Physics of Complex Systems, 2025, vol. 6, no. 4
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Condensed Matter Physics.
Solid state physics

UDC 621.396.6:621.372.852

EDN WFRSWV
https://www.doi.org/10.33910/2687-153X-2025-6-4-170-175

Filtration of water-alcohol liquids using electrically modified composite materials

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For citation: Galeeva, L. R., Galikhanov, M. F., Gilfanova, S. V. (2025) Filtration of water-alcohol liquids using electrically modified composite materials. *Physics of Complex Systems*, 6 (4), 170–175. https://www.doi.org/10.33910/2687-153X-2025-6-4-170-175 EDN WFRSWV

Received 8 September 2025; reviewed 30 September 2025; accepted 30 September 2025.

Funding: The work was carried out with a grant from the Tatarstan Academy of Sciences, provided to young candidates of sciences (postdoctoral fellows) for defending their doctoral dissertation and performing research and labor functions in scientific and educational organizations in the Republic of Tatarstan as part of the State Program of the Republic of Tatarstan 'Scientific and Technological Development of the Republic of Tatarstan' (No. 110/2024-ПД).

Abstract. This study examines the effect of the unipolar corona discharge on the filtration characteristics of polypropylene nonwoven materials, paper filters, and a two-layer composite material based on them. It shows that the two-layer filter consisting of the Red Tape ashless filter and the spunbond nonwoven polypropylene fabric provides higher filtration efficiency than each of the materials separately. Electret treatment of the samples reduced the amount of polluting particles in the filtrate by ~80% for paper filters and by ~30% for the polypropylene nonwoven material compared to untreated samples. At the same time, the filtration time increased by an average of 1.3 times. Testing the filtration efficiency of two-layer materials in a capsule cartridge with a supernatant liquid for filtering synthetic detergents demonstrated high separation efficiency — the modification of the cartridge increased its efficiency by almost 4 times.

Keywords: filters, ashless paper filter, polypropylene nonwoven fabric, two-layer material, electret, corona discharge, separation capacity, filtering capacity

Introduction

Filtration is used in various industries not only to achieve the required technological parameters (process speed, temperature uniformity, pressure drops, equipment reliability, etc.), but also to ensure product quality, functionality, safety, and attractiveness to the consumer (Sparks, Chase 2015). Filtration systems are designed to remove mechanical impurities, dust, fibers, rust, microorganisms, and other contaminants that may enter the product during various production stages or originate from raw materials. In manufacturing processes, solid particles can damage pumps, valves, nozzles, and filling machines, leading to operational failures and increased maintenance costs.

Filtration is particularly critical in the production of synthetic detergents (SD) and perfumery liquids, where products must maintain perfect clarity or uniform coloration, free from haze, sediment, or suspended particles (Divakar et al. 2022; Mousavi, Khodadoost 2019; Rodrigues et al. 2021). Undissolved particles (such as incompletely solubilized components, thickeners, dyes, or salt crystals) may sediment in packaging, clog dosing mechanisms, or block dispensers in washing machines, dishwashers, etc. Undesirable particles can act as crystallization nuclei or emulsion/suspension destabilization points, leading to product phase separation over time. Certain perfume composition components (particularly natural extracts and resins) may exhibit poor solubility or precipitate due to temperature changes or aging. Filtration effectively removes these unstable fractions, ensuring consistent fragrance stability and visual appearance throughout the product's shelf life.

Electret filters are often used for more efficient filtration and have a number of advantages over conventional ones. Electret filters are capable of trapping smaller particles though not only mechanical action but also the electric charge that holds the particles. Due to the electric field, electret filters can effectively trap particles of different sizes, which makes them more versatile (Li et al. 2024; Thakur et al. 2013). Therefore, many works are devoted to the conversion of filter materials (in particular, non-woven polypropylene fibers or cellulose-paper materials) into an electret state (Galeeva et al. 2021; Galikhanov et al. 2025; Gilfanova et al. 2020; Pan et al. 2022; Pang et al. 2024; Zhang 2020).

Modern production increasingly uses combined filter materials, which are structures combining several different filter technologies or material types in one filter (Sparks, Chase 2015). Such filters have a higher overall efficiency compared to filters composed of a single material, as they are able to combine different technologies, such as mechanical filtration, adsorption, and electrostatic filtration. Therefore, research into combined electret filter materials is relevant and timely.

The objective of this study was to investigate the effects of electrophysical treatment on the filtration characteristics of polypropylene nonwoven fabrics, paper filters, and composite materials based on them.

Materials and methods

The study utilized polypropylene nonwoven fabrics produced by the spunbond method with a basis weight of 17 g/m^2 as test samples (Technical Specifications 8390-002-71242729-2005, Polymatiz JSC) and Red Ribbon ash-free filters with a density of 84 g/m^2 (Technical Specifications 2642-001-45235143-2011, Bashkhimservis RPF LLC). A 70 vol.% aqueous ethanol solution (GOST 3639-79 standard) was used as a test filtration liquid. To evaluate filtration efficiency, a defined quantity of cellulose fibers was intentionally introduced into the solution, thereby simulating contaminated fluid conditions.

The filtration and separation efficiency of filter materials was determined in accordance with GOST 7584-89. The filtration capacity (measured as the time required to filter a specified volume of aqueous ethanol solution) was evaluated using a Büchner funnel. Evaluation of separation capacity involves calculating the percentage of particles or components retained and the total flux through the material.

The electrophysical impact on the filters on paper and polypropylene bases was carried out using a unipolar corona discharge. For this purpose, the samples were preliminarily kept in a heating cabinet at 105 °C for 10 min. After that, some of the samples on the lavsan film were placed in a corona cell consisting of a lower flat electrode and an upper electrode in the form of 196 pointed needles, evenly distributed over an area of 49 cm^2 in the form of a square (Fig. 1). The distance between sample 2 and electrode 1 was 20 mm. The samples were cooled in a corona discharge field at a polarization voltage of U = 30 kV for 30 s.

The electret characteristics of the samples (surface potential, electrostatic field strength, and surface charge density) were measured daily using an IPEP-1 instrument.

An EASYDROP device was used to measure the contact angle of the samples with water. A liquid drop was applied to the sample, which was placed on a lifting table, illuminated on one side, with a video camera on the other recording the image of the drop, which was transmitted to the computer. The DSA1 software allowed calculating the contact angle.

The electrokinetic potential of the fibers in an aqueous solution (ζ-potential of solid particles) was analyzed using a Mutek SZP-06 fiber surface charge analyzer. The filter paper was dissolved (dispersed) before the analysis using a laboratory disintegrator for 10 min at 1500 rpm. The concentration of paper fibers in the water suspension was 1.5%.

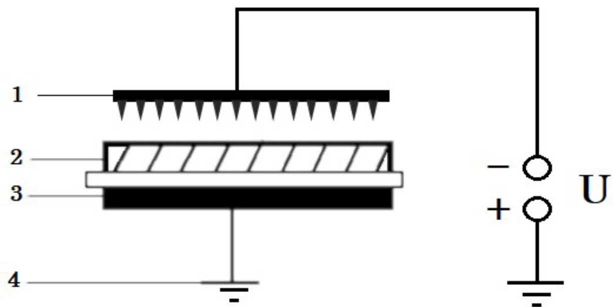

Fig. 1. Corona treater schematic: 1 — corona electrode; 2 — polarizable dielectric on the lavsan film; 3 — bottom electrode; 4 — ground connection; U — high-voltage power supply

Results and discussion

Paper filters remain unmatched in several key characteristics, including cost, filtration speed, etc. However, the filtrate quality from paper filter systems sometimes fails to meet manufacturers' expectations, as paper fibers detachw and contaminate the product. An additional polymer layer may be used to prevent these disadvantages.

Therefore, we needed to test the filtration and separation efficiency of the Red Ribbon (RR) ash-free paper filter and the polypropylene nonwoven fabric with a density of 17 g/m² (S17) individually, as well as a two-layer material combining both paper and polymer layers (RR + S17). The effectiveness of the dual 'paper filter — polypropylene fabric' material in ensuring filtrate purity during evaluation of the filter materials' separation capacity and filtration rate is shown in Fig. 2.

It can be seen that the two-layer filtering material, consisting of the ash-free Red Ribbon filter and the spunbond polypropylene nonwoven fabric, demonstrates a certain synergistic effect. The latter stems from the fact that the combined use of two materials with different properties provides significantly higher filtration efficiency than each material individually. The ash-free Red Ribbon filter possesses a high sorption capacity, while the polypropylene nonwoven material exhibits excellent mechanical properties and structural stability. Their combination increases the amount of retained fine-dispersed particles, leading to a rise in the overall filter efficiency and its improved operational characteristics.

Therefore, the next stage of our experimental research sought to study the polarizability of the Red Ribbon paper filter and the spunbond polypropylene nonwoven fabric under the action of a unipolar corona discharge (ERR and ES17, respectively). First, we determined how well these materials could accept and retain a charge. Filter paper poorly forms electrets since it is a sufficiently porous material with a through-pore system that allows charge carriers to reach the bottom electrode during electret formation, bypassing the cellulose fibers of the paper. Even the use of a lavsan substrate to enhance the electret formation capability of paper filters did not significantly improve the electret properties of the filter material. The initial values (after 1 hour of corona discharge treatment) of the electret properties of the Red Ribbon paper filter were: V_e = 0.01 kV, E = 0.9 kV/m, $\sigma_e f$= 0.01 μC/m², which dropped to zero after 5 days of storage.

Polymeric nonwoven filtering materials also have rather low electret properties, which are still sufficient for practical use. The initial values of the electret properties of the spunbond polypropylene nonwoven fabric were: V_e = 0.03 kV, E = 2.3 kV/m, $\sigma_e f$ = 0.03 μC/m², reaching the following values by 30 days of storage: V_e = 0.02 kV, E = 0.5 kV/m, $\sigma_e ff$ = 0.01 μC/m². Note that a lavsan substrate was also used for their electret formation (Fig. 1).

Under a unipolar corona discharge, charge carriers are injected into the bulk of the paper material, concentrating on the structural elements' surface (fibers, fillers, etc.). The formation of a heterocharge due to the orientation of cellulose polar groups, macromolecule segments during electret treatment, and the injection of charge carriers inside the fiber leads to the fiber surface acquiring a charge. At the boundaries of their contact with each other and other components of the paper sheet, the electric double layer is significantly enhanced, making the paper strengthened.

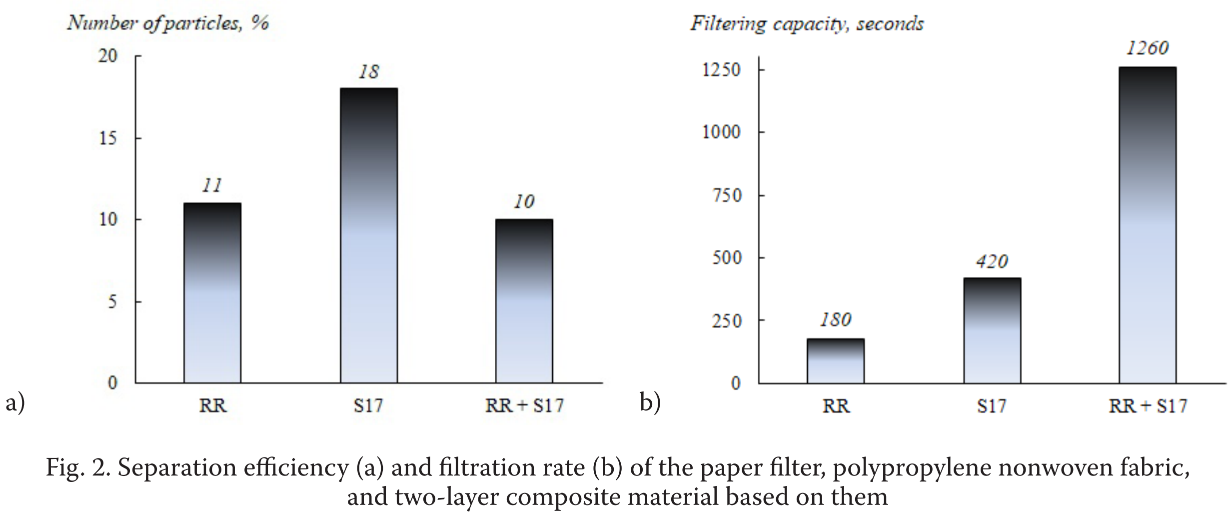

Fig. 2. Separation efficiency (a) and filtration rate (b) of the paper filter, polypropylene nonwoven fabric, and two-layer composite material based on them

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This should be accompanied by an increase in the ζ-potential of fibers of ash-free filters during electret treatment (Brouwer 1991). Comparing results for original and electret-treated ash-free filters, we found that the ζ-potential value of ERR fibers (–23.7 mV) is greater than for RR fibers (–20.5 mV) by ~15%, which confirms the assumption made.

The charge decay in filter materials is quite predictable. It is known that polarization of polymer dielectrics in a corona discharge proceeds through the injection of charge carriers into their volume and their fixation by various surface and bulk traps. The charge decay is the diffusion result of charge carriers from bulk traps to near-surface ones and further — their release. The release rate is largely determined by the value of the specific bulk electrical conductivity of the material, which in polar materials like cellulose is an order of magnitude higher than in nonpolar ones (Galikhanov, Budarina 2002).

The effectiveness of polymer and paper electret filter materials in ensuring filtrate purity was also studied when determining the separation capacity and filtration rate of the filtering materials (Fig. 3).

Electret treatment of the samples led to a reduction in the number of contaminating particles in the filtrate by ~80% for ash-free paper filters and by ~30% for the polypropylene nonwoven fabric compared to the original samples. The deposition of particles on filter paper charged samples occurs due to the attraction of neutral inclusion particles by electrostatic forces of charged paper fibers. At the same time, the ability of the filter material's electric field to extend to relatively large distances from its surface enables a rise in its operating efficiency. The filtration time after imparting an electret state to the samples increases by 1.3 times on average.

The separation and filtration capacities of cellulose-paper filter materials are closely dependent on their sorption properties. Therefore, to explain the observed patterns, the nature of the interaction between liquids and filter materials was studied. One of the most informative methods for studying the interaction between solids and liquids is the method of determining the contact angle of wetting (Fig. 4).

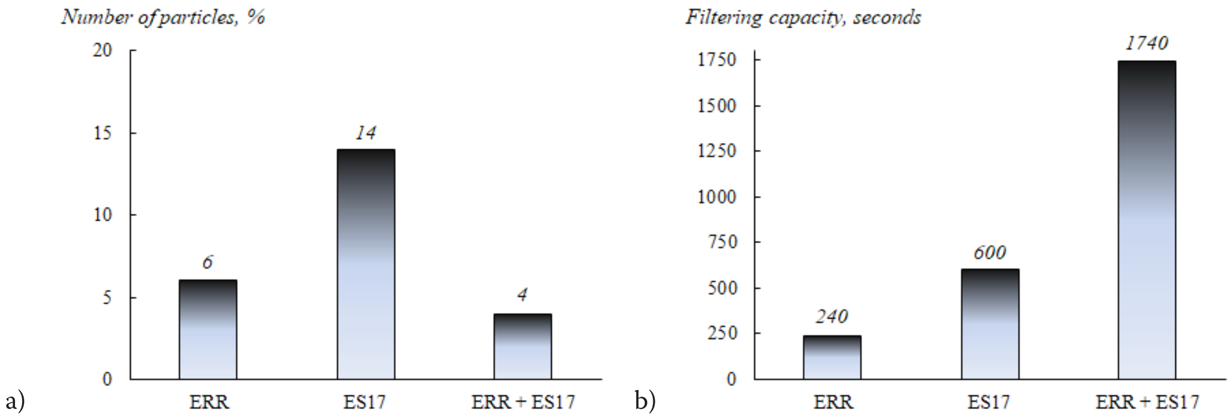

Fig. 3. Separation efficiency (a) and filtration rate (b) of the electret-treated paper filter, the polypropylene nonwoven fabric, and the two-layer composite material based on them

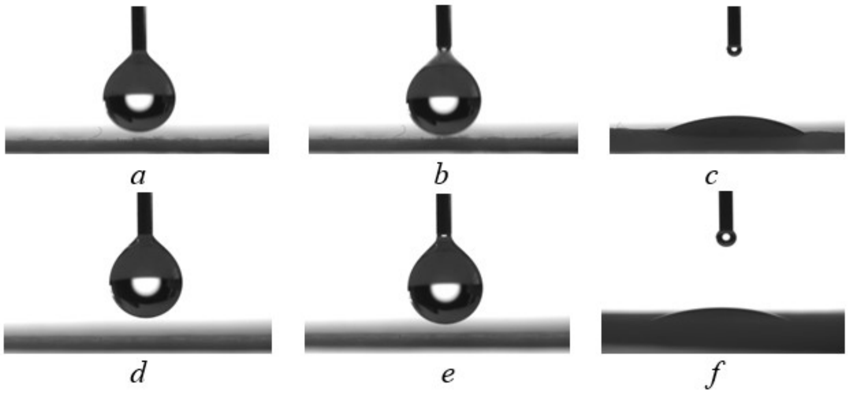

Fig. 4. Determination of the contact angle for untreated samples (a, b, c) and electret-treated samples (d, e, f) of the Red Ribbon material

According to the obtained data, the contact angle of the wetting of samples with water declined from 34.3° to 31.2° upon electret treatment of cellulose-paper filters. This can be explained by the occurrence of physicochemical and mechanical processes in the paper structure under the action of a continuous corona discharge — the increase in the number of active groups on the paper surface after corona treatment facilitates the formation of hydrogen bonds with polar water molecules, which leads to its accelerated spreading. Also, treatment of paper in a corona discharge leads to an increase in the surface roughness of fibers.

The next stage of the work was to test the filtration capacity of bilayer materials in practice. In the SNC cartridge (supernatant capsule cassette) — for example, Pall Supor or similar filters — the filter layers are arranged sequentially, which provides multilevel and effective liquid purification.

Fig. 5 shows a schematic representation of the upgraded SNC-type filter. Outer casing 1, made of chemically resistant plastic (polypropylene), protects the internal components and filtering layers. The first layer 2 is a pre-filter produced by the meltblown method, 0.3 mm thick, designed to capture large particles, fibers, and sediments to prevent premature clogging of subsequent layers. Next are the main filtering layers 3 and 4, made of polypropylene by the meltblown method, which have a thickness of 0.4 mm and a pore size of 0.5 microns. There are also known cases where the main layers are made of polysulfone, polyethersulfone, and nitrocellulose.

Fig. 5. Schematic diagram of the upgraded SNC-type filter: 1 — outer mesh casing; 2 — pre-filter; 3, 4 — main filter layers; 5 — electret-treated ash-free paper filter; 6 — electret-treated support layer made of polypropylene nonwoven fabric; 7 — central perforated tube

As the subsequent layer, we propose to place an electret-treated ash-free Red Ribbon filter 5. The supporting layer 6, located beneath the main one and responsible for the integrity and stability of the structure, preventing its deformation under high pressure, is proposed to be made of electret nonwoven polypropylene fabric. At the very center is tube 7, collecting the purified liquid and directing it further through the system. This sequence of layers provides multistage filtration and extended filter service life.

When this SNC filter was tested for the filtration of synthetic detergents, high separation efficiency was demonstrated. The modification allowed it to be increased by almost 4 times.

Conclusion

We studied the influence of the electrophysical impact — treatment in a unipolar corona discharge — on the filtering characteristics of polypropylene nonwoven fabrics, paper filters, and a two-layer material based on them. By the values of filtering and separating ability, it is shown that the two-layer filtering material, consisting of the ash-free Red Ribbon filter and the spunbond nonwoven polypropylene fabric, demonstrates a synergistic effect, which relates to the fact that the combined use of two materials with different properties provides a significantly higher filtration efficiency than each of the materials separately.

Filter paper is poorly electretized in a corona discharge — after 5 days of storage, the values of the electret characteristics dropped to zero. Electretization of ash-free filters under a unipolar corona discharge is accompanied by an increase in the ζ-potential of the fibers by ~15%. Polymer nonwoven filter materials also have low electret properties, which are still sufficient for practical application.

Electret treatment of the samples led to a reduction in the number of contaminating particles in the filtrate by ~80% for ash-free paper filters and by ~30% for the polypropylene nonwoven fabric compared to the original samples. At the same time, the filtration time after imparting an electret state to the samples increased by 1.3 times on average.

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By testing the filtering capacity of bilayer materials within the supernatant capsule cartridge assembly for filtration of synthetic detergents, we showed high separation capability of the cartridge, with the modification allowing to increase it by almost 4 times.

Conflict of Interest

The authors declare that there is no conflict of interest, either existing or potential.

Author Contributions

All the authors contributed equally to this work.

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