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Research Paper

Study of Rotating and Jet Plasma Treatments on Surface Wettability of Glass

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Abstract. This work investigates the wettability properties of a glass surfaces by using atmospheric pressure cold plasma systems. Treatments were performed by using a rotating-head unit and a jet-type torch during the plazma treatments. The nozzle-to-surface distance (8–15 mm) and the feed rate (50–400 mm/s) were modifying. The untreated glass showed limited wetting, with average water and ethylene glycol contact angles (WCA and EGCA) of 64.7° ± 1.8° and 45.2° ± 1.5°, respectively. After plasma treatment, both systems showed clear improvements, although their efficiency profiles were different. Using the rotating plasma head at 8 mm and 100 mm/s speeds, the WCA decreased to 9.3° ± 0.8°, indicating almost complete wetting. Jet plasma achieved similar results (WCA = 14.1° ± 1.2°), but slightly less uniformly. Changes in wettability were closely related to the exposure time determined by the feed rate: slower movement increased activation, while overexposure occasionally resulted in small thermally induced surface marks that were visible under an optical microscope. As the results showed the rotating plasma reached more homogeneous activation, while the jet system provided stronger local effects at a lower energy input. Based on these results the atmospheric plasma is effective in increasing the surface energy. Rotating systems appear to be advantageous for large, flat areas, while jet plasma is better suited for localized surface modification aimed at improving adhesion or coating performance.

Keywords: Glass, Surface Treatment, Cold Plasma, Wettability.

Introduction

The surface properties mainly determine how materials interact with coatings or adhesives in material science. Glass is widely used in optics, electronics, and architecture, but its surface is chemically inert and often contaminated, so adhesion and coating performance are limited. Atmospheric pressure cold plasma (APCP) offers a practical alternative for wetting or for chemical cleaning. It activates only the external nanolayers of the material, introduces polar oxygen-containing groups, and removes weakly bound contaminants. The result is increased surface energy and improved wettability without the use of chemicals or heating. Two plasma configurations are commonly used: rotating head and jet-type systems. Rotating plasma provides uniform activation over wide areas, while jet plasma provides stronger, localized effects. These two methods are compared in this study, focused on their effects on glass wettability. Contact angles of water and ethylene glycol were measured at different nozzle distances and feed rates to determine how plasma geometry and energy input affect surface activation and to support process optimization for bonding and coating applications.

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1. Literature Review

1.1. Atmospheric Pressure Cold Plasma Surface Treatment

Atmospheric pressure cold plasma (APCP) has become a very practical technique for surface activation on a variety of materials, including metals, polymers, ceramics, and glass, as it operates at ambient pressure. APCP contains a rich mixture of energetic electrons and reactive species (O, O_3, OH, N_2^+, etc.) that result in surface cleaning, oxidation/hydroxylation, and increased surface energy without significant heating of the bulk substrate [1]. Several studies confirm that APCP can significantly reduce water contact angles and increase surface free energy, allowing for better wetting and adhesion [2]. During APCP treatment, factors such as gas composition, discharge power, nozzle-to-surface distance, and treatment time are critical. These determine the flux of radicals, UV photons, and ions reaching the surface, and thus the magnitude of chemical and morphological changes [3]. Typical activation mechanism step by step: removal of weak boundary layers (adsorbed hydrocarbons, contaminants), formation of hydroxyl or oxide functional groups that increase the polar component of the surface energy, and micro- and nanoscale roughening that increases the effective contact area and promotes Wenzel-type wetting. APCP-treated surfaces transition from a hydrophobic to a hydrophilic state, often with contact angles reduced below 20° or even to single-digit degrees [4]. The industrial appeal of APCP lies in its solvent-free, low substrate damage, environmentally friendly, inline-compatible processing [5].

1.2. Two Main Configurations: Rotating-Head vs. Jet (Puncture-Type) Plasma Systems

Atmospheric plasma systems are generally classified into two main categories based on discharge geometry and energy delivery: (i) rotating head (diffuse) systems and (ii) jet or puncture-type systems. Each offers different advantages and limitations for surface treatment. In a rotating head plasma system, the electrode or nozzle assembly rotates, creating a sweeping, uniform plasma front across the substrate. This wide treatment width and stable discharge distribution ideal for the fabrication of large flat surfaces such as glass panels. The homogeneity of surface activation is a significant advantage, and the risk of local overheating is moderate due to the lower energy density per unit area. However, the disadvantage is that the local energy density is relatively lower, so treatment times or closer nozzle positions may be required to achieve equivalent surface activation compared to jet systems.

Inversely, a jet plasma system generates a narrow, high-intensity plasma torch with concentrated reactive species flux. This prepare deeper activation of micro-regions, smaller spot treatments or high precision. The higher local energy density often leads to more effective surface cleaning and activization. The downside is that the narrower beam width requires multiple passes for full coverage, and the risk of substrate damage or over-oxidation is higher if parameters aren't carefully controlled.

Comparative research [6] show that for glass surfaces, the point-nozzle (jet) plasma achieved stronger cleaning and wettability improvements than the rotating nozzle under similar conditions: the contamination removal and surface tension increase were markedly better with the jet system. This

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reinforces the notion that choosing the right plasma geometry is key depending on the substrate, coverage requirement, and process speed.

1.3. Plasma Activation of Glass Surfaces: Mechanisms and Applications

Glass — commonly SiO_2-based or borosilicate — is widely used in architecture, optics, electronics and automobiles. Its surface, however, tends to be inert, with a covalent Si–O–Si network, low surface energy and often coated with adsorbed hydrocarbons or manufacturing residues that inhibit wetting and bonding. Plasma treatment offers an industrial way to overcome these limitations. When glass is exposed to atmospheric plasma, several effects occur: (i) removal of organic contaminants, (ii) breakage of Si–O–Si bonds or restructuring of surface siloxane networks, (iii) formation of Si–OH (silanol) or O–Si–O–H groups, increasing surface polarity, and (iv) micro-scale texturing from ion/ radical impact and thermal effects, which increases real contact area [5]. These changes significantly increase the polar component of surface free energy, improve contact line wetting (reducing water contact angle), and enable better bonding of adhesives or coatings. Practically, improved wettability of glass means better adhesion of polymeric adhesives, coatings (e.g., sol-gel, UV-cured), and functional films for microfluidic applications or mirrors. From an industrial standpoint, plasma activation is cleaner than acid etching or silanization, faster, and more compatible with inline automation. A study [6] demonstrated that on automotive glass, using a both rotating and point-nozzle plasma system increased surface tension from ~32 mN/m to >44 mN/m, and improved adhesion of polyurethane–glass joints, underscoring the validity of plasma activation for glass substrates.

The performance of atmospheric plasma activation depends on process parameters: discharge power, treatment distance, gas flow rate, and exposure time. These parameters have an impact on the plasma's reactive species concentration, temperature distribution, and energy flux directly at the substrate surface [8]. Studies on dielectric barrier discharge (DBD) and atmospheric plasma jets have shown that increasing power and decreasing nozzle distance intensify the density of reactive oxygen species (ROS), increasing the formation of surface hydroxyls and oxygenated groups [9]. Despite this, excessive energy input may lead to surface re-contamination or micro-cracking on thermally sensitive substrates for example on glass or polymers surfaces [10]. The treatment speed is also an important role. A higher scanning velocity reduces residence time, lowering the effective dose of reactive species. The too slow motion may cause local overheating or over-oxidation, mainly on transparent materials where plasma–substrate coupling is strong [11,12]. An optimal processing window must balance reactivity and temperature exposure.

1.4. Research on Plasma-Activated Glass Surfaces

Plasma activated glass surfaces has received growing attention for optical, packaging, and adhesive bonding applications. Investigations using air, argon, and helium plasma have consistently shown that plasma exposure can reduce water contact angles on glass from values above 70° to below 10° within very short time [13]. Atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS) analyses have confirmed a simultaneous increase in surface roughness and formation of oxygen-rich functional groups, particularly Si–OH and Si–O–O– species [14]. For example, glass treated with atmospheric plasma before applying polyurethane or silane-based adhesives appears to a four-fold increase in shear strength compared with untreated samples [15]. Plasma activation also intensifies hydrophilicity critical for applications such as microfluidic channel sealing and optical fiber cladding [16]. Developments combine rotating and jet plasma hybrid systems, where both large-area uniform activation and high-energy local cleaning can procedure. The dual-mode configurations yield superior bonding durability under humidity and thermal cycling [3]. These findings provide the importance of plasma geometry and energy input connect to substrate chemistry and application environment. Most studies focus on polymers or metals, and systematic comparisons of plasma treatment modes are still rare on glass substrates. The better known relationship between microstructural, chemical changes and adhesive performance can help create predictive optimization models for industrial processing [17]. The present study addresses these challenges by systematically comparing rotating and jet plasma activation effects on glass surfaces, focusing on wettability and adhesion improvement. The relevance of solvent-free activation technologies has grown in parallel with stricter sustainability expectations in manufacturing. Broader analyses of vehicle-related environmental impacts in Europe also underline the need for low-emission, energy-efficient processing routes during component production [18,19]. Atmospheric plasma treatment aligns with these requirements, as it avoids volatile chemicals and reduces waste generation compared to traditional cleaning methods.

2. Materials and Methodes

2.1. Glass specimens

The treated glass samples were 76 x 21 x 1 mm, optically flat and polished microscopic glass slides. The slides were supplied in a pre-cleaned, laboratory-grade condition. These slides were selected because of their chemically inert and non-conductive nature, making them ideal model substrates for studying plasma-surface interactions under well-controlled conditions. The slides were handled with powder-free nitrile gloves and stored in airtight, dust-free containers prior to surface activation.

2.2. Rotating head plasma

For the treatments a rotary-head atmospheric plasma system was used. The device operates at a frequency range of 18-25 kHz under ambient pressure. The process gas was compressed air. The rotating electrode head provides uniform plasma exposure across the substrate surface. The system allows a treatment width of 35-80 mm. The nozzle-to-surface distance was changed for the experiment, and the rotational speed was fixed for 2000 round/minutes. This configuration provides stable discharge characteristics suitable for activating non-conductive substrates. The plasma surface modification experiments were carried out using the rotary-head atmospheric plasma device positioned vertically above the substrate surface (Figure 1).

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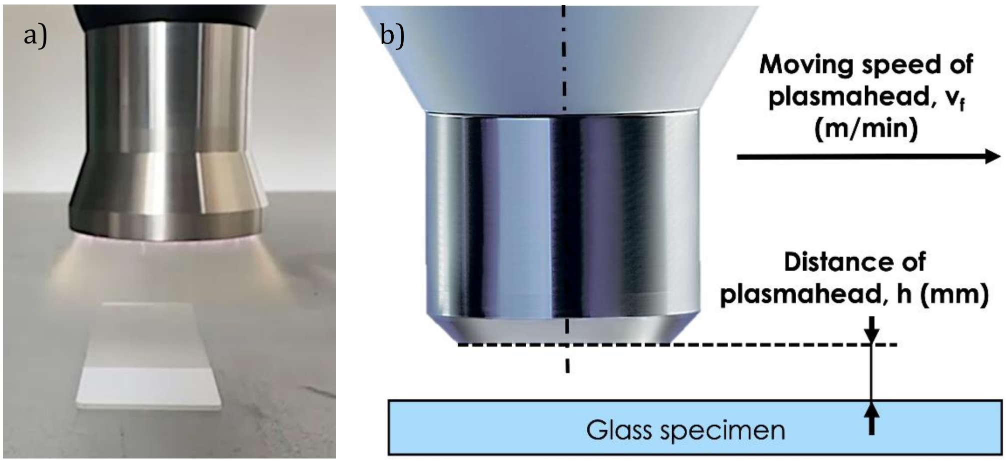

Figure 1. a) Experimental setup for the rotary-head plasma treatment of glass surface and b) schematic illustration of the plasma treatment setup showing the working distance (h) and feed rate (v_f).

he plasma torch was mounted on a CNC axis, which kept the nozzle-to-sample distance and the feed rate constant during the treatment. The discharge appeared as a faint violet glow and spread evenly over the surface. The glass slides were placed on a flat, grounded stainless-steel stage so they remained stable throughout the process. The rotating plasma head produced a sweeping discharge that moved continuously across the surface, creating a uniform activation without local overheating. This setup made it possible to control the treatment conditions precisely and to obtain reproducible results.

A parametric study was carried out to examine how the nozzle distance (h) and the feed rate (vf) influence the activation. The nozzle-to-surface distance was set to four values: 4, 10, 20, and 25 mm. For each distance, the feed rate was varied between 0.42 and 16.67 m/min in nine steps, giving 36 different parameter combinations.

The treatments were conducted at 22–23 °C and 45–55% relative humidity to ensure stable environmental conditions. Each pass covered the full 76 mm length of the glass slide, and the rotation speed of the plasma head was kept constant in all experiments.

2.3. Jet head plasma

An atmospheric jet plasma system was also used for glass surface treatment. The device generates a focused plasma jet under ambient conditions. The discharge is formed at the nozzle outlet and extends toward the substrate as a narrow, high-velocity plasma plume. It provide directional and localized surface activation. The frequency range was between 18-25 kHz with an adjustable gas flow rate. The compact design allows perfect control of the nozzle-to-surface distance and feed rate, enabling systematic comparison with the rotary plasma configuration.

The plasma head was positioned vertically above the substrate, so the gap distance was controlled. The nozzle was fixed on a CNC-controlled linear axis, and constant traverse speed and parallel alignment relative to the sample surface were guaranteed. The plasma jet impinged directly and perpendicularly onto the glass surface, creating a visible, bright-blue plume approximately 10-15 mm in length (Figure 2).

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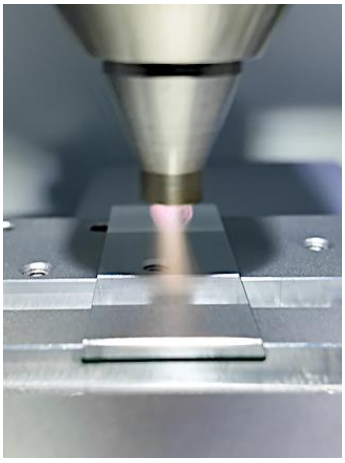
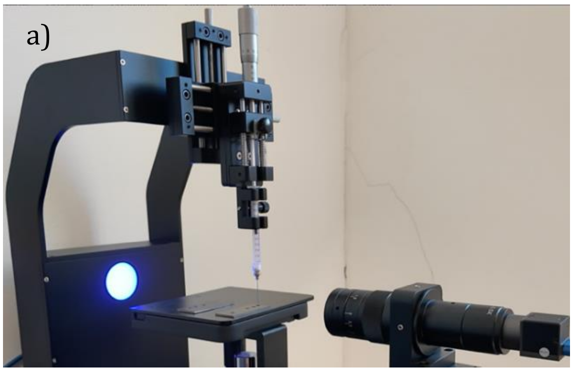


Figure 2. Experimental setup for the jet-head plasma treatment of glass

The focused discharge provided intense, localized exposure and suitable for non-conductive substrates. The high-energy jet configuration promotes effective removal of surface contaminants and activation of polar functional groups. A parametric study was also conducted using the jet plasma configuration to evaluate the influence of plasma-substrate distance (h) and feed rate (vf) on surface activation. The nozzle-to-surface distances were: 10 mm, 15 mm, 20 mm, and 25 mm, and the feed rate of the plasma head relative to the glass substrate were between 0.42 and 16.67 m/min. To treat the entire surface, the plasma head was shifted by 5 mm after each pass.

2.4. Contact angle measurement and surface energy

Surface wettability was evaluated using a contact angle analyser (Figure 3).



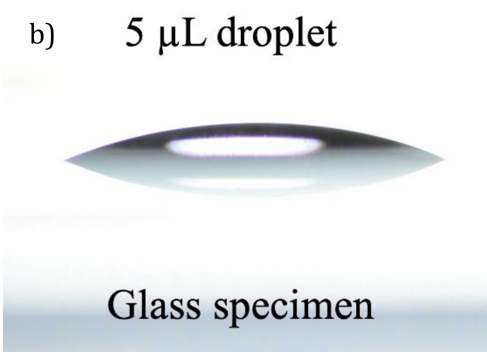


Figure 3. a) Contact angle measurement equipment and b) a water droplet on glass surface.

The instrument operates on the sessile drop method, equipped with a high-resolution optical system and image-processing software for accurate determination of static contact angles. Measurements were performed using 5 µL droplets of distilled water and 5 µL droplets of ethylene glycol as probe liquids. Droplets were dispensed onto the treated glass surfaces within one minute after plasma exposure to minimize the effect of hydrophobic recovery. Each droplet image was captured immediately after deposition, and the left and right contact angles were averaged to obtain representative values for surface wettability.

For reference, the untreated glass surface initial contact angles of approximately 64° for distilled water and 45° for ethylene glycol, indicating a moderately hydrophilic but energetically unactivated state prior to plasma treatment. These deviations for distilled water and ethylene glycol are applied through the study.

3. Results

3.1. Rotating plasma head results

Figure 4 presents the the water contact angle (WCA) as a function of the plasma-substrate distance (h) and feed rate (vf) for the rotating-head atmospheric plasma treatment.

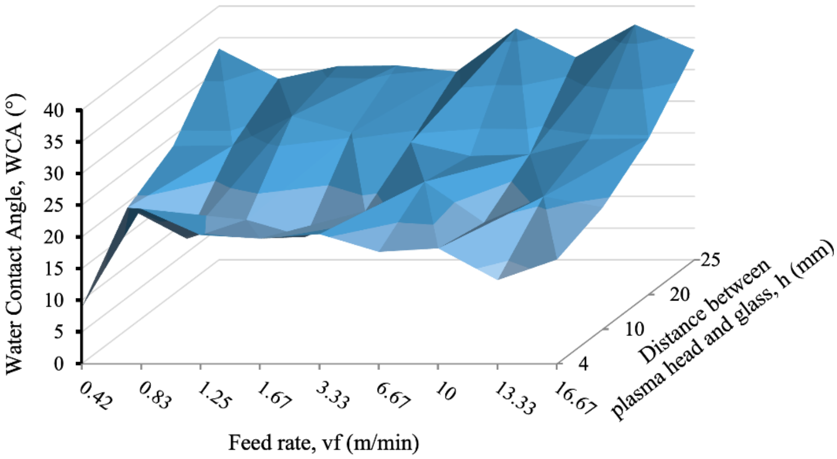


Figure 4. Effect of rotary plasma on water contact angle

The treated surface showed clear differences depending on the plasma energy reaching the glass. In general, a smaller nozzle distance and a slower movement gave lower contact angles, which means better wettability and higher surface energy.

At the shortest distance of 4 mm, the contact angle dropped to between 8.9° and 20°, depending on the feed rate. In this case, the plasma plume touched the surface directly, giving the highest energy density and the longest exposure time. As a result, the surface became much more polar and strongly hydrophilic.

When the distance increased to 10 mm, the contact angles stayed low (around 14–23°) at slower feed rates, but started to rise when the speed was higher than about 6.7 m/min. Shorter exposure means less interaction between the plasma and the surface, so a partial recovery of hydrophobicity was seen. This moderate range of energy input (10–20 mm) gives a good balance between activation strength and surface uniformity, which is useful for fragile or heat-sensitive materials.

The largest distance was 25 mm the WCA increased significantly to 30-37°, indicating a weaker activation effect. In this regime, the plasma species undergo recombination and quenching during transport through the ambient air, reducing the density of reactive radicals reaching the surface. Moreover, the convective gas expansion at larger gaps dilutes the plasma jet and limits ion bombardment energy. Consequently, only partial oxidation occurs, and the resulting surface shows moderate hydrophilicity.

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The effect of the feed rate (vf) followed a clear pattern. At low feed rates (0.42–1.67 m/min), the surface stayed longer under the plasma, so the activation was stronger. When the feed rate was high (>10 m/min), the plasma passed over each point too quickly, and the contact angle increased again. This shows that the amount of energy delivered per unit area controls the surface modification. The link between lower contact angles and higher energy exposure also indicates how sensitive glass wettability is to the chemical changes caused by the plasma.

From a chemical point of view, the improved hydrophilicity comes from new polar groups forming on the surface (such as Si–OH, Si–O–O, and C–O), and from the removal of thin hydrocarbon layers. These changes raise the surface energy and help water and ethylene glycol spread more easily. Small irregularities seen at medium feed rates (around 3–6 m/min) may be due to short-term fluctuations in the plasma flow or slight thermal effects that influence how adsorbed molecules leave the surface.

The results obtained with ethylene glycol as the measurement liquid (Figure 5) confirm the trends observed in the water contact angle measurements.

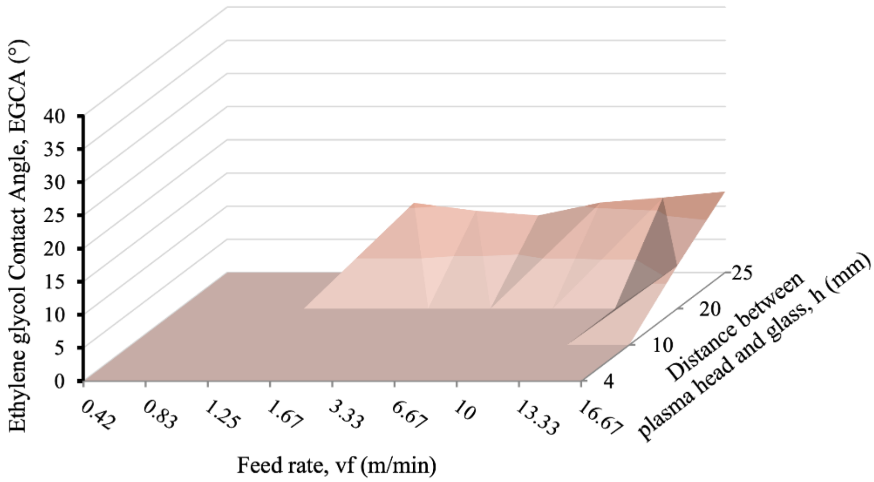

Figure 5. Effect of rotary plasma on ethylene glycol contact angle

The ethylene glycol contact angles (EGCA) were markedly lower—mostly below 20°—across all plasma conditions, indicating a highly polar and well-activated glass surface following treatment. The lowest values, approaching 0-10°, occurred at short plasma-surface distances (4-10 mm) and low feed rates (<3 m/min), consistent with the highest surface energy and strongest oxidation effects. At larger distances (20-25 mm) or higher feed rates, a moderate increase in EGCA (up to 25-30°) was observed, reflecting reduced flux of reactive species and shorter exposure time.

Compared to water, ethylene glycol, having a lower surface tension and higher polarity responds more sensitively to small changes in surface energy; therefore, its near-zero contact angles confirm that the treated surfaces became strongly hydrophilic and energetically favourable for polar interactions.

3.2. Jet plasma head results

Figure 6 shows the variation of the water contact angle (WCA) as a function of feed rate (vf) and plasma-substrate distance (h) for the jet (penetrating) plasma treatment.

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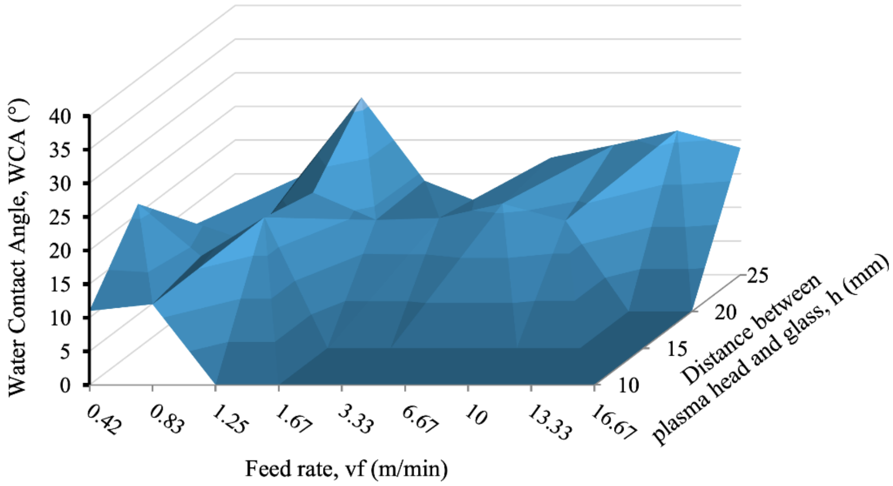

Figure 6. Effect of jet plasma on water contact angle

Compared with the rotating plasma system, the jet configuration produced consistently low contact angles across the entire parameter range, typically between 9° and 22°, indicating a highly efficient surface activation of the glass substrates. The overall trend demonstrates that the jet plasma is less sensitive to feed rate and distance variations than the rotating system. This behavior arises from the focused nature of the plasma jet, which maintains a high local energy density and a concentrated flux of reactive species even at increased standoff distances. At short working distances (10-15 mm), the contact angle values were near the minimum (≈10-13°), signifying almost complete wetting.

The contact angles showed relatively low values (typically 12-20°) at medium and larger distances (20-25 mm), but exhibited small fluctuations with feed rate. The minima observed around h = 20 mm, vf = 1.25-3.33 m/min suggest an optimal combination of energy flux and exposure time. Here sufficient plasma intensity is retained while avoiding potential thermal stress on the substrate. The slightly higher contact angles (up to ≈26°) recorded at isolated points (e.g., h = 25 mm, vf = 1.25 m/min) may reflect localized nonuniformities in jet stability or momentary variations in gas flow dynamics.

The wettability enhancement can be attributed to the efficient transfer of reactive oxygen and nitrogen species (O, OH, NO) directly to the surface in the core of the plasma jet. These species promote oxidation of siloxane bonds (Si-O-Si → Si-OH) and removal of surface contaminants, leading to increased surface polarity and reduced contact angle. Because the jet plasma maintains a laminar flow and a narrow, high-temperature discharge channel, recombination losses in ambient air are minimized, enabling strong activation even at larger stand-off distances.

The ethylene glycol contact angle (EGCA) results for the jet plasma-treated glass surfaces, presented in Figure 7, reveal an almost complete wetting behaviour across the entire tested parameter range.

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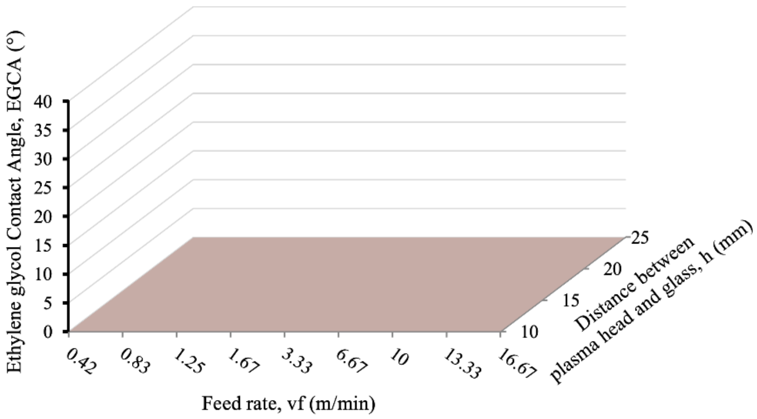

Figure 7. Effect of jet plasma on ethylene glycol contact angle

Measured contact angles remained consistently below 5° so considered to 0, indicating a highly polar and fully activated surface following plasma exposure. The lack of significant variation with either feed rate (vf) or plasma-surface distance (h) suggests that the jet plasma provides a uniformly strong activation effect, independent of small process fluctuations.

3.3. Comparison of wettability changes using different plasma treatments

A comparison of the two plasma systems showed clear differences in how they activated the glass surface. Both the rotating-head and the jet plasma reduced the water and ethylene glycol contact angles, so in both cases the wettability improved. However, the strength of the activation and how sensitive it was to the process parameters were not the same, mainly because the two systems deliver their energy in different ways.

The rotating-head plasma gave a more even treatment across the surface, but its effect changed a lot with the nozzle distance and the feed rate. The contact angle ranged from about 37° down to below 10°, depending on the settings. This means that the activation depends strongly on how much energy reaches each point and how long the plasma stays over the surface. Shorter distances and slower movement increased the energy density and the amount of reactive species, so the surface became more oxidised and more hydrophilic. When the distance was larger or the movement was faster, fewer active species reached the glass, and a slight return toward hydrophobic behaviour could be seen. Because of this, the rotating system offers good control over uniformity, but it is also quite sensitive to the chosen parameters.

The jet plasma treatment produced a very stable and strongly hydrophilic surface under all tested conditions. The water contact angle usually stayed between 9° and 20°, while the ethylene glycol angle was almost always close to 0–5°, which means nearly complete wetting. The narrow and focused jet creates a high-energy core with a dense flow of reactive species, so the surface is effectively cleaned and oxidised even when the nozzle is farther from the glass. Because the jet delivers its energy in one direction, fewer reactive species are lost in the air, and the activation remains consistent and repeatable. The strong local interaction of the jet also allows fast surface modification, and the results do not change much with different feed rates or distances.

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Although both plasma systems improved the wettability of the glass, they do so in different ways. The rotating head gives adjustable and uniform activation over larger areas, while the jet plasma creates stronger, localised changes with little sensitivity to the settings. For practical applications, the two approaches complement each other, and the choice can be made based on the required activation strength, area coverage, and integration into the process.

4. Conclusion

This study demonstrated that both rotating-head and jet-type atmospheric plasma treatments effectively modified the surface properties of glass substrates, leading to significant improvements in surface wettability and activation. By systematically varying treatment parameters such as nozzle distance and feed rate, the experiments revealed how plasma dynamics influence surface energy and contact angle behaviour. The main results are:

- Both plasma systems successfully transformed the initially hydrophobic glass surface (WCA ≈ 40° for water, 25° for ethylene glycol) into a highly hydrophilic state, reaching contact angles below 10° under optimized conditions.
- The rotating-head plasma achieved a more homogenous and stable activation due to its radial discharge distribution, resulting in consistent wettability across larger surface areas.
- The jet plasma exhibited stronger local activation, producing lower contact angles at smaller nozzle distances but with higher sensitivity to process parameters.
- Wettability improvements were most significant at smaller nozzle–surface distances (4–10 mm) and lower feed rates (<2 m/min), confirming that higher energy density enhances activation efficiency.
- The contact angle reduction correlated directly with increased surface polarity and oxygen-containing functional group formation, confirming the chemical oxidation and cleaning effect of the plasma.
- The study validates atmospheric plasma as a non-contact, environmentally friendly, and highly controllable surface activation technique for glass substrates, providing a strong foundation for subsequent adhesive bonding, coating, or functional layer deposition.

Author Contributions

Conceptualization, Z.W. and M.B.; methodology, M.B.; validation, M.B.; investigation, M.B.; resources, Z.W.; data curation, Z.W.; writing—original draft, M.B.; writing—review and editing, Z.W.; visualization, M.B.; supervision, Z.W.; project administration, Z.W.; funding acquisition, Z.W. All authors have read and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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