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**How to cite:** Liu S. Research on Visualization of Fiber Surface Modification and Fabric Properties Based on Interactive Animation. Textile & Leather Review. 2026; 9:420-431. <https://doi.org/10.31881/TLR.2026.420>

**How to link:** <https://doi.org/10.31881/TLR.2026.420>

**Published:** 28 February 2026



# Research on Visualization of Fiber Surface Modification and Fabric Properties Based on Interactive Animation

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## Article

<https://doi.org/10.31881/TLR.2026.420>

Received 24 October 2025; Accepted 21 November 2025; Published 28 February 2026

## ABSTRACT

*Understanding the complex process-structure-property relationships in textile finishing is critical for education and preliminary process screening. This study presents a novel interactive visualization framework to elucidate the dynamic effects of Glow Discharge Plasma (GDP) treatment on the wicking trends of Polyethylene Terephthalate (PET) fabrics. A semi-empirical computational model is developed to simulate the kinetic evolution of surface modification, coupling plasma-induced chemical hydrophilization with physical etching-induced roughness. Crucially, the model integrates a Wenzel-state wetting mechanism, linking nanoscale topographical changes to macroscopic fluid transport. Instead of aiming for absolute engineering predictions, the simulation outputs a Normalized Capillary Uptake Index ( $H_{vis}$ ), allowing users to intuitively compare the relative acceleration of wicking kinetics under varying power and time scenarios. The integrated tool visualizes these trends in real-time through 3D fiber surface rendering and 2D wicking animation. This framework serves as a powerful educational and exploratory tool, offering students and engineers a platform to understand the fundamental non-linear dynamics of surface finishing without the complexity of high-fidelity multiphysics simulations.*

## KEYWORDS

*interactive visualization, plasma treatment, wicking wetting, normalized wicking index, textile education*

## INTRODUCTION

The performance and functional characteristics of modern textiles are increasingly dictated by sophisticated surface engineering techniques applied at the fiber level [1,2]. Processes such as plasma treatment, chemical grafting, and nanoparticle coating are employed to modify the topography and chemistry of fiber surfaces, thereby enhancing properties like hydrophilicity, hydrophobicity, dye uptake, and biocompatibility [3,4]. Among these methods, low-temperature plasma treatment, particularly Glow Discharge Plasma (GDP), has

garnered significant attention for its efficacy, environmental cleanliness, and ability to impart desired functionalities without altering the bulk properties of the material [5,6]. By bombarding a polymer surface, like that of Polyethylene Terephthalate (PET), with energetic ions and reactive species, plasma treatment can simultaneously etch the surface to increase its roughness and introduce polar functional groups, leading to a marked decrease in water contact angle and a corresponding improvement in wettability [7-9].

While the physical and chemical changes induced by these modifications are well-documented through advanced analytical techniques such as Atomic Force Microscopy (AFM) and X-ray Photoelectron Spectroscopy (XPS), the direct, dynamic relationship between the modification process parameters and the ultimate macroscopic performance of the fabric can be difficult to grasp [10,11]. Traditional research methods rely on static data (e.g., graphs, tables, micrographs) that, while accurate, fail to capture the continuous and causal nature of this relationship [12]. A textile engineer seeking to optimize a plasma treatment process, for example, must conduct numerous discrete experiments to understand how adjusting power or duration impacts a property like wicking speed [13,14]. This iterative, physical prototyping process is both time-consuming and resource-intensive. Consequently, there is a compelling need for a pedagogical and research tool that can bridge this conceptual gap, allowing for the dynamic exploration of "what-if" scenarios in a virtual environment.

This paper addresses this need by developing and presenting a novel methodology for the visualization of fiber surface modification and its impact on fabric performance using interactive animation. We focus on a specific, well-understood case study: the GDP treatment of PET fibers to enhance fabric wicking. The core of this research is the creation of a computational tool that integrates empirical models of plasma-surface interaction with physical models of fluid dynamics in porous media. This tool allows a user to interactively control key plasma parameters—power and treatment time—and witness in real-time the predicted changes in fiber surface morphology, contact angle, and the subsequent wicking behavior of the fabric. The contribution of this work is not the discovery of new physical phenomena, but rather the creation of a scientifically grounded, interactive visualization framework that makes the complex relationship between nanoscale modification and macroscale function intuitive, accessible, and explorable. This approach has the potential to accelerate material design, enhance student comprehension in textile science, and provide a platform for more sophisticated virtual experiments in the future.

## MATERIALS AND METHODS

### Model Overview and Design Philosophy

The primary objective of this study is to develop an interactive visualization framework that elucidates the dynamic relationships between plasma processing parameters and fabric performance trends. Unlike high-fidelity multiphysics simulations intended for precise engineering predictions of specific fabric structures, the proposed model serves as a semi-empirical educational and exploratory tool. It focuses on capturing the characteristic kinetic trends—specifically the acceleration of wetting kinetics and the evolution of surface morphology—under varying treatment conditions. The system integrates three coupled mathematical modules: (1) plasma-induced surface chemical modification, (2) topographical evolution, and (3) simplified capillary transport dynamics. The output is presented as a normalized index to facilitate relative comparisons of process efficiency.

### Plasma-Induced Surface Modification Model

The modification of the Polyethylene Terephthalate (PET) fiber surface is modeled as a function of two user-controlled variables: plasma power ( $P$ , in Watts) and treatment time ( $t$ , in seconds).

#### *Chemical Contact Angle Evolution*

The rapid reduction in the intrinsic water contact angle ( $\theta_{\text{chem}}$ ) due to the introduction of polar functional groups (e.g., C-O, C=O) is described by an exponential decay function, consistent with adsorption kinetics observed in surface modification literature:

$$\theta_{\text{chem}}(t) = \theta_f + (\theta_i - \theta_f) \cdot e^{-k_p(P) \cdot t} \quad (1)$$

$\theta_i$  ( $85^\circ$ ) represents the nominal contact angle for the untreated hydrophobic PET surface, and  $\theta_f$  ( $35^\circ$ ) represents the saturation limit for a fully hydrophilized surface. The modification rate constant,  $k_p$ , is modeled to scale linearly with plasma discharge power ( $k_p = C_1 \cdot P$ ), reflecting the higher flux of reactive species at elevated power settings.

### Surface Topographical Evolution

Simultaneously, plasma etching increases the surface roughness ( $R_a$ ), modeled as a saturation process where the etching rate competes with surface stabilization:

$$R_a(t) = R_{a,0} + \Delta R_{max}(P) \cdot (1 - e^{-k_e \cdot t}) \quad (2)$$

Here,  $R_{a,0}$  is the initial roughness (~5 nm). The maximum achievable roughness increase,  $\Delta R_{max}$ , is proportional to the discharge power ( $\Delta R_{max} = c_2 \cdot P$ ), and  $k_e$  is the characteristic etching rate constant. Parameter Calibration: To ensure the visualization reflects realistic kinetic timescales, the model parameters are fixed to representative values derived from PET plasma treatment literature. Specifically, the hydrophilization coefficient is set to  $c_1 = 0.002 \text{ s}^{-1}W^{-1}$ , the etching magnitude coefficient is  $c_2 = 0.1 \text{ nm}W^{-1}$ , and the etching rate constant is  $k_e = 0.15 \text{ s}^{-1}$ . These explicit values ensure the reproducibility of the simulation outputs and align the visualized trends and approximate orders of magnitude with representative experimental observations (e.g., roughness increases of 10–20 nm).

### Apparent Wettability and Wenzel Coupling

A critical feature of this framework, often omitted in simplified models, is the coupling of surface chemistry and topography. As plasma treatment increases surface roughness, the wettability of the hydrophilic surface is further enhanced according to the Wenzel state (Figure 1).

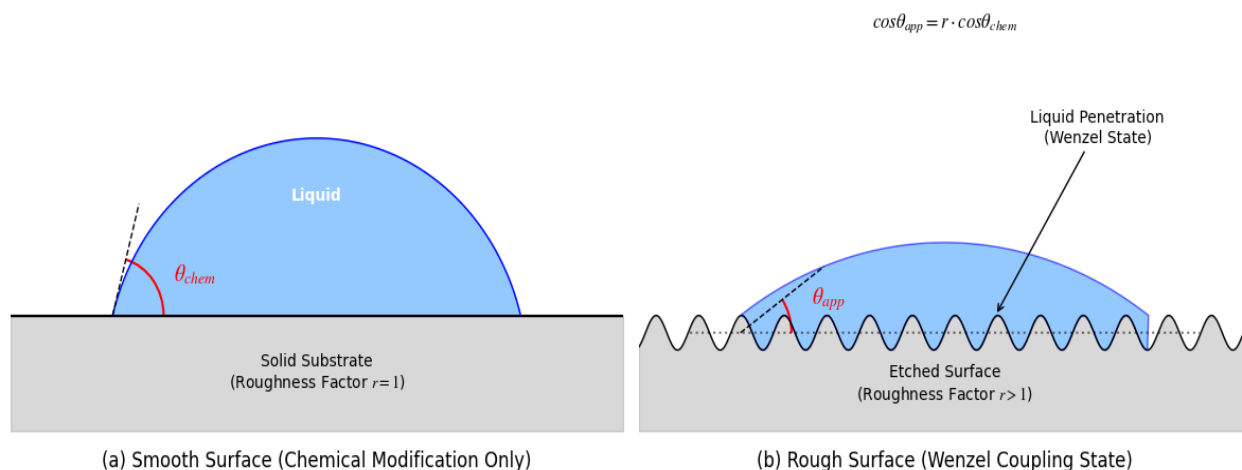


Figure 1. Schematic representation of the Wenzel coupling mechanism. (a) Ideally smooth surface where wettability is governed solely by chemical modification ( $\theta_{chem}$ ). (b) Plasma-etched rough surface illustrating the Wenzel state

The apparent contact angle ( $\theta_{app}$ ), which governs the macroscopic capillary flow, is calculated as:

$$\cos\theta_{app} = r(t) \cdot \cos\theta_{chem}(t) \quad (3)$$

The roughness factor  $r(t)$  (dimensionless) is derived from the calculated arithmetic mean roughness  $R_a(t)$  (in nm) using a linear geometric mapping suited for the visualization scale:

$$r(t) = 1 + \alpha \cdot (R_a(t) - R_{a,0}) \quad (4)$$

where  $\alpha$  is a dimensional coupling coefficient set to  $0.02 \text{ nm}^{-1}$ . This coefficient bridges the length scales, mapping the nanometric roughness increase ( $\Delta R_a \approx 20 \text{ nm}$ ) to a macroscopic Wenzel roughness ratio ( $r \approx 1.4$ ), providing a qualitatively consistent input for the capillary uptake model. To maintain physical consistency, the computed value of  $\cos\theta_{app}$  is capped at unity, ensuring that  $\theta_{app}$  remains within the physically admissible range.

### Simplified Capillary Uptake Dynamics

To visualize the transient liquid transport behavior, the framework employs a simplified Lucas-Washburn approach. Since the primary focus of this tool is on the initial kinetic response and relative comparison of treatment efficacy rather than equilibrium height prediction in complex porous media, gravitational effects and pore tortuosity are omitted in this trend-based model.

The theoretical capillary penetration length ( $h_{theo}$ ) in an equivalent idealized capillary channel representation of the fabric structure is given by:

$$h_{theo}(t) = \sqrt{\frac{\gamma \cdot r_{eff} \cdot \cos\theta_{app}(t)}{2\eta}} \cdot t \quad (5)$$

where  $\gamma$  is the surface tension,  $\eta$  is the viscosity of the liquid, and  $r_{\text{ref}}$  is the effective capillary radius. The parameter  $r_{\text{ref}}$  is treated as a fixed nominal geometric scale parameter representing an effective pore radius of the fabric structure. Its absolute value does not affect the relative trends generated by the model and is selected solely to set a convenient time scale for visualization.

#### Normalized Visualization Index

To translate this theoretical length into a bounded visual representation for the user interface and to avoid physical misinterpretation of infinite rise times, we define a Normalized Capillary Uptake Index ( $H_{\text{vis}}$ ):

$$H_{\text{vis}}(t) = \min\left(\frac{h_{\text{theo}}(t)}{h_{\text{scale}}}, 1.0\right) \quad (6)$$

where  $h_{\text{scale}}$  is a normalization constant representing the characteristic observation window (e.g., the length of a fabric test strip).  $H_{\text{vis}}$  ranges from 0 to 1 (or 0% to 100%), representing the relative progression of the liquid front. This approach allows users to intuitively compare the *speed* of uptake under different conditions (power/time) without implying absolute predictions of equilibrium heights, which would require rigorous porous media modeling including gravity and evaporation terms.

#### Interactive Visualization Mapping

The calculated parameters directly drive the interactive components of the GUI:

- 3D Fiber View: The surface mesh vertices are displaced using a procedural noise function, where the noise amplitude is proportional to the calculated  $R_a(t)$  from Eq. 2, visualizing the etching effect.
- 2D Wicking Animation: The vertical position of the liquid front is updated in real-time based on  $H_{\text{vis}}(t)$  from Eq. 6.
- Dynamic Plots: The system plots  $\theta_{\text{chem}}$  and  $H_{\text{vis}}$  to provide immediate quantitative feedback on the process-property relationships.

## RESULTS

The results presented in this section represent scenario-based simulation outputs generated by the interactive tool. They are intended to illustrate the relative dynamic trends of surface modification and liquid

transport under varying plasma conditions, rather than to provide absolute physical predictions for specific commercial fabrics. The data confirms that the coupled mathematical models (Eqs. 1-6) successfully capture the non-linear dependencies between processing inputs and wicking performance.

### User Interaction and System Response

The primary output of this work is the real-time responsiveness of the visualization platform. Figure 2 presents the complete graphical user interface (GUI). Users can manipulate the sliders and observe instantaneous feedback. For instance, setting the 'Plasma Power' to a low value (e.g., 75 W) results in a gradual decay in the displayed contact angle and a minor topographical change ( $\Delta R_a < 10$  nm). Conversely, maximizing parameters (200 W, 60 s) triggers the visualization of a highly rough surface and a rapid drop in contact angle to the saturation limit ( $\theta_{chem} \approx 35^\circ$ ), driving the wicking animation to completion significantly faster.

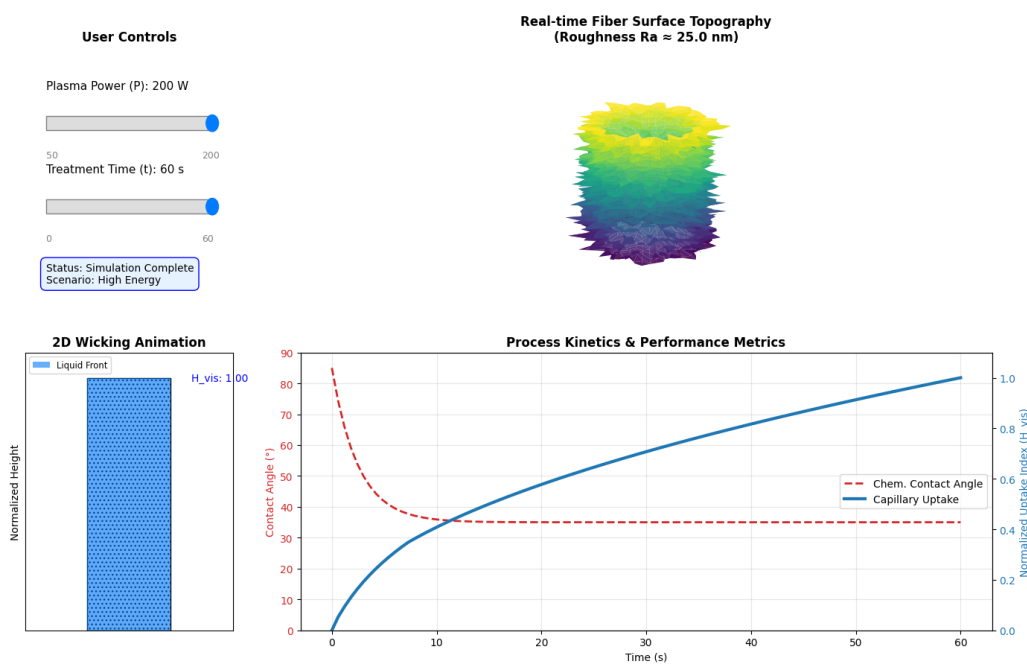


Figure 2. presents the complete graphical user interface (GUI)

### Visualizing the Effect of Treatment Time

Holding the 'Plasma Power' constant at a mid-range value ( $P = 150$  W) and increasing 'Treatment Time' reveals the distinct time-constants of the underlying models:

- **Surface Chemistry:** The plot of Contact Angle vs. Time shows a sharp exponential drop that stabilizes within the first 10–15 seconds. This reflects the high reactivity rate constant ( $k_p = 0.3 \text{ s}^{-1}$  at 150 W) defined in the model.
- **Topography:** The 3D fiber surface roughens more gradually, following the etching rate constant  $k_e = 0.15 \text{ s}^{-1}$ .
- **Wicking Dynamics:** Consequently, the simulated wicking speed increases rapidly for short treatment times ( $t < 20$ ) and then plateaus, demonstrating the "diminishing returns" effect often observed in industrial processing.

### Visualizing the Effect of Plasma Power

- By fixing the time ( $t=20 \text{ s}$ ) and varying 'Plasma Power' from 50 W to 200 W, the tool highlights the power-dependence of the modification magnitude: Roughness Amplification: Higher power settings lead to a visibly rougher 3D fiber. At 200 W, the model generates a representative roughness increase approaching  $\sim 20 \text{ nm}$  within the model's nominal roughness scale (based on  $c_2 = 0.1$ ), compared to only  $\sim 5 \text{ nm}$  at 50 W.
- **Wenzel-Enhances Wetting:** The tool demonstrates that this increased roughness at high power further amplifies wettability. The computed Normalized Capillary Uptake Index ( $H_{vis}$ ) for the 200 W scenario is significantly higher than the 50 W case, illustrating the synergistic effect of chemical hydrophilization and physical etching described by Eq. 3.

### Comparative Scenario Analysis

- Figure 3 presents the quantitative output of the tool for two distinct processing scenarios: minimal treatment (50 W/5 s) and intensive treatment (200 W/60 s). The Low Treatment scenario results in a normalized index that rises slowly, reaching only a fraction of the scale capacity. This corresponds to a surface that retains significant hydrophobicity ( $\theta_{chem}$  remains high).
- In contrast, the High Treatment scenario produces a steep uptake curve that quickly approaches the upper bound ( $H_{vis} = 1.0$ ). This visually quantifies how the combination of maximum chemical modification and etching-induced Wenzel wetting transforms the fabric's performance.

Importantly, the parabolic shape of the curves reflects the underlying  $\sqrt{t}$  kinetics of the short-time Lucas–Washburn-type kernel (Eq. 5), while the normalization (Eq. 6) ensures the output remains within a

conceptually valid "progress" range (0-1) for educational visualization, avoiding physically unrealistic infinite height predictions.

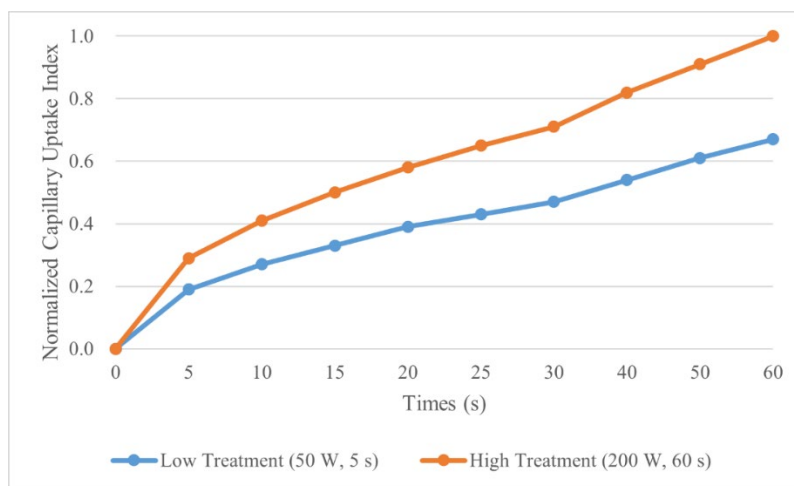


Figure 3. Comparison of simulated uptake dynamics under two extreme scenarios. The plot shows the Normalized Capillary Uptake Index ( $H_{vis}$ ) as a function of time. The 'High Treatment' curve (200 W, 60 s) approaches saturation ( $H_{vis} \rightarrow 1.0$ ) rapidly due to the combined effects of low contact angle and high Wenzel roughness, while the 'Low Treatment' curve (50 W, 5 s) shows a sluggish response

## DISCUSSION

### Coupling Surface Chemistry and Topography

A key theoretical contribution of this visualization framework is the explicit coupling of surface roughness and wettability. While traditional simplified models often treat contact angle as a purely chemical variable, our results demonstrate that at high plasma power (200 W), the physical etching contributes significantly to the accelerated uptake. By implementing the Wenzel equation (Eq. 3), the model quantitatively illustrates how the increased roughness factor ( $r$ ) amplifies the hydrophilic effect of the polar groups. This helps users visualize a critical physical concept: that effective super-hydrophilicity is often a synergy of chemistry and geometry, not chemistry alone.

### Rationale for the Normalized Uptake Index

In interpreting the wicking dynamics, it is crucial to understand the choice of the Normalized Capillary Uptake

Index ( $H_{vis}$ ) over absolute height values. Traditional Lucas-Washburn kinetics ( $h \propto \sqrt{t}$ ) imply infinite growth if unchecked. In real porous media, gravity and evaporation eventually limit this rise. However, incorporating these factors requires complex structural parameters (e.g., tortuosity, pore connectivity) that are often unknown in a generalized exploration context. By normalizing the output to a 0-1 scale (Eq. 6), we intentionally isolate the kinetic trends (the "speed" of the process) from the equilibrium limits. This design choice prevents physical misinterpretation of the "infinite rise" while still allowing users to clearly distinguish between the "sluggish" response of low-power treatment and the "rapid saturation" of high-power scenarios.

### Limitations and Educational Scope

It must be acknowledged that this tool is a simplified reduced-order model designed for conceptual understanding, not precise engineering design.

- Gravity Omission: The model omits gravitational forces, which is why the output is strictly defined as a "kinetic index" rather than a physical height prediction for long durations.
- Geometric Simplification: The fabric is idealized as a bundle of effective capillaries, ignoring the stochastic nature of real yarn structures. Therefore, the tool is best utilized for comparative trend analysis (e.g., "How much faster is 200W compared to 50W?") rather than absolute quantification (e.g., "The liquid will rise exactly 50mm").

### CONCLUSION

This research successfully demonstrates a "scenario-based" interactive simulation tool for visualizing fiber surface modification. By integrating semi-empirical kinetic models with a normalized fluid transport framework, the tool effectively captures the non-linear impact of plasma parameters on fabric performance.

The study highlights two main achievements:

1. Physical Insight: The incorporation of the Wenzel coupling mechanism allows the visualization of how plasma etching enhances wettability beyond simple chemical modification.
2. Educational Value: The introduction of the Normalized Capillary Uptake Index provides a robust method for comparing process kinetics without getting entangled in the complexities of gravitational equilibrium in undefined porous media.

While not a substitute for physical experiments, this framework bridges the gap between abstract theory and observable phenomena. It provides a valuable platform for textile engineering education, enabling students

and researchers to rapidly screen process parameters and build an intuitive understanding of surface finishing dynamics.

#### *Author Contributions*

Songlin Liu designed, collected and analyzed the data, and drafted the manuscript. Songlin Liu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Songlin Liu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

#### *Conflict of Interest*

The author declares no conflict of interest.

#### *Funding*

This research received no external funding.

#### *Availability of Data and Materials*

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

#### *Acknowledgments*

Not applicable.

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