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A comprehensive electric field analysis of cylinder-type multi-nozzle electrospinning system for mass production of nanofibers

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ABSTRACT

Electrospinning is the commonly used method for fabrication of micro/nano fibers due to simple setup and intuitive understanding of mechanism. In laboratory scale, single or dual nozzle systems are mainly used to conduct specific experiments and use simple electric power connections and it has uncomplicated electric field distributions. An industrial scale mass production of micro/nano fiber is an essential prerequisite for price competitiveness. For the first time in South Korea, we developed a novel upward cylindrical-type electrospinning system and the study demonstrates the comprehensive electric field simulations of multi-nozzle system and practical test results of the electrospinning system.

Introduction

Electrostatic fiber formation technology broadly termed as Electrospinning, which utilizes electrical forces to produce polymer fibers with diameters ranging from nanometers to several micrometers employing both natural and synthetic polymer solutions. Electrospinning utilizes a high-voltage power source to inject charged polymer solution, which is then accelerated toward a collector connected to opposite charge or polarity. As the electrostatic attraction between the oppositely charged polymer solution and collector as well as the electrostatic repulsions between similar charges in the liquid become stronger, the edge of the polymer solution changes from a rounded meniscus to a cone (the Taylor cone). A fiber jet is ultimately expelled out from the Taylor cone as the electric field strength exceeds the surface tension of the polymer solution. The fiber jet travels through the atmosphere allowing the solvent to evaporate, thus leading to the deposition of solid polymer fibers on the collector. The process of using electrostatic forces to form synthetic fibers has been known for many years. But there has been a tremendous increase in research and commercial attention in this field over the past few decades. Considerable amount of efforts have been invested in research and industrial community to increase the production of nonwoven fabrics for different applications including filters, textile, tissue scaffolds, drug delivery, sensors, and nanocomposite [1–8].

Electrospinning and melt-blowing are the most commonly used processes for production of nonwoven fibers. Melt-blowing technique produced microfibers and has already been applied widely in commercial manner. Even though electrospinning can produce high aspect ratio nanofibers, but the mass production of electrospun fibers has just reached the commercial stage. Therefore, electrospinning is superior to melt-blowing technique to produce fibrous materials for different applications because the fiber diameters have remained larger and uniformity poorer in melt-blowing than those produced by means of electrospinning. However, the production rate of a conventional single-nozzle electrospinning system is very low and cannot be applied for mass production [9].

One-dimensional (1D) nanostructures have been extensively studied because of their importance in various applications [16,17]. Among the reported nanostructures, nanofibers have received special consideration due to several advantages such as, an extremely high surface-to-volume ratio, tunable porosity, malleability to conform to a wide variety of sizes and shapes and the ability to control the nanofiber composition to achieve the desired results from its properties and functionality [18]. Nanofiber

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possesses the characteristic features of high length-to-diameter ratio and specific surface areas, enabling it to be applied for protective clothing, filter, catalyst support, reinforced composite, and tissue engineering. Consequently, nanofibers are excellent candidates for a variety of applications. Electrospinning is the most widespread technique used to prepare nanofibers due to simplicity, low cost, high yield, and good efficiency [19,20]. Electrospinning is a process by which a fiber diameter in the range of 50–1000 nm can be formed. Electrospun nanofibers possess approximately double the surface area of continuous thin films. The electrospun nanofiber mat collects many feature advantages making it unique candidate for the nanotechnological approaches; high surface area, porosity, and ease handling and separation from the reaction media.

Several methods have been developed to enhance the electrospinning production rate. Cylinder-type nozzleless electrospinning system was introduced by ElMARCO and multi-nozzle electrospinning set-ups were developed to increase the mass production of nonwoven matrix [10–14]. The multi-nozzle system still needs study as it can be designed to both increase productivity and to produce composite fibers of two or more than two polymers where they have no common solvents. To improve the mass production and morphology of nanofibers, several types of multi-nozzle electrospinning systems have been studied. However, several multi-nozzle electrospinning studies have shown that electric field distribution in less than two nozzle system influenced the electrospinning process and the morphology of obtained nanofibers [15,16]. Kong et al. [17] studied the electric field effect on the shape of deposited fibers and showed that the design of the electric field is a significant parameter in the attempt to control web formation. Similarly, Yang et al. [18] reported the effect of electric field distribution uniformity on the cone formation, jet path, and the morphology and the diameter of the resultant electrospun fibers. They also showed that the more uniform electric field produced a suitable electric field distribution for producing thinner nanofibers. The variation in the strength of the electric field at the tip of the needle in a multi-jet arrangements was investigated using experimental and computer simulation methods, which showed that the local field deterioration at the needle tips in this arrangements degraded the electrospinning process significantly and resulted in a considerable variation in the morphology of the fibers [19].

Multi-nozzle electrospinning is still under continuous investigation, since it is not only an easy way to enhance the productivity but also a simple technique to fabricate composite fibers of those polymers that cannot form blend solution in common solvent. The disadvantage of multi-nozzle system is the repulsion from the adjacent jets and the non-uniform electric field on each nozzle tip of the spinneret [20–23]. The repulsion of the jets will lead to collecting difficulty, whereas the non-uniform electric field will

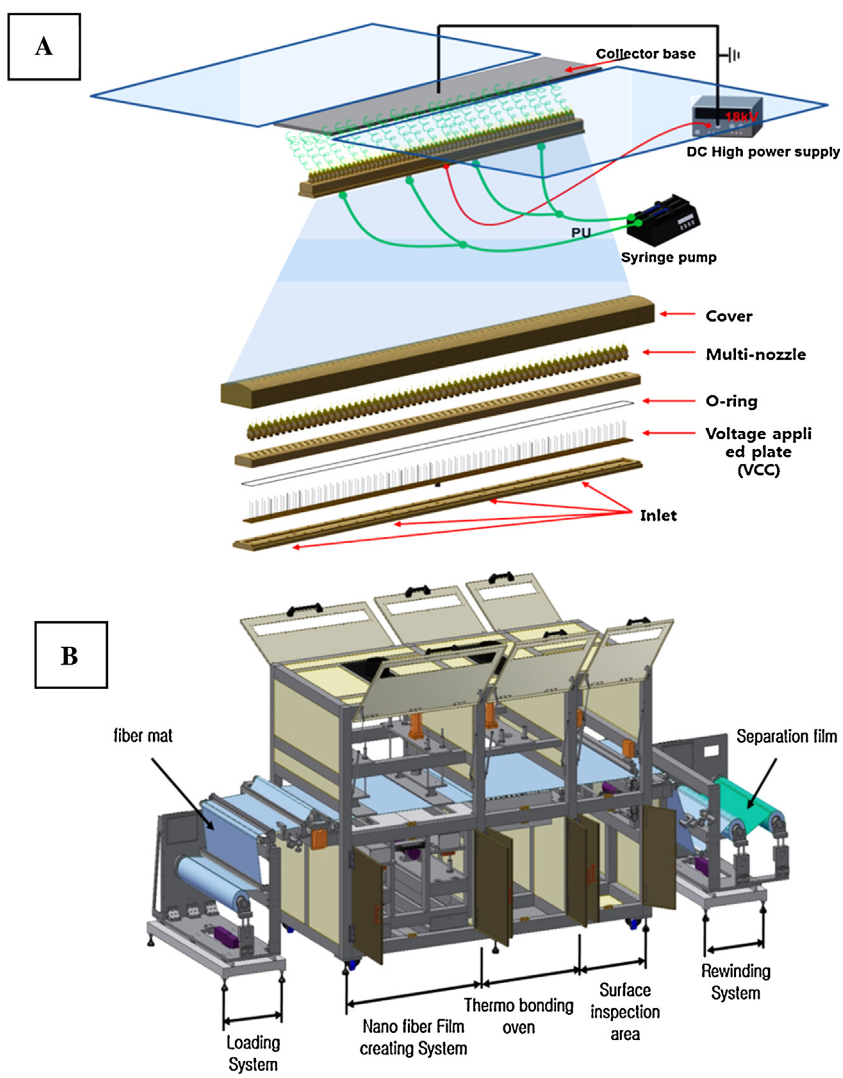

Fig. 1. (a) Schematic diagram of the components of multi-nozzle electrospinning system (upper part), (b) The nanofiber mass production system.