EQUIPMENT FOR PRODUCING MULTILAYER NANOFIBROUS STRUCTURES

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https://doi.org/10.37904/nanocon.2025.5215

Abstract

The article presents the development of a laboratory device for producing combined nanofibrous structures using DC electrospinning (DCES), AC electrospinning (ACES), and electrohydrodynamic printing (EHD printing). The objective was to assess the applicability of these techniques for preparing multilayer and hybrid structures and to design a device concept that enables their implementation.

Experimental work focused on identifying key parameters influencing process stability and fibre quality. The effects of applied voltage, capillary-to-collector distance were investigated. In addition, simulations of the electric field were carried out to provide a basis for optimising electrode geometry and the arrangement of functional components.

Based on experimental data and simulation results, a device concept integrating the three techniques into a single system was proposed. The article describes the configuration of individual modules and their adjustment options. Initial tests are presented, showing the preparation of nanofibrous structures with different morphologies and properties depending on the selected process parameters.

The findings indicate that combining DCES, ACES, and EHD printing is suitable for the fabrication of composite nanostructures. The proposed device concept provides a foundation for further development aimed at applications in tissue engineering, functional coatings, and biomedical materials.

Keywords: electrospinning, EHD printing, tissue engineering, nanofibrous structures

1. INTRODUCTION

In recent decades, nanofibers have gained significant attention across various fields due to their unique structural properties, large surface area, and versatile functionality. Applications range from air and water filtration [1, 2], protective textiles [3], medical dressings with controlled drug release [4], to advanced scaffolds for tissue engineering [5]. The most common method for nanofiber production is electrospinning, an electrohydrodynamic process where polymer solutions or melts are stretched into fibers under a high-voltage electric field [6, 7].

The DC electrospinning (DCES) method, utilizing a direct current (DC) electric field, is widely used in laboratory and industrial practice for its relative simplicity and scalability [8]. In contrast, AC electrospinning (ACES) employs an alternating current (AC) field, which can enhance fiber alignment and potentially increase production throughput due to reduced charge accumulation on the fibers [9]. Another promising technology, EHD printing, combines the precision of additive manufacturing with the nanoscale resolution of electrospinning, allowing controlled deposition of nanofibrous filaments into predefined 3D architectures [10].

Despite extensive research on individual methods, there is a lack of integrated technological solutions combining DCES, ACES, and EHD printing within a single device. Such an integrated approach could enable the production of complex, multi-layered nanofiber structures with tailored properties for advanced applications in medicine, filtration, and functional materials.

This paper presents the design and construction of a laboratory device capable of combining DCES, ACES, and EHD printing within a modular framework. The proposed solution is based on detailed theoretical analysis, electrostatic simulations, and practical experiments, which define key technological parameters for stable fiber formation and deposition. By integrating these methods, the developed equipment offers new possibilities for fabricating sophisticated nanofibrous 3D structures (so-called scaffolds), which are particularly relevant for tissue engineering applications.

2. EXPERIMENT

In the experimental part of the work, technological parameters of three fiber-forming methods – DC electrospinning (DCES), AC electrospinning (ACES), and EHD printing – were systematically investigated (see **Figure 1**) with the aim of determining the conditions for their practical implementation and assessing the feasibility of their combination within a single device. Particular attention was paid to the method and accuracy of polymer solution dosing, as this factor has a decisive impact on process stability and the properties of the resulting nanofiber layers.

In the initial stage of the experiments, gear pumps, which are commonly used in ACES technologies, were tested. Their advantage lies in the possibility of operating in overflow mode; in fact, for ACES, it is generally required to overflow the electrode with the polymer solution in order to maintain a stable process [11]. However, it was found that these pumps are not suitable for EHD printing, as they do not allow for extremely low flow rates in the range of tens of µl/h, which are required for this process. On the other hand, their functionality was confirmed for both DCES and ACES, where stable process conditions and appropriate nanofiber structures were achieved. During ACES testing, fiber formation was achieved at an effective voltage of approximately 4.5 kV and a collector distance of 30–50 mm, although the fibers did not deposit on the collector surface. Only when the distance was reduced to 15–20 mm did fiber deposition occur, but the resulting structures closely resembled those typically formed by DCES. This finding demonstrated that collector geometry and manufacturing precision have a critical influence on the fiber-forming process.

To ensure more precise dosing, an infusion syringe pump was subsequently employed, allowing flow rates from tens of µl/h up to several ml/min. This adjustment enabled the successful implementation of EHD printing and the determination of its optimal process parameters. It was established that with a needle diameter of 0.9 mm, a collector distance of 3 mm, an applied voltage of 3 kV, and a dosing rate of 20 µl/h, a stable Taylor cone could be formed, resulting in a single continuous fiber with a diameter of approximately 1.8 µm. Microscopic analysis confirmed the capability of this technology to generate oriented and homogeneous structures.

Figure 1 illustrates both the course of the experiments and the resulting structures: in **Figures 1a–c** the deposition of fibers on the collector is shown for DCES, ACES, and EHD-printing, respectively, while **Figures 1d–f** display the corresponding nanofiber structures obtained by each technology. The experiments clearly demonstrate stable fiber production across all tested methods.

Comprehensive evaluation revealed that all three technologies can be implemented within a single device, although their combination is limited by the type of dosing system used. With a gear pump, DCES and ACES can be combined, while the infusion pump enables the combination of DCES and EHD printing. The combination of ACES and EHD printing requires alternating use of both systems. The experimental results thus provide essential groundwork for the design of a multifunctional device capable of producing combined nanofiber materials with controlled parameters and variable structure.

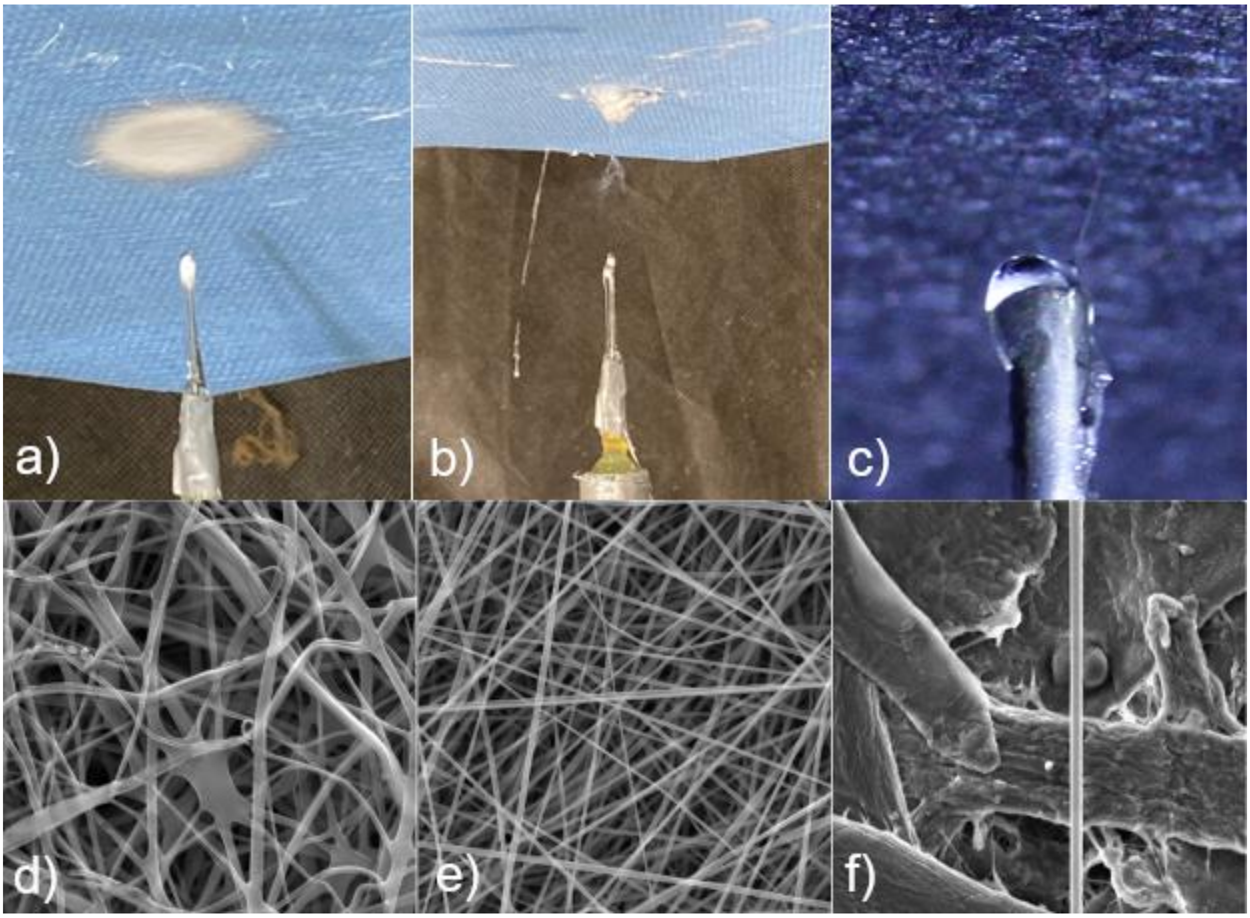

Figure 1 examples of experiments, a) DCES experiment, b) ACES experiment, c) EHD printing experiment, d) DCES fiber structure, e) ACES fiber structures, f) EHD printing fiber

3. SIMULATION

The aim of the simulations was to investigate the behaviour of the electric field intensity at different positions of the nozzle and the collector, with particular emphasis on the edge of the working area. The analysis was motivated by the fact that sharp collector edges may cause a critical increase in electric field intensity, potentially leading to process instabilities. **Figure 2** shows the computational model, including the arrangement of the nozzle, the polymer solution droplet, and the collector. The simulations were carried out in 2D, with local mesh refinement in regions expected to exhibit high electric field intensity.

Two collector designs with edge rounding were evaluated. The first employed a 3D-printed PLA annulus, offering simple and rapid fabrication (hereafter referred to as the PLA design). The second is considered a fully metallic, rounded collector, manufactured, for example, by sheet metal drawing; although it is more challenging to produce, this variant was expected to deliver superior physical performance (hereafter referred to as the metallic design).

The results for the PLA design are presented in **Figure 3**. The electric field intensity reached its maximum directly above the nozzle and decreased symmetrically in both directions. This distribution remained nearly unchanged up to a certain distance from the centre, while the maximum value directly under the nozzle was preserved. When the nozzle approached the outer edge of the collector, however, the electric field intensity began to increase sharply.

The corresponding results for the metallic design are shown in **Figure 3**. The overall distribution pattern was similar, with the maximum again located directly above the nozzle and decreasing symmetrically outward. In contrast to the PLA variant, however, the metallic edge more effectively suppressed the sharp rise in electric field intensity near the collector rim.

A direct comparison of both solutions indicates that the maximum values of electric field intensity in the edge region were higher for the PLA design than for the metallic one. This demonstrates that the metallic variant, owing to its different permittivity, provides a more uniform field distribution and reduces the risk of local intensification.

From a practical perspective, the PLA design can still be considered suitable for mitigating corona discharges and offers a readily available solution for rapid prototyping or cost-sensitive applications. Nevertheless, for nanofiber fabrication, it is recommended to utilise only part of the collector surface up to 80% of its area so that the nozzle does not approach the edge region. The metallic design, on the other hand, ensures a more uniform electric field distribution across the full area of the collector and is therefore preferable in applications requiring high process stability and consistent nanofiber quality.

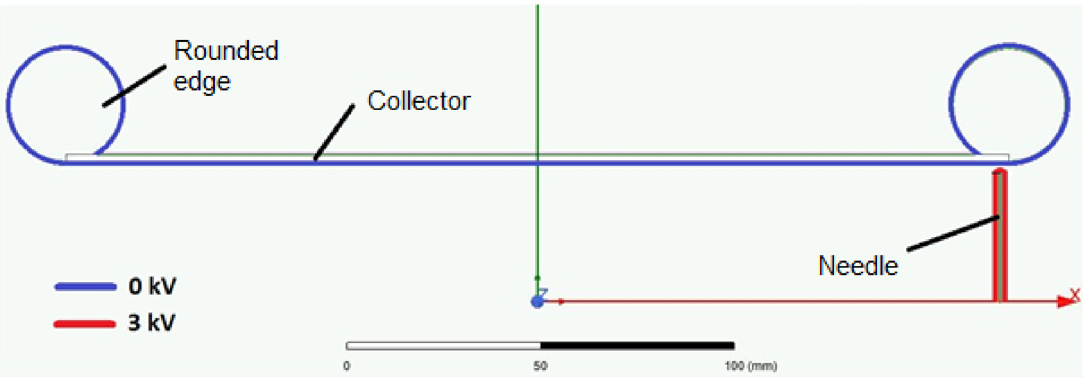

Figure 2 computational model

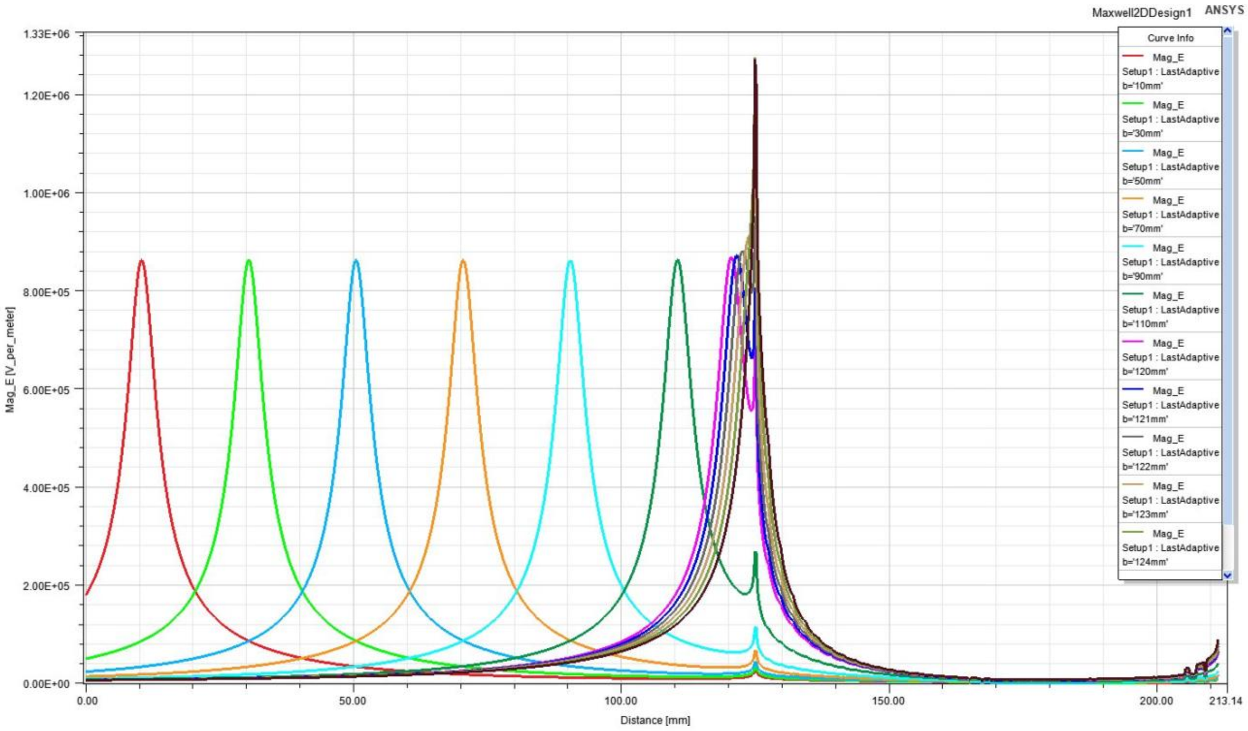

Figure 3 Graph of the distribution of the electrostatic field intensity on the collector with PLA edge

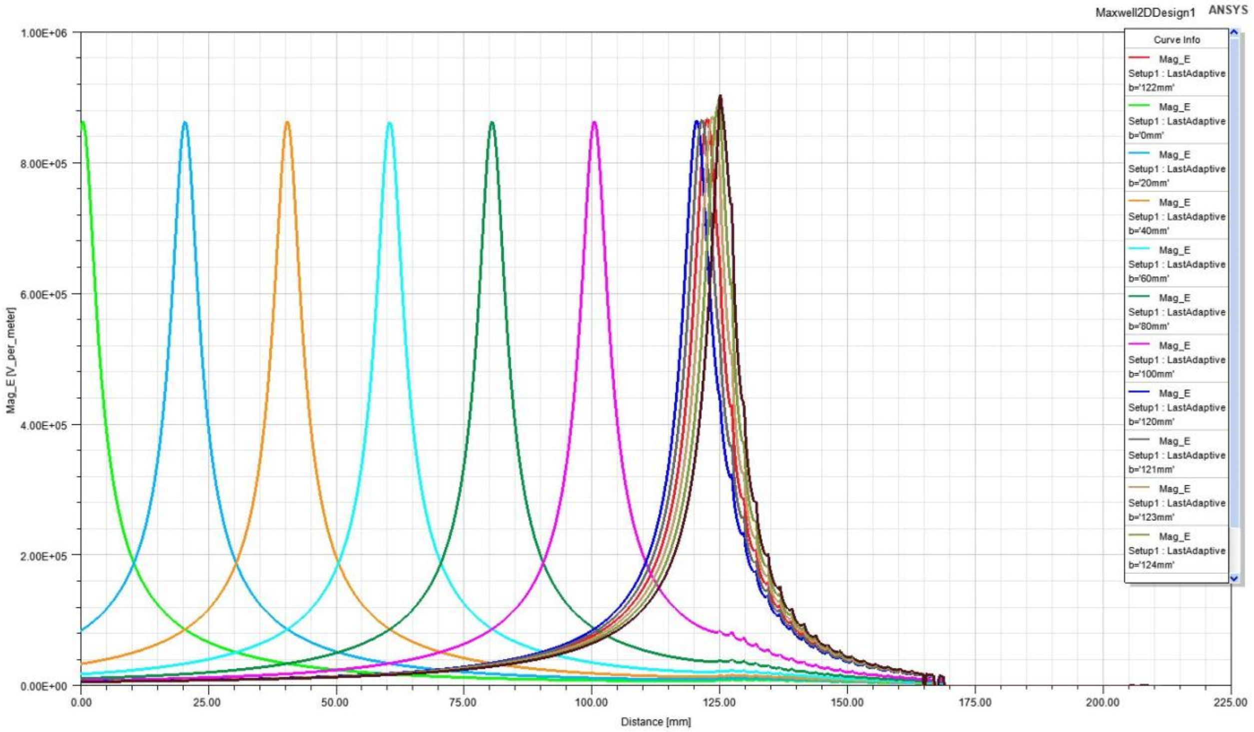

Figure 4 Graph of the distribution of the electrostatic field intensity on the collector the collector with metal edge

4. CONCLUSION

The work identified process parameters suitable for the combination of DC electrospinning, AC electrospinning and electrohydrodynamic printing in an integrated compact device. The optimal voltage values, distances between the electrodes and the collector, and technological conditions such as the polymer solution dosing rates were determined, which ensure stable process flow and the formation of high-quality nanofibrous structures. At the same time, it was demonstrated that the structural arrangement of the collector and the choice of its geometry significantly affect the distribution of the electric field and thus the stability and resulting morphology of the fibers. Simulation results showed that appropriate optimisation of these parameters allows for a more uniform field and higher process reliability. The obtained knowledge represents a significant step towards the development of a new generation of devices for the production of nanofibrous materials. An integrated and modular approach paves the way for the effective preparation of multilayer and hybrid structures with precisely controlled properties. Such a device has the potential to expand the possibilities of applications in tissue engineering and biomedicine and become a freely available technological platform for future innovations in these fields.

ACKNOWLEDGEMENTS

This publication was written at the Technical University of Liberec as part of the project with the support of the Specific University Research Grant 2025- 5546.

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