International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
Vol. 55 No. 1 January 2026, pp. 270-276

Enhancing Hydrophilicity of 100% Cotton Fabric Using Negative Corona Plasma: Correlation Study between Energy Dose and Gap Distance Optimality

Herli Darliawati[1], Zaenul Muhlisin[1,2*], Fajar Arianto[1,2]

1. Department of Physics, Faculty of Science and Mathematics, Universitas Diponegoro, Semarang, Indonesia.
2. Center for Plasma Research, Faculty of Science and Mathematics, Universitas Diponegoro, Semarang, Indonesia.

Corresponding author : Zaenul Muhlisin, muhlisin@lecturer.undip.ac.id

Abstract: This study investigates the characterization and optimization of surface treatment for 100% cotton fabric using a wire-plane Dielectric Barrier Discharge (DBD) system operated with Negative Corona DC voltage. The primary objective was to determine the optimal electrical and geometric parameters for enhancing surface hydrophilicity without damaging the material. The methodology involved systematic Current-Voltage (I-V) characterization to identify stable discharge modes and subsequent plasma irradiation of cotton samples at varying time intervals and gap distances. Results indicated that the system successfully transitioned from a spark discharge to a stable non-thermal DBD mode at larger gap distances (greater than or equal to 3.9 cm) due to the dominance of gas gap impedance. Functionally, the plasma treatment significantly improved wettability, reducing water absorption time by over 60% through the functionalization of polar groups on the cellulose surface. The efficiency of activation was governed by the cumulative energy dose, with 30 minutes identified as the optimum irradiation time. Furthermore, a gap distance of 4.5 cm yielded slightly superior absorption times compared to 3.9 cm, implying that gap geometry influences the chemical composition of reactive plasma species. These findings offer a controlled protocol for sustainable textile finishing.

Keywords: Negative Corona DC treatment, Cotton fabric, Hydrophilicity, Surface modification, Sustainable textiles.

1. Introduction

In response to global market demands for sustainable functional materials, the textile industry is at the forefront of innovation, striving to develop materials with superior performance without relying on traditional wet chemical processes that are energy-intensive and generate significant waste [1], [2]. 100% cotton fabric, as the most widely used natural fiber, inherently possesses good mechanical properties but often requires surface functionality enhancement, such as increased water absorption (hydrophilicity), for technical applications like medical textiles and filters [3].

In the context of dry processing, non-thermal plasma technology has emerged as a revolutionary and environmentally friendly method [4]. This technology allows for precise surface modification at the molecular level without affecting the bulk properties of the material, making it an ideal solution for textile functionalization [5], [6]. Negative Corona Glow Discharge operated at atmospheric pressure, particularly in the Dielectric Barrier Discharge (DBD) configuration, is a major trend in industrial applications [4], [7]. The key characteristic of this discharge is its ability to produce high concentrations of Reactive Plasma Species (PRS)—such as free radicals, ions, and electrons—at low gas temperatures (near room temperature) [8]. This property enables high-energy

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species to activate the material surface through etching (cleaning hydrophobic contaminants) and grafting (attaching polar functional groups such as hydroxyl and carboxyl) onto the cotton cellulose polymer chains [9].

The increase in polar group density directly correlates with increased surface energy and a significant improvement in wetting speed and water absorption, a crucial functional parameter [10], [11]. The relevance of this technology is reinforced by industrial reports indicating that plasma treatment can reduce water consumption by up to 80% compared to conventional finishing processes [6]. However, the application of Negative Corona technology, especially in asymmetric wire-plane configurations operated with DC voltage sources, faces fundamental and technical challenges. The primary challenge lies in controlling discharge stability at atmospheric pressure. In highly non-uniform electric fields, corona discharges are prone to rapid transitions into destructive sparks that can damage textile materials [12].

Operational stability relies heavily on determining the correct Breakdown Voltage (V_b), which is a complex function of the gap distance (d). Additionally, there is the issue of geometric optimization: how varying gap distances affect electrical discharge characteristics (I-V curves) and, more importantly, how such variations alter the chemical composition of PRS reaching the fabric surface. The greatest challenge is ensuring the Energy Dose (D) absorbed by the fabric is accurately measured and controlled to avoid under-treatment or over-treatment [13].

To address this knowledge gap, this study aims to characterize and optimize a DC Negative Corona system in a wire-plane configuration. Specifically, the objectives are: (1) to systematically characterize the reactor's I-V behavior for various gap distances; (2) to optimize treatment parameters by finding the combination of gap distance and irradiation time that yields the most optimum hydrophilicity increase; and (3) to analyze the correlation between discharge stability and functional efficiency.

2. Material and Methods

2.1. Materials and Reactor Design

This study was designed to investigate changes in the characteristics of 100% pure cotton fabric treated using corona plasma radiation. The material used was 100% pure cotton fabric that had not undergone a washing process, cut to a standard size of 12×10 cm².

The plasma reactor utilized a wire-plane electrode configuration. The wire electrode consisted of 9 horizontal lines made of stainless steel string number 2 with a diameter of 0.38 mm, spaced 1.3 cm apart with a length of 12 cm. This diameter was selected to facilitate the enhancement of local electric field intensity crucial for corona initiation. A mica sheet (16×16 cm²) was used as an insulator and electrode holder to dampen discharges and prevent sparking. The plane electrode served as the counter electrode.

2.2. Instrumentation

A high-voltage DC source (0-30 kV) was used to generate plasma. Voltage measurements were facilitated by an HV Probe (DC max 40 kV, Code EC 1010, EnG1010) connected to a WENS 700S Digital Multimeter. Current was measured using a SANWA Analog Multimeter type YX-380R.

2.3. Experimental Procedure

The research was conducted in two phases:

1. **Characterization:** The I-V characteristics were determined by varying the gap distance (d) from 1.8 cm to 4.5 cm. For this phase, the wire electrode was given negative polarity (Cathode) and the plane electrode acted as the Anode to determine the best corona range.
2. **Irradiation:** Cotton fabric was placed on the plane electrode. For fabric treatment, positive polarity was used: the wire acted as the Anode (+) and the plane as the Cathode (-). The current was maintained in the range of 100-150 mA, with

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voltage between 10-15 kV. Gap distances were fixed at 3.9 cm and 4.5 cm. Irradiation times varied from 0 (control), 5, 10, 15, 20, 25, to 30 minutes.

2.4. Testing

The final stage involved testing the water absorption of the treated textiles using a drop test. A 2 mL buret was used with a distance of 1 cm between the fabric and the buret tip, and a droplet size of 1 mm. The water absorption time was measured after a delay of 2 minutes post-irradiation.

3. Results and Discussion

3.1. Electrical Characterization

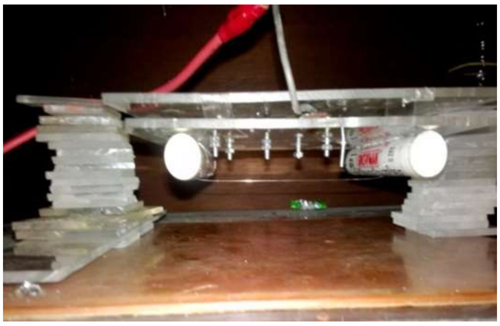

Figure 1. Wire-plane electrode

The study began with the characterization of the asymmetric wire-plane electrode configuration. Figure 1 illustrates the setup. The Current-Voltage (I-V) characteristics measured without a dielectric barrier confirmed the classical DC gas discharge mechanism. As shown in Figure 2, the I-V curve exhibits three distinct behavior zones: a leakage current zone at low voltage (< 6 kV), followed by a Negative Corona Discharge zone where current increases non-linearly, and finally a Spark Breakdown zone.

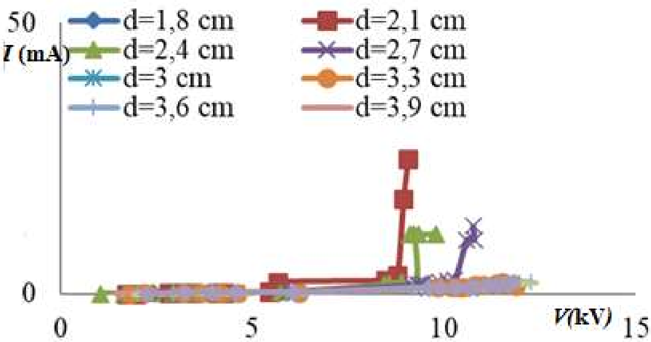

Figure 2. Current characterization as a function of voltage without fabric

A critical phenomenon observed is the significant dependence of the breakdown voltage (V_b) on the gap distance (d). generally, V_b increases with d. For instance, $V_b \approx 8.5$ kV at $d = 2.1$ cm and increases to $V_b \approx 11.5$ kV at $d = 3.3$ cm. This increase is a direct consequence of gas breakdown theory dominated by the Streamer Mechanism. At larger gap distances ($d = 3.6$ cm and 3.9 cm), full spark discharge did not occur up to the measurement limit of 13 kV, confirming that increased gap distance proportionally increases gas gap resistance [14].

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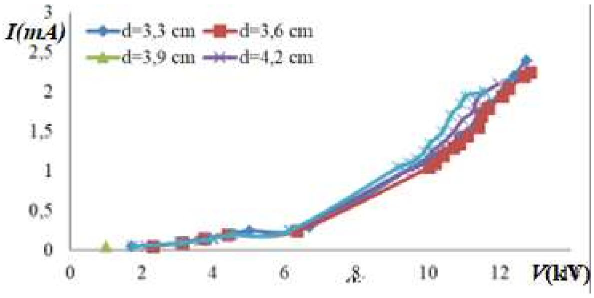

Figure 3. Current characterization as a function of voltage with fabric

The addition of the dielectric fabric layer to the plane electrode fundamentally changed the system's operation mode from free corona to Dielectric Barrier Discharge (DBD). As seen in Figure 3, for gap distances $d = 3.3$ cm to 4.2 cm, the vertical current spikes indicating full breakdown were absent. The fabric acts as a capacitive barrier; accumulated surface charges create a reverse electric field that self-terminates micro-discharges, preventing the transition to a destructive spark channel [15].

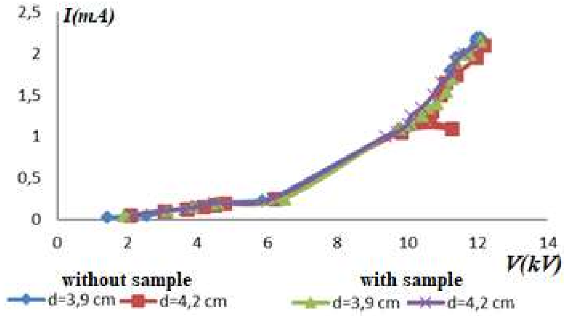

Figure 4. Comparison curve of I-V characteristics with sample fabric

Figure 4 compares the characteristics with and without fabric. The results indicate that at large gap distances ($d \geq 3.9$ cm), the gas gap impedance (Z_{gas}) dominates the total system impedance. Consequently, the presence of the fabric does not drastically alter the current magnitude but functions primarily to stabilize the discharge. This stability at larger gaps ensures the discharge remains in a stable DBD (Glow-like) mode, which is ideal for uniform surface activation.

3.2. Hydrophilicity Optimization

The success of the plasma treatment was assessed via the drop test. Figure 5 shows the relationship between irradiation time and water absorption time. Data indicates a clear inverse relationship between plasma irradiation time (t) and water absorption time. Untreated fabric exhibited a long initial absorption time (≈ 6.3 seconds), reflecting the presence of hydrophobic contaminants.

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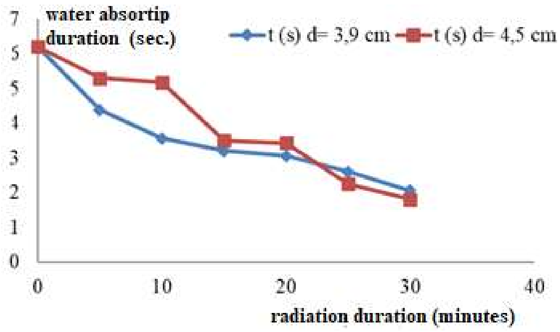

Figure 5. Relationship curve between irradiation time (minutes) and water absorption time (seconds) on cotton fabric

Plasma treatment significantly reduced this absorption time, indicating the effective removal of impurities and the introduction of hydrophilic functional groups [20]. The enhancement of hydrophilicity is a direct result of surface functionalization, involving the ablation of contaminants and the implantation of polar groups (-OH, -COOH) by Reactive Plasma Species [16], [17].

Two phases were observed:

1. **Rapid Improvement Phase (0-10 minutes):** Absorption time decreased sharply as the energy dose created new polar groups.
2. **Saturation Phase (20+ minutes):** The rate of decrease slowed as the number of active sites on the surface reached saturation. Excessive treatment can lead to degradation [9], [23].

The optimum irradiation time was achieved at 30 minutes for both gap distances. The optimum absorption time achieved was 1.81 seconds at $d = 4.5$ cm and 2.06 seconds at $d = 3.9$ cm. Despite similar average plasma power, the minor difference suggests that the 4.5 cm gap produced a slightly more effective chemical composition of Reactive Plasma Species, likely due to more favorable diffusion and recombination processes in the wider gas zone [18].

4. Conclusion

This study successfully characterized and optimized a wire-plane Dielectric Barrier Discharge (DBD) system operated with Negative Corona DC voltage for cotton fabric modification. Electrically, the system demonstrated a transition from a destructive spark mode at narrow gaps to a stable non-thermal mode at large gap distances ($d \geq 3.9$ cm). This stability is achieved because the gas gap impedance becomes the dominant current-limiting factor. Functionally, plasma treatment proved highly effective in increasing the hydrophilicity of 100% cotton fabric, evidenced by a significant reduction in water absorption time (over 60%). The quality of activation was controlled by the cumulative Energy Dose, with 30 minutes being the optimum time. The minor optimality achieved at a gap distance of 4.5 cm implies that discharge geometry influences the chemical composition of Reactive Plasma Species, leading to slightly superior surface functionalization efficiency.

Acknowledgment

The authors acknowledge the Center for Plasma Research, FSM Universitas Diponegoro, for supervising the prototyping, irradiation, and wet testing processes.

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