DEVELOPMENT AND RESEARCH OF A NEW TECHNOLOGY FOR CORE- SHEATH NANOFIBER YARN PRODUCTION

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Abstract

The aim of this work is the development of a new technology for the production of core-sheath nanofiber yarn based on applying a nanofiber bundle onto a ballooning yarn core in a parallel orientation. In contrast to the currently used perpendicular deposition methods, this concept enables the fibers to be applied at a single point, which is expected to achieve higher cohesion between the nanofiber sheath and the core. An innovative design of a core spinning electrode enabling the passage of the yarn core through the center of the spinning electrode was proposed and manufactured. Several electrode variants, including single-stage and two-stage configurations, were experimentally tested, and their productivity, process stability, and yarn quality were evaluated. The best performance was achieved with a two-stage electrode, where a productivity of 0.35 ± 0.02 g/min was measured at a voltage of 50 kV. Initial experiments confirmed the feasibility of long-term production of core-sheath nanofiber yarn using the proposed technology. However, several areas requiring further optimization were identified, particularly ensuring uniform fiber drying and minimizing defects in the yarn structure. The results indicate that the newly developed technology has significant potential to expand the possibilities of industrial production of nanofiber-based materials and open up new application areas.

Keywords: Core-sheath nanofiber yarn, AC electrospinning, core electrode, nanofibers

1. INTRODUCTION

The introduction should provide a clear statement of the study, the relevant literature on the study subject and the proposed approach or solution. Nanofibers represent a specific class of nanomaterials with diameters typically below 100 nm, characterized by an extremely high surface-to-volume ratio and the ability to control their morphology and internal structure. Owing to these properties, they are considered highly promising materials for a wide range of industrial and biomedical applications. The most common fabrication technique is electrospinning, which allows the production of continuous nanofibers from polymer solutions or melts in macroscopically useful quantities. This method is relatively simple, easily scalable, and has been intensively studied for more than two decades, both in terms of experimental optimization and theoretical modelling of the fiber jet behaviour [1–3]. In recent years, alternative methods such as solution blow spinning and centrifugal spinning have been developed, further broadening the possibilities for tailoring fiber morphology and enabling the preparation of specific structures [4].

In addition to the widely studied nanofiber mats, which typically form thin nonwoven layers, research has increasingly focused on the fabrication of nanofiber yarns. These yarns are created by assembling nanofibers into linear formations that can subsequently be processed by twisting or plying and used in textile or composite applications. Their main advantage lies in combining the unique properties of nanofibers—namely, large surface area and the ability for functional modification—with the mechanical strength and flexibility of conventional textile fibers [5,6]. As a result, nanofiber yarns are considered promising materials for advanced filtration systems, smart textiles, biomedical implants, conductive or semi-conductive structures, and composite reinforcements [7–10].

Currently, a technology for producing core–shell nanofiber yarns is known, in which a nanofiber bundle prepared by AC electrospinning is deposited perpendicularly onto a ballooning yarn core. This principle has also been described in patent literature, where both the method and the device for producing a yarn coated with a nanofiber layer are presented [11]. Although this approach enables the preparation of stable nanofiber-coated yarns, there remains the question of whether the adhesion and homogeneity of the nanofiber sheath could be further improved by modifying the deposition configuration. The aim of this work is therefore to develop a technology in which the nanofiber bundle is deposited parallel to the yarn axis, with the yarn core passing through the center of the bundle and the spinning electrode.

2. METHODS

Technological configuration

Figure 1 schematically illustrates the design concept of the core electrode for the production of core–shell nanofiber yarns. This approach is expected to improve the adhesion between the nanofiber sheath and the yarn core, as fiber deposition theoretically occurs at a single point. At the same time, the torque acting on the nanofibers is increased, which enhances their entanglement with the yarn core. As a result, the produced core–shell nanofiber yarns are expected to exhibit a more homogeneous structure, potentially enhanced mechanical properties, and broader application potential.

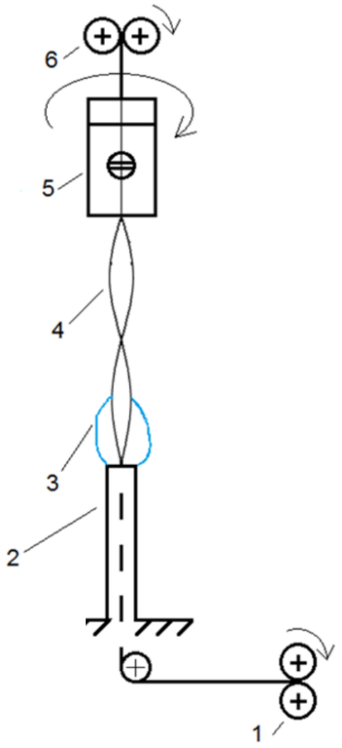

Figure 1 Schematic of the proposed system for the production of core–shell nanofiber yarn; 1 – unwinding unit, 2 – spinning electrode, 3 – nanofiber bundle, 4 – ballooning core, 5 – twisting unit, 6 – winding unit

Design of the core– sheath spinneret

In the second stage of developing a new technology for core–shell nanofiber yarn production, it was necessary to focus on the design of a spinneret that allows the yarn core to pass through its center. For AC electrospinning, so-called overflow spinnerets are commonly used. The principle of such a spinneret is illustrated in **Figure 2**. Typically, it consists of a tube with a conical top (**Figure 2a** (1)). A polymer solution (2) is extruded through the center of the spinneret, from which nanofibers are generated on the electrode surface under a supercritical electric field. The residual, non-spun solution flows back along the outer surface of the spinneret into a reservoir; this surface is referred to as the overflow surface. Continuous overflowing is essential to prevent the electrode surface from being contaminated by parasitic nanofibers, which would lead to process instability [4].

When designing a spinneret for core–shell nanofiber yarn production, this effect must be considered. If the yarn core is to pass through the center of the spinneret, it must be guided by a separate inner tube coaxial with the spinneret, as indicated in **Figure 2b** (3). Passing the core directly through the polymer solution is not feasible, since wetting would occur and the deposited solution would degrade the nanofibers collected on the yarn. However, the arrangement shown in **Figure 2b**, where tube (3) extends above the polymer solution surface, is also unsuitable: its unwetted portion would be contaminated by nanofibers, again leading to process instability. Therefore, it is necessary to design a new spinneret configuration suitable for the production of core–shell nanofiber yarns.

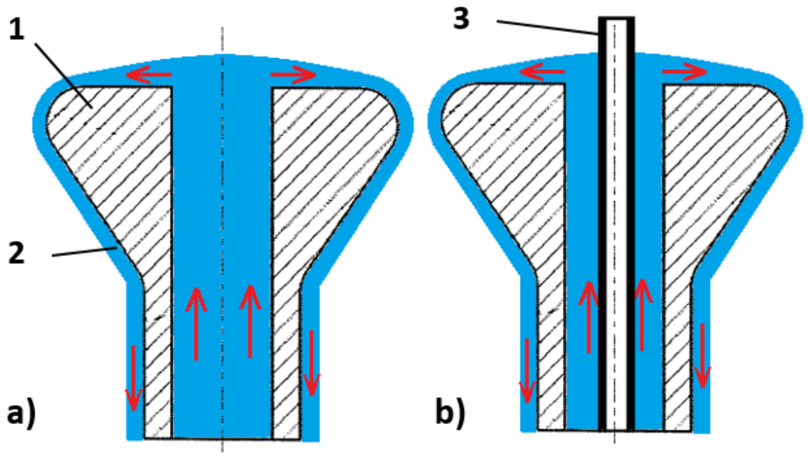

Figure 2 Schematic of the overflow spinneret a) standard design: electrode body (1), polymer solution (2); b) unsuitable design with inner tube (3)

The proposed design and function of the new core–sheath spinneret are illustrated in cross-section in **Figures 3 I.a and I.b**. The spinneret consists of an inlet channel (1), which delivers the polymer solution (6) to the top of the electrode. From there, the solution flows over the electrode edges, where nanofibers are typically formed, and further overflows along both the outer overflow surface (2) and the inner overflow surface (3). The yarn core passes through the electrode via the guiding channel (5). The solution flowing down the inner overflow surface (3) is drained from the space between this surface and the core guiding channel (5) by means of a bypass channel (4). A cylindrical partition ensures that this drained solution remains separated from the solution supplied through the inlet channel (1).To ensure the full functionality of the spinneret, the stem of the electrode must also consist of two separate chambers. This is achieved by two coaxial tubes (7) and (8), which together form a double-walled stem.

Figure 3 II. shows various electrode designs developed for experimental verification of functionality and for identifying the geometry that ensures high nanofiber production efficiency. All variants are based on the principle of a conical termination. In variants e), f), and g), a single cone was used, positioned at different distances from the top of the electrode. In variants h), i), and j), a two-stage electrode concept was applied, which is known for its high productivity. These variants differ in their construction, specifically in the spacing between the stages and in the diameter of the first stage. It is well established that these parameters significantly affect both the productivity and the stability of the process. The proposed electrode types were experimentally tested to verify their functionality and to determine productivity, which is discussed in the following chapter.

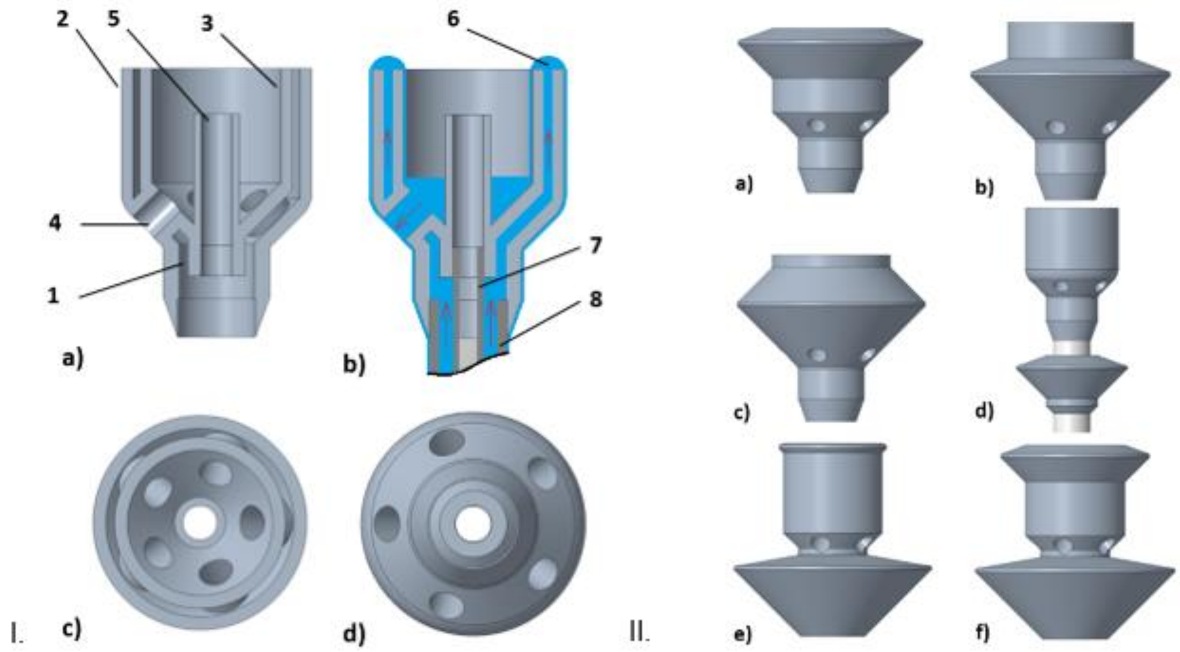

Figure 3 I. Design of the core–sheath spinneret; a) cross-section of the spinneret: inlet channel (1), outer overflow surface (2), inner overflow surface (3), bypass channel (4), inner guiding channel for the yarn core (5); b) principle of spinneret overflowing: polymer solution (6), inner spinneret stem (7), outer spinneret stem (8); c) top view of the spinneret; d) bottom view of the spinneret. **II.** Variants of spinneret design; a) spinneret with a cone at the top; b) spinneret with a cone offset from the top; c) alternative spinneret with a cone offset from the top; d) two-stage spinneret with an additional stage attached to the stem; e) compact two-stage spinneret with the first stage diameter of 22 mm and the lower stage diameter of 40 mm; f) compact two-stage spinneret with the first stage diameter of 30 mm and the lower stage diameter of 40 mm.

3. EXPERIMENT

To verify the functionality of the proposed electrodes, it was first necessary to ensure reliable feeding of the inlet channel, i.e., the spinneret stem, with the polymer solution without undesired inflow into the inner chamber intended for guiding the yarn core. For this purpose, a specially developed polymer dosing system was employed (**Figure 4a**).

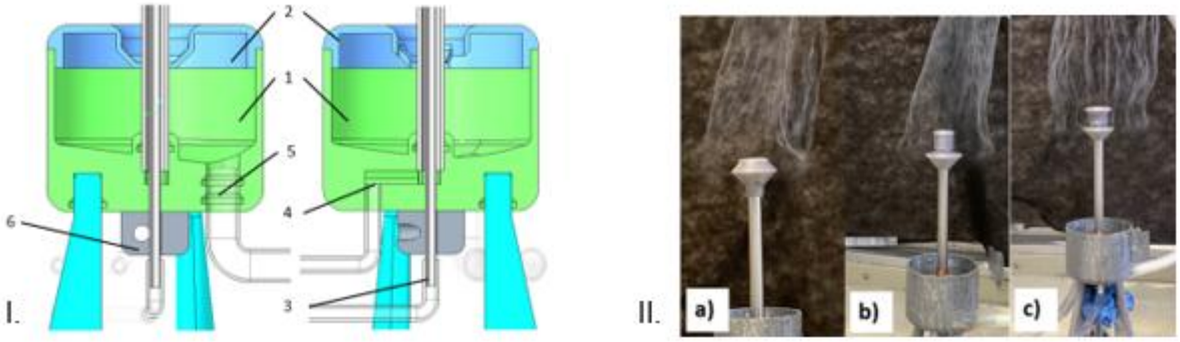

Figure 4 I. Polymer container – reservoir; (1) reservoir vessel, (2) lid, (3) hose connection for the inner tube, (4) hose connection for the outer tube, (5) hose connection for outflow, (6) high-voltage (HV) connector. **II.** Examples of performed experiments; a) spinneret with a cone offset from the top; b) compact two-stage spinneret with the first stage diameter of 22 mm and the lower stage diameter of 40 mm; c) compact two-stage spinneret with the first stage diameter of 30 mm and the lower stage diameter of 40 mm.

4. RESULTS

Preliminary trials of core–sheath nanofiber yarn production were carried out using the electrodes shown in **Figure 4 II**. The results demonstrated that this approach allows long-term and stable yarn fabrication. Selected images from the experiments are presented in **Figure 5**. The experiments were conducted at different rotation speeds of the twisting eyelet, and it was found that this parameter enables control over the point at which the nanofiber bundle is deposited onto the core. The difference is illustrated in **Figure 5**. The initial experiments confirmed the feasibility of producing core–sheath nanofiber yarn using the proposed technology. However, analysis of the produced yarn revealed the presence of certain defects along its length. These defects are likely caused by fibers being deposited onto the core too soon after their formation, before sufficient solvent evaporation had occurred. The presence of residual solvent may have led to partial fiber degradation. This phenomenon could be mitigated by ensuring more efficient fiber drying, for example by increasing the temperature in the spinning chamber and reducing the relative humidity. It is well established that humidity significantly affects the amount of residual solvent in nanofiber structures.

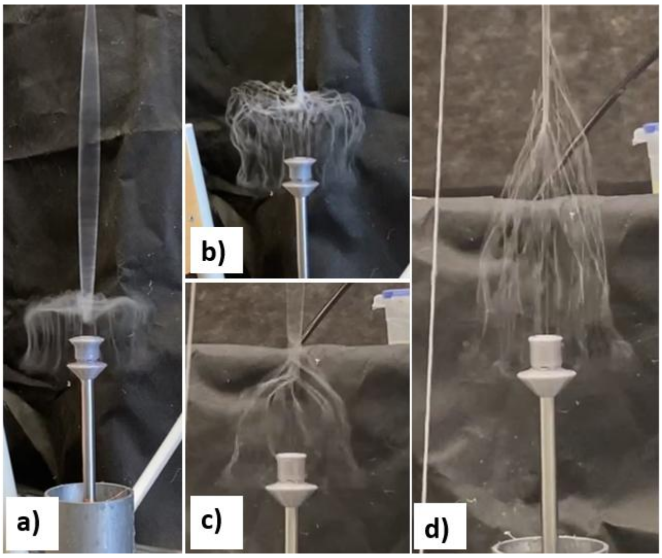

Figure 5 Examples of experiments on core–sheath nanofiber yarn production; a), b) spinneret according to Figure 4c at two different rotation speeds of the twisting eyelet (8000rpm and 11000rpm); c), d) spinneret according to Figure 4b at two different rotation speeds of the twisting eyelet (8000rpm and 11000rpm).

5. CONCLUSION

The preliminary experiments demonstrated that the proposed concept represents a feasible and promising pathway for the development of a new technology for core–sheath nanofiber yarn production. The results confirmed that core–sheath nanofiber yarns can be produced in a continuous and stable manner using specially designed electrodes and a novel technological arrangement. These findings clearly indicate that the concept holds significant potential, and further systematic research and development in this direction are fully justified. At the same time, the experiments also revealed several challenges that must be addressed in the future. In particular, issues of process stability and the occurrence of defects along the produced yarn were observed, mainly caused by insufficient drying of fibers during their deposition onto the core. It was demonstrated that environmental parameters such as temperature and humidity have a decisive effect on yarn quality, and thus must be carefully controlled and optimized. Moreover, the geometry of the applied spinneret, especially the design and spacing of the conical stages, was shown to strongly influence both productivity and process stability. The most stable nanofiber bundle was obtained in the configuration shown in **Figure 5b** at a twisting eyelet speed of 11,000 rpm, which represents an important starting point for further research. In conclusion, the conducted experiments open new opportunities for scientific investigation in the field of nanofiber structure production. Future research should focus not only on a detailed understanding of the influence of individual process parameters but also on the development of a comprehensive technology suitable for industrial implementation. Provided that the identified challenges are successfully addressed and production conditions optimized, it is realistic to expect that this new technology could eventually find application in industrial practice and extend the range of advanced nanomaterials available for diverse applications.

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