AC ELECTROSPINNING: DEVICE FOR CONTROLLED PRODUCTION OF PLANAR, SINGLELAYER NANOFIBER PLUME

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Abstract

The work focuses on the development of a linear electrode for the production of flat nanofibrous material by spinning a polymer solution using the AC electrospinning technique. This method is characterized by high productivity and the absence of an electrically active collector, which predisposes it to the production of advanced nanofibrous structures that will find application in medical and technical applications such as filtration or tissue engineering.

Current spinning electrodes for AC electrospinning are characterized by a spinning surface with an overcritical electric field strength, from which polymer jets and subsequent nanofibers are created in all directions. A spatial, hollow nanofibrous plume is created by the natural periodic interconnection of fibers in the area of the virtual collector. The transport and deposition of such a nanofibrous structure on the supportive spunbond is unstable, when due to the air emerging from the inner space with higher concentration of the residual solvent, folds and other defects are created.

By the geometrically modified electrodes with the help of simulation tools for electric field analysis, it is possible to efficiently modify the geometry and the working surface of the electrode so that the nanofibers are formed only in a single plane, thereby eliminating the negative effects of the spatial nanofibrous plume.

Based on the analyses, electrodes capable of continuous operation producing nanofibers in the single plane and in the desired direction producing a planar nanofiber structure are developed and tested.

With the use of these advanced devices, it is possible to produce more homogeneous surface layered nanofiber materials and advanced nanofiber structures for use especially in medical applications.

Keywords: AC electrospinning, polymeric nanofibers, flat nanofibrous layer, electric field analysis, spinning electrode

1. INTRODUCTION

One of the essential added values of nanofibrous materials is their high specific surface area, which significantly increases their reactivity and efficiency in many applications. Due to their high porosity while maintaining a small pore size, nanofibrous layers can be advantageously used for filtration. Many nanofibrous materials are also biocompatible, predisposing them to biomedical applications. Thanks to these properties, nanofibrous materials are used in biomedicine [1], [2] and tissue engineering [3], filtration [4] and in energy as components of advanced batteries and fuel cells [5]. With continued intensive development, the application of nanomaterials continues to expand [6].

There are several technologies for the production of polymeric nanofibers, such as drawing [7] or forcespinning [8], but electrospinning in a direct electric field (DC electrospinnig) [9] is the most used one in industrial production. Electrospinning in an alternating electric field (AC electrospinning) is a new, highly productive technology for the production of polymer nanofibers, which does not require a counter-electrode typical for direct current spinning, thus opening the way for the production of unique nanofiber structures [8].

Electrospinning technique is based on the difference in electric potentials in the order of tens of kilovolts. In DC electrospinning, the difference is ensured by the presence of a charged counter-electrode. In AC electrospinning technology, an electric field is created between the electrode and the so-called virtual collector. A virtual collector is formed in the air in the vicinity of the electrode due to a periodical change in its polarity and, according to the theory of AC spinning, is formed by charged ions of the air environment and charged segments of nanofibers. The nanofibers are then always created in the direction of the gradient of the electric field from the spinning electrode to the virtual collector to its entire surroundings.

In the area of the virtual collector, fibers moving from the electrode slow down and their mechanical interconnection occurs. The structure of interconnected nanofibers floating above the electrode is called a nanofiber plume. It is possible to manipulate the plume further, for example by placing it on a spunbond or wrapping it on a yarn for the production of a composite yarn with a nanofiber coating [10].

Electrodes used for AC electrospinning, such as the rod-like electrode [10] or the cable electrode, are designed especially towards high productivity. From their working surface with a supercritical electric field strength, nanofibers are created in all directions, which after their connection leads to the formation of a hollow or otherwise closed nanofiber plume.

When the hollow plume is deposited on the spunbond, especially with rod-like electrodes, two layers are applied at once. Leaking air from the space between them then causes irregular folds and other errors in the laying of the plume. The inner space may also contain an increased concentration of vaporized solvent of the polymer solution, which may be the cause of defects in the produced fibers.

2. THEORY OF AC ELECTROSPINNIG

In order to initiate the process of nanofibers spinning on the electrode, a high electric field strength must be applied to the polymeric solution, which will cause the surface tension to be overcome and form Taylor cones. This is determined by the difference in electric potential - the magnitude of the spinning voltage, the relative permittivity of the environment and the geometry of the electrode parts. As the radius of curvature decreases, the concentration of electric charge on the surface of the electrode increases and, as a result, the strength of the electric field is highest in the region of the apexes. This physical principle is used in the design of the spinning area of the electrode. Spinning of the polymeric solution occurs only if the limiting critical value of the electric field strength is exceeded. Not all nanofibers that are created by the effect of the electric field have sufficient energy to connect with the plume. Due to gravity and electrical forces, some of the fibers fall back onto the electrode and into its surroundings. These residual fibers, if deposited on the dry surface of the electrode, gradually change its geometry and can lead to defects in the produced material or to a complete interruption of spinning. Therefore, the design of the electrode for continuous operation must appropriately prevent contamination of the key parts of the electrode with nanofibers. Among the simplest solutions is redissolving of the incident nanofibers in excess of polymeric solution.

The spinning area of the electrode can be closed, without ends (ring, circle), or open, with ends (linear electrode). The closed construction of the spinning region has an indisputable advantage in the homogeneity of the electric field in its vicinity, thanks to which it produces a homogeneous nanofibrous structure around its entire area. However, a nanofibrous plume in the shape of a hollow tube is created. The open spinning region generally has a different overall curvature at its ends than in the part in between. Therefore, a nanofibrous plume with a slightly different structure or different specific weight is formed at the ends.

3. DESIGN OF THE ELECTRODES

Two designs of spinning electrodes for AC electrospinning producing a planar nanofibrous plume were designed. The first, the disc electrode (see **Figure 1.A**) is a suitable design adaptation of the linear electrode so that a continuous homogeneous supply of the polymeric solution and cleaning of the spinning area can be simply provided. It consists of a thin disk rotating around its horizontally oriented axis. In the lower part, where the strength of the electric field is reduced thanks to the frame, the outer edge of the disc is cleaned and a polymeric solution is applied to it, while in the upper part fibers are formed. Thanks to spinning from the thin edge of the disc, a planar nanofibrous plume is formed. Its width is proportional to the diameter of the disc and is limited for use on small widths of the produced material, approximately up to 500 mm.

For the production of material with a larger width, theoretically unlimited, a cable electrode is suitable (see **Figure 1.B**). It consists of a wire or cable wound between a pair of pulleys. The polymeric solution can be applied to the cable while pulleys are going through the solution or with a nozzle. The strength of the electric field in the vicinity of the cable is supercritical and spinning takes place here.

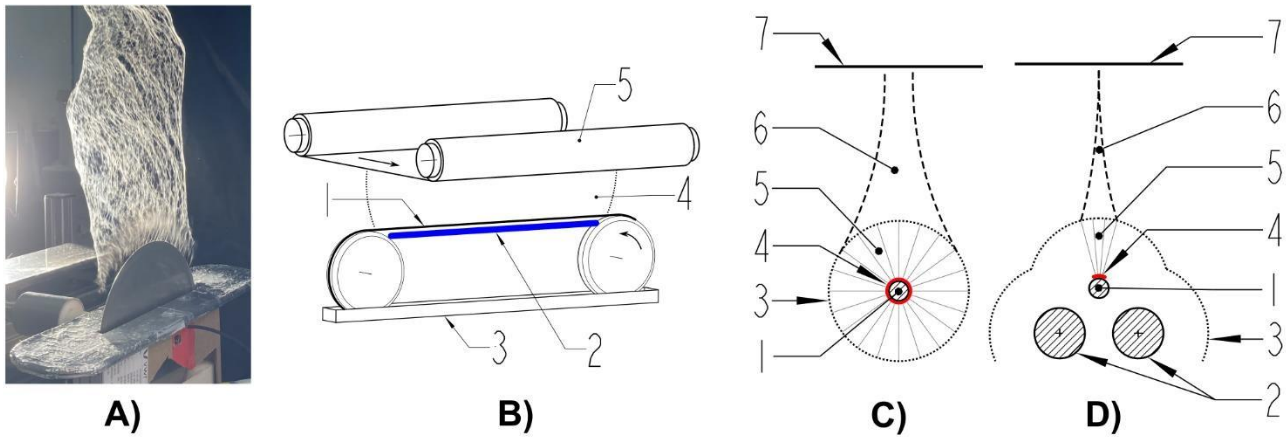

Figure 1 A) Disc-like electrode, **B)** Modified cable electrode: Cable (1), shielding elements (2), reservoir with polymeric solution (3), nanofibrous plume (4), spunbond (5). Schematic representation of spinning of nanofibers on unsuppressed **(C)** and partially-suppressed cable electrode **(D)** in section: cable with polymeric solution (1), shielding elements (2), area of virtual collector (3), area with supercritical strength of electric field (4), nanofibers (5), nanofibrous plume (6) and spunbond (7).

From the point of view of the size of the nanofiber plume, it is a hybrid type showing the characteristics of all the mentioned variants. In general view, this is an electrode with an open spinning area, the nanofibrous plume is flat with edges above the pulleys on both sides. However, in a detailed view of the section of the spinning area (see **Figure 1.C**), the area with supercritical strength of the field on the surface of the cable is closed, spinning runs homogeneously in the entire surroundings, and there is a hollow, closed space between the plume in the area of virtual collector and the spinning electrode. The interconnected nanofibrous plume does not have a clearly defined direction of motion and goes most often up due to external suction and the weak effect of the electric wind.

The aim of modifying the cable electrode is to reduce the strength of the electric field by means of shielding elements on part of its surface, as shown in **Figure 1.D**, so that the character of fiber spinning is similar to a disk electrode. Shielding elements made of electrically conductive material are connected at the same electric potential as the spinning electrode (see **Figure 3.B**). Thanks to this arrangement, the strength of the electric field on the spinning electrode surface exceeds the supercritical value only on a certain section. The nanofiber plume has thus a narrow planar character with a preferred direction of movement.

4. VERIFICATION OF DESIGN WITH PARTIALY SUPPRESSED CABLE ELECTRODE

Simulation tools for electric field analysis are used to study the effect of design and geometric arrangement on the size and shape of the electrode spinning region. To define the task, it is necessary to make several simplifying assumptions. The task is simplified to a static one, so instead of an alternating voltage, a direct current voltage with the same effective value is considered on the electrode. To specify the boundary condition, the theory of a virtual collector is used, which surrounds the spinning electrode with a constant distance, and a voltage of 0 V is assumed here. It is observable during spinning as a region with rapid decrease of nanofibers, and its distance is dependent, among other things, on the frequency of the spinning voltage waveform.

Numerical simulations were performed in the ANSYS Electronics Desktop 2019 program. The boundary condition of the effective electrode voltage U_{ef} was considered to be 35 kV. The distance of the virtual collector from the surface of the electrode, or each element with the boundary condition U_{ef}, was considered to be 50 mm. The model was built using symmetry as a half 2D problem (see **Figure 2** and **Figure 3**).

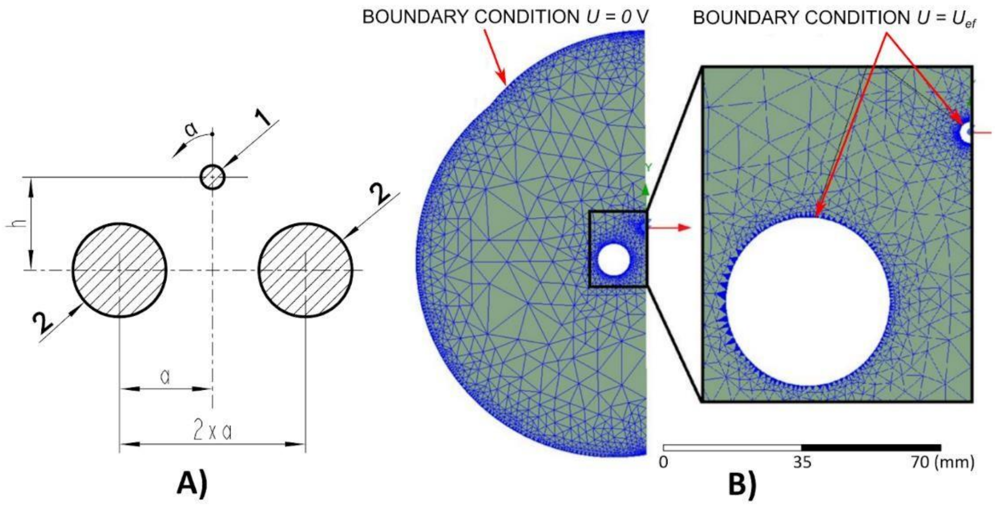

Figure 2 A: Schematic representation of cable electrode (1) with shielding elements (2) in section. **B:** Model of the air environment around the electrode, the shielding elements and the virtual collector with the maximum mesh size: near the electrode - 0.001 mm, near the shielding elements - 0.01 mm.

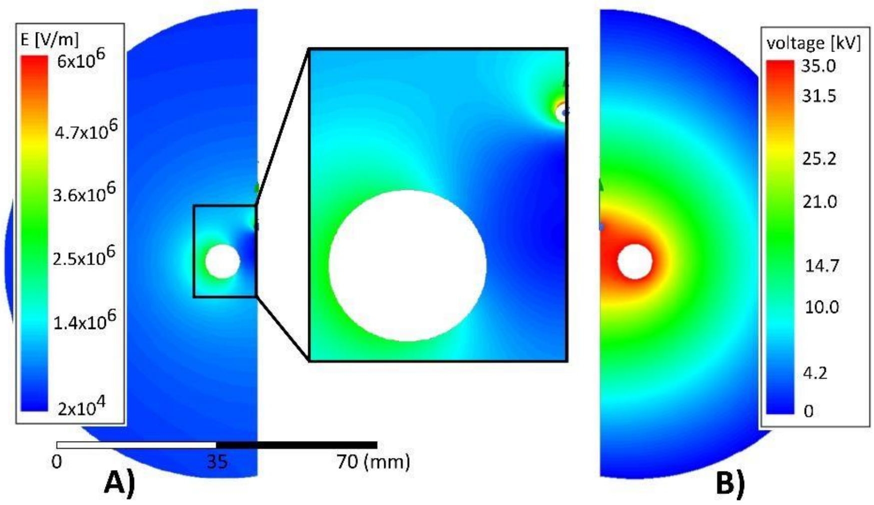

Figure 3 Distribution of electric field strength **(A)** and voltage **(B)** around the electrode with shielding elements according to Fig. 2.A. Applied effective voltage is 35 kV.

A total of 64 variants of the dimensional arrangement of the electrode and shielding elements were simulated in order to find a suitable solution so that spinning occurs only on the part of the electrode facing away from the shielding elements and at the same time so that the strength of the field increase to the supercritical value is as steep as possible. The parameters of the spacing of the shielding elements and their distance from the electrode according to **Figure 2.A** were analyzed in the range a: 8-12 mm and h: 2-10 mm. The diameter of the wire electrode was 1 mm and the diameter of the shielding elements was 8 mm, when the guaranteed subcritical strength of the electric field is experimentally verified, so that there are no electric discharges or possibly spinning on them. Based on experience and comparing experiments with simulations, the critical value of the electric field strength was set at 3000 kV/m.

5. RESULTS AND DISCUSSION

In the performed 2D planar analysis, the value of the electric field strength on the surface of the spinning cable part around the entire perimeter was evaluated (see **Figure 3**). For the selected variants the field strength value is shown in the **Figure 4**. The processing of the obtained data and selection of the best dimensional arrangement was carried out according to the criterion of the highest steepness of the increase in the electric field strength in the region of the transition over the critical value for spinning. From the point of view of the spinning process and fiber formation, a constant value over the spinning area with a jump increase and decrease at the ends is suitable, which is what the design tries to approach.

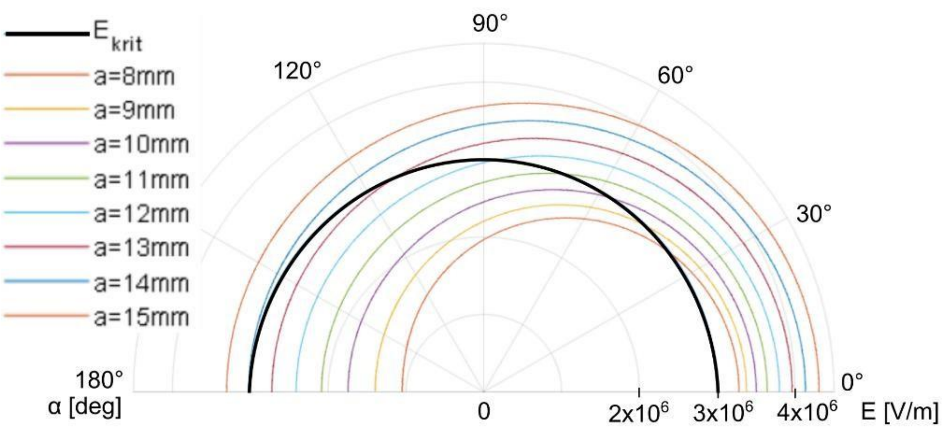

Figure 4 Electric field strength on the electrode surface as a function of the alpha angle according to Fig. 2.A for selected variants. The black line shows the critical electric field strength.

The obtained dependences of the electric field strength on the electrode surface were interleaved with a polynomial curve of degree 9 and then derivative to determine the dimensional arrangement with the highest steepness of the strength of the field increase according to the highest value of the derivative. Based on this analysis, the dimensional option with parameters a=8 mm and h=8 mm was selected as the most suitable for the design.

6. CONCLUSION

Due to its simple design and easy supply of polymer solution, the disc-like electrode is a suitable adaptation of the linear electrode for laboratory purposes and for the production of small-width layers. It forms a singlelayer planar nanofibrous siding with a clear preferred direction of advancement upward from the electrode.

The designed modified cable electrode retains the similar character of nanofiber plume produced by the disc electrode and additionally allows for increasing the fiber production and width of the material produced. Thanks to additional shielding elements, it produces a low thickness nanofibre plume with a preferred direction of motion.

The shielding elements of the cable electrode shall be made of conductive material and placed close to the electrode according to simulation results. For tests, these may be stationary metal rods, but for long-term operation, continuous cleaning is required. A variant with shielding elements as circular belts rewinded together with the cable electrode was already tested. A layer of polymer solution is applied to the belts enabling continuous dissolution of the residual fibers. The polymer solution also provides the electrical charge to the shielding belts, however, due to the subcritical field strength, the spinning does not occur on their surface.

Due to the preferred direction of the motion of the nanofiber plume, the partially suppressed cable electrode does not require such a high level of additional suction, which reduces the energy demands on the device, but due to the spinning only on a part of the surface of the electrode, its productivity is reduced.

The designed electrodes are capable of producing a nanofibrous material with the specific property of a single layer of a planar nanofibrous plume and thus have the potential to be used in the production of specific multilayer materials or even linear nanofiber structures.

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