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Needleless Electrospinning: A Practical Way to Mass Production of Nanofibers

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Nanofibers produced by electrospinning have many unique characteristics, such as high surface-to-mass (or volume) ratio, ability to form a highly porous fibrous membrane with excellent pore interconnectivity, controllability in fiber diameter, surface morphology and fibrous structure, and easy to be functionalized by using functional polymers or adding functional chemicals into polymer solutions for electrospinning. These unique features have provided electrospun nanofibers with enormous opportunities to be used in various fields including tissue engineering scaffolds, filtration, catalyst and enzyme carriers, release control, sensors and energy storage, affinity membranes, recovery of metal ions, and many others [1-3].

The conventional approach to electrospinning nanofibers often uses a needle-like nozzle. Despite the enormous application potential, needle electrospun nanofibers meet difficulties in broad applications in practice, due to the lack of an economic and efficient way to scale up the electrosprining process.

Recently, needleless electrospinning has emerged as a new electrospinning mode and shown ability to produce nanofibers on large-scales [4]. Needleless electrospinning is featured as electrospinning of nanofibers directly from an open liquid surface; numerous jets are formed simultaneously from the fiber generator without the influence of capillary effect that is normally associated with needle-like nozzles.

The first needleless electrospinning system was patented in 1979 [5], and it used a ring as spinneret for electrostatic production of fiber fleece. In 2005, a rotating roller was invented as fiber generator for mass electrospinning of nanofibers [6], and this technique was rapidly commercialized by Elmarco Co. with a brand name “Nanospider™”.

In needleless electrospinning, fiber generator plays a key role in determining the productivity and fiber morphology. According to the method to initiate the spinning process, needleless electrospinning can be classified into rotating or stationary electrospinning.

Rotating Needleless Electrospinning

Rotating needleless electrospinning uses mechanical vibrations to assist in the initiation of jets from polymer fluid surface. Several rotating spinnerets have been reported, including ring, ball, cylinder, coil and helical blade.

When the collector electrode is set on the uppermost of the rotary spinneret, nanofibers are generated upward and deposited on the collector. In this case, the spinneret is often immersed partially into a polymer solution underneath the spinneret. The rotation of spinneret has two functions: loading the polymer solution onto electrospinning sites and electrospinning the loaded solution into nanofibers. The later process is driven by a high electric field and enormous number of solution filaments is generated upward from the roller surface. Ring [5] and roller [6] setups belong to the category of upward rotary needleless electrospinning.

The jet formation in needleless electrospinning has been proposed to follow a few steps: 1) A thin layer of polymer solution is formed on the spinneret surface as a result of its partially immersion in the solution and rotation; 2) The rotation also causes perturbations on the solution layer thus inducing the formation of conical spikes on the solution surface; 3) When a high voltage is applied, the spikes concentrate electric forces thus intensifying the perturbations to form “Taylor cones”; 4) Jets are stretched out from the “Taylor cones” and finally result in fibers.

Niu et al. [7] compared rotating cylinder, ball and disc spinnerets using polyvinyl alcohol as model polymer. They also analyzed electric field in the electrospinning zone using a finite element method. Under the same working conditions, the disc produced finer nanofibers with a narrower diameter distribution compared to the ball and cylinder spinnerets. High electric field was found to be narrowly distributed on the disc top, which led to highly stretching of the solution jets. The cylinder spinneret had a large surface area, but the electric field distributed unevenly on the fiber-generating surface. The ball formed an electric field with low intensity thus generating fewer jets when compared to disc and cylinder generators. In comparison with the needle electrospinning, these spinnerets had much higher productivity.

Lin et al. [8] invented a new needleless electrospinning setup using a spiral coil as spinneret. They also compared the coil spinneret with rotary cylinder and disc spinners. The spiral coil had a higher fiber production rate than the cylinder spinneret of the same dimension [9]. The nanofibers produced from the coil spinneret were much thinner with a narrower fiber diameter distribution when compared with those from needle electrospinning. However, for disc, ball and cylinder spinnerets, they normally produced coarser nanofibers.

Rotating needleless electrospinning has been used to process different polymers, such as poly(vinyl alcohol) [7,10], polyacrylonitrile [11], polyurethane [12], carbon nanotube/poly(vinyl alcohol) [13], polyactic acid [14], polyspyrene [15], cellulose acetate butyrate [16] and polylpropylene [17]. Most of the processes were based on solution based electrospinning process except for polylpropylene. It was reported that the solution concentration played a vital role in the electrospinning process [18]. When the polymer concentration was low, the chain entanglement was insufficient, which resulted in beads or beaded fibers instead of uniform fibers. However, if the polymer concentration was too high, the high viscosity restricted stretching of polymer
fluctuations of the solution surface. The jet initiation was observed to be more widespread in the upward rotating electrospinning mode than that in the downward rotating mode. For example, Tang et al. [21] reported that the jet initiation occurred more frequently in the downward rotating electrospinning mode than in the upward rotating mode. This difference in jet initiation frequency can be attributed to the differences in fluid dynamics between the upward and downward rotating electrospinning modes. In addition, the jet initiation is influenced by various factors such as the solution properties and the electrospinning parameters. For instance, the jet initiation frequency increases with the solution density and viscosity, and decreases with the solution conductivity and the applied voltage.

The jet initiation process is also affected by the electrospinning parameters. For example, the jet initiation is more likely to occur at a lower voltage and a higher solution flow rate. In addition, the jet initiation is influenced by the electrospinning system design. For instance, the jet initiation frequency is higher in a stationary electrospinning system than in a rotating electrospinning system. This is because the electrospinning parameters are more easily controlled in a stationary system, which allows for better control of the jet initiation process.
Conclusion

Needleless electrospinning shows great potential in electrospinning of nanofibers on large scales. Although diversely different spinnerets could be chosen for needleless electrospinning, they may not be ideal and some of them still need a further experimental verification in terms of the ability to control the fiber quality and electrospinning process. It still lacks extensive understanding on how the polymer types and solution properties, especially for those using organic solvent systems, affect the electrospinning process and productivity. It still remains a challenge to electros pin bicomponent nanofibers using a needleless electrospinning technique. It is expected that with the further development of this electrospinning technology, high quality, low cost nanofibers will be widely used in our daily life in the not far future.

References