltage decreases with the increase in corona charging voltage.

Table 4: Flashover voltage comparison for untreated samples with corona charging voltage applied

Existing flashover voltage	Decreased flashover voltage	Applied charging voltage	Time of charging voltage applied
11.9 KV	10.1 KV	7 KV	1 Minute

Table 5: Flashover voltage for plasma-treated samples with corona charging voltage applied

Existing flashover voltage	Decreased flashover voltage	Applied charging voltage	Time of charging voltage applied
13.7 KV	10.8 KV	7 KV	1 Minute

The phenomenon of surface charge has a major impact on the flashover which is demonstrated and proved by the experiments performed by T. Shao *et al.* [10] and Y. A. N. Jiyuan *et al.* [11]. The layer of epoxy resin is deposited through different methods of plasma treatment. The flashover voltage phenomenon is measured with and without surface charges. It has been concluded that with the exposure of the sample to the plasma treatment the peak value of the surface charge of the sample decreases. The phenomenon of flashover voltage is closely related to the amount of surface charges. The surface charge with the same polarity of flashover discharge can reduce the surface flashover voltage.

The improvement of the surface flashover voltage in a vacuum is demonstrated by the experiment performed by T. Shao *et al.* [10] and S. Li *et al.* [12]. Hydrophilic surface modification is done using the application of a non-thermal argon plasma jet to improve the surface flashover performance in a vacuum. The argon plasma jet is employed which is being driven by a microsecond duration pulsed generator, having a voltage range of 0-30 KV and a rise time of 300 ns. It has been concluded that the flashover voltage increases with

the reduction of applied pulse duration, and the lowest flashover voltage occurs at 50/60 hertz power frequency [13].

The plasma treatment on Al₂O₃ Epoxy Resin samples for the enhancement of the surface flashover voltage using both Silicon and Fluorination decomposition was studied by Y. A. N. Jiyuan *et al.* [11] and was carried out by the following methods:

- Dielectric Barrier Discharge fluorination (DBD-F)
- Dielectric Barrier Discharge Silicon deposition (DBD-Si).
- Atmospheric Pressure Plasma Jet Fluorination (APPJ-F).
- Atmospheric Pressure Plasma Jet Silicon (APPJ-Si).

The increment of the surface flashover of the DBD-F sample is the largest (that is increased by 21.2% at most), whereas the APPJ-F sample has the worst increment in the flashover voltage.

When the plasma treatment is applied for a short period of time, the increment in the flashover voltage is ranked as:

$$\text{DBD-F} > \text{APPJ-Si} > \text{DBD-Si} > \text{APPJ-F}$$

On the other hand, when the plasma treatment is applied for a comparatively longer period of time, the increment in the flashover voltage is ranked as:

$$\text{DBD-F} > \text{DBD-Si} > \text{APPJ-F} > \text{APPJ-Si}$$

The implementation of Atmospheric pressure DBD is used to treat the Polymethyl Methacrylate (PMMA) surface to improve the surface flashover strength is performed by T. Shao *et al.* [14]. The increment of the surface resistance of the treated PMMA is consistent with the improvement of the surface flashover performance. The surface resistance of untreated PMMA is about 5.72×10^{13} ohms, whereas the surface resistances of plasma-treated PMMA samples are 1.88×10^{14} ohms and 2.63×10^{14} ohms respectively. With the increment in the surface flashover voltage, performance also enhances significantly.

The treatment of the Low-Density Poly Ethylene (LDPE) surface in the ozone atmosphere for various time durations (0 h, 1 h, 2 h, 4 h, and 6 h) for enhancing the surface flashover voltage was studied and analyzed by Y. Nie *et al.* [15]. The surface flashover voltage when the LDPE sample is treated for 4 hours with ozone is treated by 25.59% as compared to the untreated LDPE samples.

The DC flashover voltage of silicon rubber

can be improved by DBD plasma treatment under ambient atmospheric air was studied by H. Guan *et al.* [16]. It is found from the analysis that on the application of DBD plasma treatment, the DC surface flashover voltage starts increasing at the beginning and then starts decreasing with the increased time of the plasma treatment. The reduction of the surface flashover voltage with the increased time of plasma treatment results in the increased mobility of the charge carriers on the sample surface.

Table 6: Flashover voltage comparison of untreated and treated Silicon Rubber specimens

Types of Silicon Rubber Samples	Time Duration of DBD Plasma treatment	Flashover Voltage (Increasing/Decreasing) Remarks
Untreated Silicon Rubber specimen sample	Untreated	17.26 KV
DBD Plasma treated Silicon Rubber specimen sample	180 Seconds	20.4KV (Increased Flashover Voltage)
DBD Plasma treated Silicon Rubber sample	300 Seconds	18.76KV (Decreased Flashover Voltage)

From the above table and comparison, we can conclude that the surface flashover voltage is increased at the beginning and then keeps on decreasing when the DBD plasma treatment time on Silicon Rubber is increased.

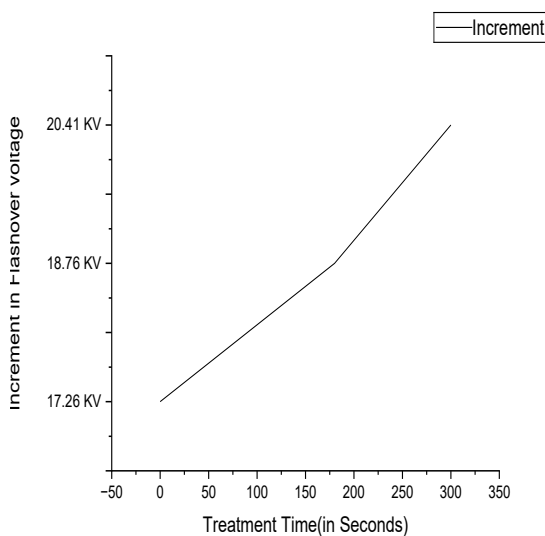


Figure 5: Flashover Voltage Comparison Curve of Treated and Untreated Silicon Rubber Samples

The study of the enhancement of the surface flashover voltage of Epoxy Resin with nano Aluminium Nitride (AlN) treated by DBD plasma treatment in open air/vacuum is studied by X. Chen

et al. [17].

In the case of 1st sample of Epoxy Resin, the flashover voltage of the untreated epoxy resin sample is found to be 11.23 KV, and with the increase in the treatment time to 4 minutes the surface flashover voltage increases to 14.91 KV that is there is an increment of 32.77% of the plasma treated samples along with the increase in the treatment time. Whereas, in the case of 2nd sample, the flashover voltage of the untreated epoxy resin sample is 14.64 KV, and with the increase in the treatment time to 4 minutes, the surface flashover voltage increases to 16.55 KV, that is there is an increment of 13% of the plasma treated samples along with the increase in the treatment time.

X.-L. Sun *et al.* [18] studied the effect of “micro holes” on the surface flashover properties of a disc-type vacuum insulator under the condition of high pulsed voltages. The main aim of the study was to enhance and improve the insulation reliability and performance of the insulators. The study also concluded that the width and depth of the micro holes enhance the flashover properties of the insulators.

The gas pressure also significantly impacts the surface flashover voltage [19]. The gas adsorption phenomenon improves the surface flashover voltage by enhancing the process of electron collision in compressed gas.

Table 7: Flashover voltage comparison of treated and untreated Epoxy Resin samples

Samples	Flashover voltage of untreated Epoxy Resin sample	Increased Flashover voltage of Epoxy Resin sample after treatment	Treatment time	Percentage increase in the Flashover voltage
1 st Sample	11.23 KV	14.91 KV	4 Minutes	32.77%
2 nd Sample	14.64 KV	16.55 KV	4 Minutes	13%

The surface flashover and its dependency on different solid insulators in atmospheric air and in high vacuum using DC, AC, and microsecond lightning pulse voltages have been further studied [13, 20-31]. The material properties of solid insulators, the shape, and composition of electrodes (Stainless Steel, Copper, Aluminium, etc.); along with background pressure, and the impact of those electrodes on flashover voltage have been studied in these papers.

The surface flashover characteristics are being carried out by using nanosecond pulses of 10 ns rise time and 30 ns at full width at half maximum [30, 32-37]. The insulator dielectrics chosen for the experiment are Teflon, PMMA (Poly Methyl Methacrylate), and Nylon and the tested factors include:-

- Gas pressure.
- Cone angle of the conical frustum.
- Materials and shape of electrodes.
- Contact style between insulators and electrodes.

From the experiments conducted by T. Shao *et al.* [14] for the investigation of various materials (Teflon, PMMA, and Nylon) of surface flashover using nanosecond pulses, and it is experimentally concluded that for the cylindrical shape of the insulator, the flashover voltage non-linearly with an increase in axial length/diameter of insulator. However, in the case of electrode materials, none of the materials has an appreciable effect on flashover voltage under the experimental conditions. It is also concluded from the study that the flashover occurs at the rising edge of applied nanosecond pulses.

2.2 Contact Angle

The contact angle in the case of insulators is defined as the angle formed between the liquid droplet and the surface of the insulators at the point where the droplet meets the surface. It actually demonstrates the interaction of the liquid with the surface of the insulator. Based on the interaction of the contact angle with the outer surface of the insulators, the insulator surface is classified as:- (A)Hydrophilic surface and (B) Hydrophobic surface. The contact angle less than 90° indicates a hydrophilic surface that is the liquid spreads well on the surface. On the other hand, a contact angle greater than 90° indicates a hydrophobic surface, which indicates that the liquid beads up and does not spread well on the surface of the outdoor insulators.

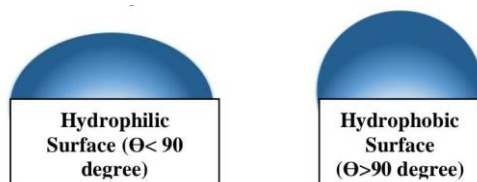


Figure 6: Surface with varying water contact angle

The experiment for hydrophobic surface modification on the surface of Epoxy Resin was performed by Z. Fang *et al.* [38] and they concluded that the hydrophobic behavior of a surface and its properties can be improved by using an Atmospheric Pressure Plasma Jet (APPJ) in Ar/Trimethyl Silane. The surface properties of the treated Epoxy Resin

before and after treatment with APPJ are studied and analyzed using contact angle measurement, Scanning Electron Spectroscopy (SEM), and Fourier Transform Infrared Spectroscopy. It has been found that the surface after APPJ treatment shows a remarkable increase in water contact angle and the surface hydrophobicity property is improved to a greater extent. The maximum contact angle is thereby obtained when the APPJ treatment is applied for a time period of 300 seconds and Ar/Trimethyl silane content is 0.04%. The water contact angle increases from 46° to 95° , thus enhancing the surface hydrophobicity properties.

The effect of non-thermal plasma treatment generated by dielectric barrier discharge (DBD) on the material's surface was studied by Z. Fang *et al.* [39]. The non-thermal plasma thus generated results in the enhancement of the surface hydrophobicity which leads to better insulation performance. The parameters thus considered for enhancement of surface hydrophobicity are based on contact angle and surface resistance measurement and verified by wet flashover test. The improvement in the hydrophobicity property depends on the DBD voltage and the time it takes for the APPJ plasma treatment to be applied to the surface. The improvement of the water contact angle on the glass surface is enhanced by using the plasma treatment as studied and analyzed by Z. Fang *et al.* [39]. Experimentally it was found that with the increase in the plasma treatment time and the plasma treatment voltage, the water contact angle reaches the maximum of 121° when a voltage of 10KV is applied for a time period of 11 minutes. From the experiments thus conducted, it has also been observed that with the further increase in the treatment time (that is above 11 minutes), there occurs a small decrease in the contact angle.

The Atmospheric Pressure Plasma Jet (APPJ) treatment for decreasing the water contact angle and for enhancing the surface hydrophilicity on the surface of the Polyethylene Terephthalate (PET) was studied by Z. Fang *et al.*[40] After applying the APPJ treatment on the PET surface for a time duration of 10 seconds, the water contact angle on the PET surface decreases to 39.5° , 42.4° , and 50° respectively, whereas the surface energy increases to 50.1, 59.8 and 63.4 mJ/m^2 for the treatment distances of 10, 20 and 30 mm respectively. It has also been found from the experiment that with the increase in the time period of APPJ treatment to 15 seconds, the water contact angle of the PET surface decreases to 46° , 38.2° , and 34.8° respectively, whereas the surface energy increases to 55, 64.2, and 68.3 mJ/m^2 . From the experimental results, the minimum value of the water contact angle is 25° , which is obtained at a treatment distance of 10 mm and a treatment time

period of 10 seconds respectively. The decrease in the water contact angle to a minimum 25° from the experiments thus conducted implies the enhancement in the hydrophilicity properties of the APPJ-treated PET samples.

The hydrophobicity property improvement of contaminated High-Temperature Vulcanization (HTV) silicon rubber is of great significance in avoiding the phenomenon of flashover when exposed to wettability conditions [41-45]. The low-temperature plasma jet produced from dielectric barrier discharge enhances and improves the hydrophobicity property of contaminated HTV surfaces. Silicone Rubber plays a vital role in avoiding the risk of flashover during its contact with water when exposed to external weather extremities. In the experimental investigation performed, the low-temperature plasma jet produced by DBD under atmospheric pressure was used to increase the hydrophobicity properties of the contaminated HTV surface. The untreated HTV Silicon Rubber has a maximum contact angle of 40° , but the plasma jet treatment on the outer surface of the Silicon Rubber samples greatly enhanced the contact angle and thus enhanced the hydrophobicity properties. When the plasma treatment time is increased from 30 seconds to 2 minutes. The water contact angle of the treated area varies between 90° to 110° , thus improving the hydrophobicity properties of the HTV Silicon Rubber surface.

The effect of the plasma jet treatment in enhancing the hydrophobicity properties was studied by S. Li *et al.* [45], in which the introduction of LMW (Low Molecular Weight) siloxanes to enhance the hydrophobicity properties after treating the Silicon Rubber samples with suitable plasma jet treatment was studied. From the study, it has been concluded that with the increase in the plasma treatment time, the water contact angle also increases, thus enhancing the hydrophobicity properties. The contact angle increased up to 120° after undergoing the plasma treatment for 10 seconds. Consequently, the water contact angle was found to be 102° and 110° for treatment time of 20 seconds and 30 seconds respectively. The hydrophobicity properties of the contaminated Silicon Rubber composites cannot be enhanced by the plasma treatment. But with the addition of Low Molecular Weight (LMW) siloxanes, the enhancement in the hydrophobicity properties by the plasma treatment can be induced.

Atmospheric pressure non-thermal plasma has been proven to be an efficient tool for surface modification of polymers [46-49]. The experiment to enhance the surface hydrophilicity property of polyethylene terephthalate using APPJ treatment was studied by Z. Fang *et al.* [41]. The surface

properties of Polyethylene Terephthalate are analyzed before and after the APPJ treatment. The parameters taken into account before and after APPJ treatment include the water contact angle and surface energy measurement. It is concluded from the experiment that the water contact angle and the surface energy measurement. It is concluded from the experiment that the water contact angle decreases with the increase of APPJ treatment time and the surface energy increases with the increase of treatment time and both of them reach a specific saturated value at a certain treatment time. The surface hydrophilicity can also be improved by including the oxygen-containing polar groups. The increase in hydrophilicity property provides a good bonding even at low temperatures due to the presence of hydroxyl groups [51].

2.4 Flame Resistance

The flame resistance of insulators refers to the ability of the material to resist catching and spreading of flames when exposed to high temperatures or direct flame. This property is crucial in various applications where electrical safety, fire prevention, and thermal protection are essential, such as in the protection scheme of buildings, electrical systems equipment, and industrial equipment.

The most common flame-resistant insulating materials are considered to be: (1) Ceramic insulators, (2) Silicone rubber, (3) Fiberglass, (4) Polyimide films, (5) PVC, (6) Phosphorus based polymers.

The plasma-treated nanoparticles possess a strong interaction with the liquid molecules. The same phenomenon is observed in some literature [51-53]. The application of low-frequency plasma treatment is applied to the polyester fabrics at low temperatures ($<50^\circ\text{C}$) [54]. It has been found that the application of low-frequency oxygen plasma treatment on polyester fabrics improves the hydrophilic properties. An increase in LOI (Limiting Oxygen Index) percentage, whereas there is a sharp reduction in the flame-retardant concentration to 50 g/liter in the padding system. The measurement of hydrophilicity improvement properties of polymer fabrics is determined with an increase in LOI% values, surface roughness properties determined by Scanning Electron Microscopy (SEM) analysis and an enhancement in the hydroxyl group after the oxygen plasma treatment.

The properties like LOI, flame retardancy, electrical breakdown, mechanical and surface hydrophobicity enhancement of polydimethyl siloxane-based silicon rubber filled with Aluminium Trihydroxide (ATH), Milled Glass Fires (MGF),

and Graphene Nanoplatelets (GNP) filled Silicon Rubber (SR) composites in solely ATH filled SR could be one of the major approaches for attaining suitable LOI and flame retardancy property without disturbing the electrical breakdown voltage.

The flame retardancy property enhancement of firewood is studied by F. Sohbatazadeh *et al.* [52]. Surface modification using various non-thermal atmospheric plasma sources has also been investigated [55-57] and this technology is widely used. However, the application of wood is not that widespread due to its low flame retardancy and low thermal resistance properties. The flame retardancy property of wood can be enhanced upon surface modifications [58] as well as to control its wettability. The cost-effective and eco-friendly approach for the production of thin films to enhance flame-retardant properties is explained and performed in the studies [58]. The coating is prepared through halogen-free plasma polymerization using a novel version of DBD. The treatment results in the static contact angle of firewood surfaces increasing to 137.73°, thus making it more hydrophobic, also it enhances the surface roughness from 57.3 pm to 22.5 nm, and a significant reduction in the maximum rate of thermal decomposition that is from 0.94 to 0.65 mg/minute.

The flame-retardant technique includes various flame-retardant coatings such as UV curving, plasma coating, vapour deposition, and sol-gel technique, etc. [53]. With the enhancement of the research in the field of flame-retardant technology, the use of halogenated compounds in various coatings to achieve flame retardancy is replaced by various other FR systems like the addition of inorganic additives to enhance the flame retardancy property, use of phosphorus and silicon-based deposits and coatings to enhance the FR properties. The use of elements like Phosphorus, Nitrogen, Sulphur, Silicon, etc. ensures a superior flame-retardancy property and low smoke-emission characteristics without causing any damage to the surrounding environment.

The flame-retardant property using the novel-plasma-based method in Polyethylene Terephthalate (PET) fabric surface was studied by T. Zhou *et al.* [59] combined with pad dry cure treatment finishing. The non-thermal plasma can graft Maleic acid onto a PET polymer backbone, which can activate PET fiber and provide an excellent flame-retardant capacity in PET fiber. The novel-plasma-treated surface samples of PET showed the maximum LOI value of 29.3 possessing excellent property of thermal stability and flame-retardant properties.

Flexible Polyurethane Foams (FPUF) are

widely used in the manufacture of furniture, carpets, automobiles, etc., as it possesses high thermal insulation, low bulk density, and superior chemical-resistant properties. The FPUFs are extremely ignitable and possess a very low ignition temperature, and upon burning they release a large amount of combustion heat accompanied by plenty of smoke and toxic gases upon ignition, thus imposing a potential threat to the lives and environment as a whole. The surface coating strategy can enhance the flame retardancy properties without compromising the mechanical properties. The various strategies used and implemented for surface modifications for achieving the flame-retardant properties include in-situ deposition, Sol-gel process, plasma technique and layer-by-layer assembling.

Plasma treatment enhances flame-retardant properties. It is an eco-friendly method for depositing a layer of flame-retardant coatings on various substrates [60, 61]. The plasma treatment technique is also employed to deposit a thin layer of nano-coatings on the surface of the substrate, enhancing the flame-retardant properties of the applied surface.

The enhancement of the flame-retardant properties of Flexible Polyurethane Foams (FPUFs) using Plasma Induced Graft Polymerization (PIGP) techniques of phosphonates was studied by M. Jimenez *et al.* [62]. In the experiment performed, Diethyl Vinyl phosphate (DEVp) is used as a precursor with or without using the cross-linking agent (1,4-Butanedioldiacrylate). The coating applied on the surface of the DEVp precursor prevents it from dripping during the burning test and enhances and promotes the flame-retardant properties. The experimental studies also proved that the non-reacted liquid form of DEVp samples does not react in a condensed phase when exposed to external environmental conditions, resulting in the enhancement of flame-retardant properties. The DEVp precursor samples, after rinsing with covalently grafted phosphorus-containing species, result in the formation of phosphonic acid, which limits the spread of the flame and enhances the flame-retardant properties.

In the experimental work done by A. R. Horrocks *et al.* [63], the ability of a novel Maximum Likelihood Sequence equalizer (MLSE) technology to provide an acceptable level of durability to enhance the flame-retardant properties has been applied. From the experiment performed, it has been inferred that the enhancement of flame-retardant properties, when applied simply by a pad-dry process, is non-durable, but it is extraordinarily durable when exposed and subjected to 3 minutes, 150°C treatment and then tested under water soaking

treatment.

2.5 Thermal Conductivity

The ability of any material to conduct heat through it is called Thermal Conductivity. Phonons and various other factors mainly influence the thermal conductivity of the insulators influence it, including their material composition, density, temperature, and structural properties. Insulators with low thermal conductivity values are critical and play a major role in minimizing heat transfer, promoting energy efficiency, and protecting sensitive components.

The factors affecting the thermal conductivities in insulators are:

- a) Material Composition
- b) Density
- c) Porosity and Air Content
- d) Moisture Content
- e) Temperature dependence
- f) Crystal structure and Lattice configuration.

Based on the thermal conductivity values the various materials are broadly classified as conductors or insulators. The thermal conductivity properties greatly affect any material's conductivity and insulating properties. The broad classification is explained below:

- (1) Materials with high thermal conductivity are considered to be good conductors (e.g., Silver, Copper, Gold, Aluminium, Brass, Steel, Iron). These metals are very good conductors of heat and are often used in applications where efficient heat transfer is needed such as heat sinks, cooking utensils, and electronics components.
- (2) Materials with moderate thermal conductivity are considered to be comparatively moderate conductors (e.g., Graphite, Concrete, Glass, Marble). These materials have moderate thermal conductivity and are used in construction where some level of heat transfer is acceptable/desirable, such as in building walls or flooring.
- (3) Materials with low thermal conductivity are considered to be good insulators (e.g., Wood, Water, Polystyrene Foams, Fiber glass, Mineral wool). These materials are widely used in thermal insulation, particularly in buildings, refrigeration & other applications requiring thermal resistance.
- (4) Materials with extremely low thermal conductivity are considered to be the best insulators (e.g., Air, Argon, Aerogel, vacuum).

These materials provide excellent thermal insulation and are often used in specialized applications such as double-pane windows (Argon), Space equipment (Aerogels), and vacuum flasks (vacuum insulation).

The thermal conductivity increases with the increase in the filling content of Boron Nitride Nanosheets (BNNS) as experimentally stated and proved by Y. Mi *et al.* [5]. Along with the increase in the BNNS filling content from 10% (Silane Coupling Agent treated) to 20% (Silane Coupling Agent and Plasma treated), the thermal conductivity increases by 67%.

In the experiment conducted by J. Yu *et al.* [64] for the enhancement of the thermal conductivity of the plasma, sprayed $\text{Sm}_2\text{Zr}_2\text{O}_7$ (abbreviated as SZ) powder coatings and 8% Y_2O_3 stabilized Zirconia (8YSZ) coatings are analyzed and investigated. It has been found from the experiment that the external heat treatment enhanced the thermal conductivity of SZ and 8YSZ coatings significantly. Even after the treatment, it has also been concluded that the SZ coatings contributed to lower thermal conductivity as compared with 8YSZ coatings.

In another experiment conducted by C.-R. Yang *et al.* [65], the surface of Aluminium Nitride (AlN) / Polydimethylsiloxane (PDMS) powder is treated with the Atmospheric Pressure Plasma (APP) treatment to modify the surface and also to enhance the value of Thermal Conductivity. The APP-treated sample of AlN/PDMS has a better thermal conductivity as compared to that of the untreated samples. From the experiment performed in the sample of AlN, it is found that the APPJ-treated sample has 1.60 times (for AlN) and 1.48 times (for PDMS) higher value of thermal conductivity as compared to that of the untreated AlN/PDMS samples.

In the experimental work performed by J. You *et al.* [66], the thermal conductivity and enhancement procedure of metal heat sinks have been studied. The heat sink is used for temperature control by transferring or dissipating heat to the outer environment, thus protecting the device's thermal resistance [67, 68]. Using metal heat sinks is challenging because of their weight and less processable characteristics [69]. To overcome this issue, heat sinks composed of polymers and thermally conductive fillers have been developed and implemented due to their various advantageous characteristics, lightweight and low cost of production [70-74]. Carbon materials with improved thermal conductivity are used as fillers to manufacture polymer composites for heat sinks [75-79]. The thermal conductivity of the polymer composites used for the manufacture of heat sinks

has been achieved by using mechano-chemical bonding techniques with plasma treatment. The components, namely Polyamide-66 (PA66) and Graphite Nanoplatelets (GNP) are mixed together by the process. After the mechano-chemical bonding techniques with plasma treatment, the internal interaction between PA66 and GNP is enhanced greatly, thus enhancing the thermal conductivity properties of the heat sink. Therefore, through this approach, high-performance and low-cost heat sinks are developed.

The thermal conductivity and the removal of the generated heat during the operation pose a great challenge that effectively influences the performance and the lifetime of devices [80, 81]. In order to avoid such damage to the microelectronic devices caused due to thermal conductivity, silicon rubber consisting of polymeric materials is used in the field of packaging, leading to various superior features such as stability, good electrical insulation, and high resistance implemented [82]. In another experiment performed by Y. Ouyang *et al.* [83], the enhancement of the thermal conductivity property of silicon rubber composites by plasma treatment has been studied. The traditional polymer composites used for the manufacture of silicon rubber show comparatively unsatisfactory enhancement due to poor dispersion and weak interfacial adhesion, which results in high interfacial resistance. Thus, for the improvement of thermal conductivity, the Al_2O_3 nanospheres manufactured by using high-frequency thermal plasma are used as a filler which in turn enhances the thermal conductivity of silicon rubber composites. The thermal conductivity of silicon rubber after the high-frequency thermal plasma treatment enhances by 6.65% as compared to that of the untreated silicon rubber samples.

Y. Mo *et al.* [84] studied the enhancement of the thermal conductivity of the insulating paper used in transformer insulation. The introduction of the low-temperature plasma-treated Kevlar pulp and Nano-Cellulose fibrils (NCF) results in good mechanical properties and better thermal stability. From the experiment, it can be concluded that the composite material (Kevlar Pulp, NCF, and softwood pulp) used in the preparation of insulating paper improves the thermal and insulation properties and it can be used as the insulating material in case of high voltage AC transformer insulation.

3. Discussion and Conclusion

3.1 Breakdown Strength

With the application of DBD Plasma treatment on aramid fibers and Atmospheric Pressure Plasma treatment (APP) on LDPE nanocomposites, the breakdown strength gets enhanced. With the

increase in the nanoparticle fillers concentration, the breakdown strength also gets enhanced. However, with the addition of microfillers, the breakdown strength decreases but if the microfillers are incorporated with the nanofillers, the breakdown strength is enhanced. The variation of the AC breakdown of the material is enhanced if the material is added with SiO_2 nanoparticles. With the simultaneous increase in the weight percentage of SiO_2 added, the breakdown strength also improves simultaneously.

3.2 Flashover Voltage

The flashover voltage phenomenon increases with the increase in the plasma treatment for a specific time duration but after a certain time duration, the flashover voltage starts to decrease significantly. Hence, the application of the plasma treatment on the specific base materials should be controlled with time in order to maintain the flashover voltage within a specific range. From the overall review, it has also been found that with the increase in the corona charging voltage, the flashover voltage decreases significantly. Therefore, for a better protection against flashover voltage phenomenon, the corona charging voltage must be controlled experimentally. From the review, it has also been found that the application of the non-thermal Argon plasma jet for a specific period of time also enhances the flashover voltage, i.e., we can conclude that the non-thermal plasma treatment enhances and improves the flashover voltage phenomenon of the insulators if it is applied for a certain specific time duration. With the increase in the exposed time duration of Non-Thermal Plasma on the surface of the base material, the flashover voltage starts degrading. So, for a better and improved flashover voltage protection of the material, the exposure time of the non-thermal plasma should be controlled from the user-end for the proper enhancement of protection against the flashover voltage.

3.3 Contact Angle

The application of Atmospheric Pressure Plasma Jet (APPJ) treatment in the Argon/Trimethyl Silane samples remarkably enhances and improves the hydrophobicity properties. The outcomes and the improvement in the water contact angle can be studied and analyzed using Scanning Electron Microscopy (SEM) and FTIR analysis. The water contact angle can also be enhanced if the base material is glass by the application of the Non-Thermal Plasma treatment for a specific time duration. The plasma jet treatment also enhances the hydrophobicity of the HTV silicon rubber samples. The water contact angle increases with the increase in the plasma treatment time on the HTV Silicon Rubber surface. The introduction of low molecular

weight (LMW) siloxanes acts as a catalyst to enhance the hydrophobicity and water contact angle of HTV silicon rubber samples. The water contact angle therefore increases with the increase in the plasma treatment time. From the overall review study, we can conclude that the APPJ treatment has been proven to be a better tool for enhancing the hydrophobic properties and water contact angle on the polymeric surface.

3.4 Flame Resistance

The materials like ceramic insulators, silicone rubber, fiber glass, polyimide fibers, PVC, and phosphorus-based polymers are the most common flame-resistant insulating materials. The application of the low-frequency oxygen plasma treatment on polyester fabrics as the base material results in a significant increase in the Level of Oxygen (LOI) percentage, whereas there is a sharp reduction in the flame-retardant concentration of the system. The addition of the various fillers in the base material results in the significant enhancement of LOI and flame-retardant values by the addition of the hydroxyl group to the base materials. The flame retardancy of the firewood can also be enhanced by using the applications of various non-thermal atmospheric plasma sources. The use of the halogenated coatings of phosphorus, nitrogen, sulphur, and silicon also enhances the flame retardancy property and results in low smoke emission characteristics without causing any damage to the surrounding environment. The novel plasma-based method also enhances the flame retardancy properties in Polyethylene Terephthalate (PET) by improving the LOI level. The NTP treatment techniques deposit a thin layer of nano-coatings on the surface of the substrate, which results in the enhancement of the flame-retardant properties on the applied surface. The introduction of the application of the phosphorus coatings on the surface of the Diethyl Vinyl Phosphate (DEVP) results in the enhancement of the flame-retardant properties. The MLSE (Maximum Likelihood Sequence Estimation) Equalizer technology also provides an acceptable level of durability to enhance the flame-retardant properties when the required sample is exposed for a time duration of 3 minutes under the temperature of 150°C.

3.5 Thermal Conductivity

The materials with high thermal conductivity are considered to be the best insulators. With the addition of the filling content, such as Boron Nitride Nanosheets (BNNS) the thermal conductivity increases by 67%. The addition of the plasma-sprayed $\text{Sm}_2\text{Zr}_2\text{O}_3$ (abbreviated as SZ) and 8% of Y_2O_3 stabilized Zirconia enhances the thermal conductivities significantly. The application of

Atmospheric Pressure Plasma (APP) treatment on the surface of Aluminium Nitride (AlN) or Polydimethyl Siloxane (PDMS) also enhances the thermal conductivity by 1.60 times (for AlN) and 1.48 times (for PDMS), respectively. The mechanochemical bonding techniques implemented by plasma treatment enhance the internal interaction between Polyamide-66 (PA66) and Graphite Nanoplatelets (GNP), enhancing the thermal conductivity properties of the insulators. The Al_2O_3 nanospheres manufactured by high-frequency thermal plasma are used as a filler in the Silicon Rubber composites in order to enhance the thermal conductivity of the Silicon Rubber samples. The addition of the high-frequency plasma treatment enhances the thermal conductivity property by 6.65% as compared to that of the untreated Silicon Rubber samples. Also, the thermal conductivity of the insulating paper used in transformer insulation can be enhanced by using composite materials like (Kevlar Pulp, NCF, and softwood pulp), and it can be used as the insulating materials in case of high voltage AC transformer insulation.

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