Production Scale Up of Nanofibers: A Review

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***Abstract*— This article is a perspective that includes an introduction to nanofibers, nanofiber production methods, and the scale up of nanofiber production. It has been proven that nanofibers have huge application potentials in diverse areas. Therefore, many attempts have been made to scale up the nanofibers production in the recent decade. In most cases, mass production involved the use of arrays of nozzles. The production rates of these designs were limited by the spacing between jets or nozzles and the electric field interference that occurs when the jets are too close to each other. Several researchers have tried to mass-produce nanofibers by using a free surface of polymer solution, including electrospinning based on a two-layer system, bubble electrospinning, spider spinning, ball electrospinning, disc electrospinning, cleft electrospinning, porous tube electrospinning, porous electrospinning with drilled hole, ring electrospinning, stepped pyramid stage, wire electrode, and etc. Among them, the most successful one which has the ability to produce nanofibers on a large scale is spider spinning. In addition, more recently some works on mass production were based on utilizing other forces rather than electrostatic force. In this case, centrifuge spinning is a viable alternative for mass production of nanofibers. Also, some other works used a secondary force to assist electrostatic force such as magnetic force aided method, air-flow force aided method and centrifugal force aided method. The examples illustrated herein have shown that free surface electrospinning as well as hybrid electrospinning can be promising technologies for the mass production of continuous polymeric nanofibers.**

***Keywords*: centrifugal spinning, hybrid electrospinning methods, multi-nozzle electrospinning, nanofibers, needleless electrospinning, scale-up**

I. Introduction

Although the term nanotechnology is relatively new, it has been found in ancient history, because the term "submicron" was used in the production of extremely small materials. Nowadays, nanotechnology concerns the science and engineering of materials at the dimension between 1 and 100 nm [1]. National Nanotechnology Initiative has defined nanotechnology as understanding, manipulation and control of materials at the dimension less than 100 nm, such that the material properties could be engineered physically, chemically and biologically to develop the next generation of improved materials, devices, structures, and systems [1]. In recent years, nanotechnology has become a topic of great interest to scientists and engineers, and is now established as a prioritized research area in many countries [2]. Nanofibers as one of many nanotechnology products have attracted considerable attention in recent decades [3]. While the fiber diameter is reduced down to below one micron, interesting properties such as high specific surface, flexibility and functionality are raised [4]. Therefore, nanofibers have potential to be used in many fields of research and development [5]. Hitherto, nanofibers are used for insulation and reinforcement of composites, filtration, conductors, sensors, drug delivery, wound healing, and tissue engineering, and many materials and structures incorporating nanotubes as well as nanowires are under development [6]. So far, many different techniques such as drawing, template synthesis, phase separation, self-assembly, bicomponent spinning, islands-in-the-sea, and electrospinning have been developed to fabricate polymer nanofibers [7]. Among them, electrospinning was recognized as a simple and efficient technique for the fabrication of nanofibers from wide variety of materials such as polymers, composites, ceramics and so on [8]. Electrospinning which is able to fabricate ultrathin fibers continuously relies on utilization of electrostatic forces [9]. An essential challenge associated with electrospinning is its production rate versus commercial fibers production rate, which has limited the industrial applications of nanofibers [10]. Single-needle electrospinning has very low throughput (nearly 1–5 mL h^{-1} by flow rate or 0.1–1.0 g h^{-1} by fiber weight) in comparison with conventional fiber spinning [11]. The flow rate is an essential parameter in increasing the production rate of nanofibers, though nanofiber diameter increases with increasing the flow rate. It is clear that electrospun nanofibers have a diameter of about several nanometers to several hundred nanometers, therefore in order to fabricate the same weight of fibers that is produced in a conventional fiber spinning, it is necessary to increase the jet speed of the electrospinning process nearly 10000–1000000 times, which is the order of sound speed in air [12]. Therefore, it is not possible to reach such a speed and other solutions have to be found.

Accordingly, several methods have been developed and the majority of them are based on increasing the jet numbers. Increasing the jet numbers is possible by: modifying the single needle, increasing the number of needles, and needleless electrospinning. Recently, nanofibers have been fabricated using centrifugal force. Centrifugal spinning has proven to be a viable alternative to ordinary electrospinning for mass production of

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nanofibers. Several methods, based on increasing the jet numbers and utilizing centrifugal force have been described below.

II. Modified Single-Needle Electrospinning

In order to increase the production rate of electrospinning, a grooved needle has been utilized instead of an ordinary needle. In this method, a jet initiates from each groove through the needle by increasing the voltage, therefore the jet number increases [13]. However, there is no clear evidence of increase in the production rate of nanofibers by using the modified needle. Also, some disadvantages of this method are unstable droplet formation, higher nanofiber diameter, and unclear mechanism behind the fiber formation (Table I).

III. Modified Collector

It has been found that several Taylor cones can be observed on the tip of a single needle due to a curved collector. In fact, a modified electric field can lead to jet splitting [14]. There is no information on the production rate of this method. However, in this method the jet formation has been controllable and in comparison with single needle electrospinning, this method has produced thinner fibers (Table I).

IV. Multi needle electrospinning

Multi-needle electrospinning is a straightforward way to the mass production of nanofibers. Needles arrangement and the number of the needles and the distance between them are essential parameters in designing a multi needle electrospinning. Two possible geometry of needles are: linear array (1-D) [15-17] , 2-D array like square array [15, 16], circular or elliptical array [17], hexagonal array [18] and triangular array [10] (Table II). However, there are some limitations on the number of nozzles. For example, the size of the setup will be huge with increasing the number of nozzles. Also, the interaction between the electric fields applied on each nozzle limits the increase in the nozzles to a critical number. The distance between the nozzles could not be greatly reduced because the pending droplets on the nozzles tip are likely to stick to each other at the first step of the process. In addition, the electric field repulsion between the jets limits the decrease in the distance between the nozzles. Some researchers have been successful in modifying the traditional electrospinning method to enhance nanofiber production.

In multi-nozzle electrospinning, several linear arrays have been used to increase the nanofiber production rate; for instance 4-nozzle series array [19], 7-nozzle series array and 9-nozzle series array [15] (Table II). However, their production rate is not available. It has been observed that the behavior of border jets along the linear array were different from that of central jets with respect to envelope cone and bending direction [15] (Table II). For example, side jets bent more than central jets; also, the deflection of border jets increased with increasing the jet number. In addition, nanofibers fabricated via 4, 7, or 9 nozzle series array were deposited non-uniformly. In the study of a 26-needle linear array, it was observed that jets initiated from border needles and the central needles were inactive (Table II). This phenomenon can be due to the electric field shielding near the central needles [17]. There is no clear evidence that the production rate was increased by this method.

Zhou *et al.* [20] studied a flat spinneret with three holes in a linear array and observed three separated spots of nanofiberous mat formation. The deposition areas from the side jets were larger than the center jets. They also observed that fiber diameter distribution of electrospun nanofibers became broader with increase in the polymer flow rate (Table II).

Many researches related to multi jet electrospinning have focused on 2-dimensional arrays such as elliptical and circular arrays to provide process stability and achieve efficiency enhancement. It has been found that the circular array developed the efficiency as well as the process stability in comparison to other arrays (Table II) [17]. The production rate achieved by elliptical array was 0.4 ± 0.1 mg min^{-1} per needle, while the concentric array was capable of producing nanofibers at a rate of 1.0 ± 0.2 mg min^{-1} per needle. However, nanofibers were deposited at a non-uniform order and nanofiber loss occurred during process. Yang and coworkers [18] have presented a 7-needle electrospinning, so that 6 needles were arranged at a hexagonal shape and one needle was placed on the hexagonal center. They found that the central jet was similar to single needle electrospinning jet, while surrounding jets were bent outward due to electric field repulsion. The jet density was reported to be 2.69 jets per cm^2 and the setup needed high voltage to fabricate nanofibers. In another research, a multi-jet electrospinning system containing 1000 needles was developed. The setup was capable of producing nanofibers at a rate of 1.2 g min^{-1}. Some disadvantages of this setup were droplet bonding under narrow spacing between needles and fluid dripping (Table II) [10].

V. Needleless Electrospinning

Most research projects on mass production of nanofibers have been developed based on increasing the needle numbers. But there were many problems involved in multi

TABLE I
SINGLE-NEEDLE ELECTROSPINNING SETUPS FOR MASS PRODUCTION OF NANOFIBER

nanofiber formation setup	throughput	advantage	disadvantage
modified single-needle electro-spinning [13]	not available	increase in the jet number	not steady in droplet formation, higher nanofiber diameter, unclear mechanism
modified collector [14]	not available	thinner fibers	unclear mechanism

TABLE II
MULTI-NEEDLE ELECTROSPINNING SETUPS FOR MASS PRODUCTION OF NANOFIBER

nanofiber formation setup	throughput	advantage	disadvantage
4-needle linear array setup [19]	not available	simple setup	interference between jets, uneven fiber deposition
7&9-needle linear array setup [15]	not available	Stable electrospinning process	interference between adjacent jets, uneven fiber deposition
26 needle linear array setup [17]	not available	simple setup	interference between adjacent jets, inactive central needles
circular array setup [17]	1.0 ± 0.2 mg min^{-1} per needle	compact 2D array, relatively stable process	interference between jets, uneven fiber deposition
elliptical array setup [17]	0.4 ± 0.1 mg min^{-1} per needle	compact 2D array, relatively stable process	interference between jets, uneven fiber deposition
hexagonal array setup [18]	2.69 jets cm^{-2}	uniform electric field distribution	higher applied voltage
9 needles in 3 × 3 matrix array [15]	22.5 mL cm^{-2} min^{-1} -22.5 L m^{-2} min^{-1}	stable process	interference between jets, higher applied voltage
1000 needles [21]	1.2 g min^{-1}	higher production efficiency	droplet bonding because of narrow spacing between needles, higher applied voltage

nozzle electrospinning. A good electrospinning method suitable for improving the fiber productivity should have minimal dependence on the nozzle numbers. In the recent decade, experimental as well as theoretical efforts have been done to increase nanofiber production rate by using a polymer solution with a large free surface. Great numbers of jets initiate from the free surface of the polymer solution and depart for the collector. There are several methods based on electrospinning from the free surface of polymer solutions, such as needleless electrospinning based on a two-layer system; bubble electrospinning; spider spinning; ball electrospinning; disk electrospinning and so on.

A. Needleless Electrospinning Based on a Two-Layer System

Yarin and Zussman [22] reported a two-layer-fluid electrospinning setup that could fabricate large scale of nanofibers without serious problems which are involved in multi nozzle electrospinning. In this setup, a ferrofluid was placed at the bottom of a container as the lower fluid layer and the upper layer was the polymer solution. When the two-layer fluid was subjected to a normal magnetic field, steady vertical spikes were formed which perturbed the interlayer interface. The upper layer polymer solution was also perturbed by vertical spikes. Once a high voltage was additionally applied to the fluid at the same time, thousands of jets initiated and moved upward to the upper collector. The jet density in such a needleless process was approximately 26 jets per cm^2. In comparison with 2.25 jets per cm^2 in a 9-nozzle electrospinning, a 12-fold increase in the production rate was expected.[15]. Problems related to multiple needles as well as clogging could be eliminated through this setup. However, this system required a complicated setup and the resultant nanofibers had a large fiber diameter and wide diameter distribution, therefore the equipment was not easy to operate (Table III) [23].

B. Bubble Electrospinning

Bubble electrospinning was another way of mass producing of nanofibers. In this method nanofiber jets were initiated from the bubbles generated by a high pressure gas on the free surface of a polymer solution. By inserting a high pressure gas tube to the bottom of the solution reservoir many bubbles were formed on the free surface of the solution. When a high voltage was applied between the polymer solution and a collector placed above the solution, Taylor cones were easily formed from the bubbles. The gas pressure, the solution properties, and the applied voltage affect the production rate as well as the nanofiber morphology. In contrast to the classical electrospinning, in which the electrospinability mainly depends on solution properties, bubble-electrospinning depends geometrically on the size of the produced bubbles. This method can eliminate some main shortcomings such as low throughput, low efficiency and easy clog in the ordinary electrospinning process [24]. However, fibers prepared by this method contained large beads (Table III) [23].

C. Spider Spinning

A simple technique was invented by Jirsak *et al.* [25] to produce nanofibers on a large scale . This setup consists of a rotating drum immersed into a bath of a liquid polymer. When the rotating drum is partially immersed into a polymer solution, a thin layer of polymer is carried on the upward drum surface. Exposing to a high voltage electric field, an enormous number of jets can be initiated from the drum surface and move toward collector. So far, several types of rotating roller have been developed for free liquid surface electrospinning. However, one of the most productive types is still the drum type [26]. This setup has been commercialized by Elmarco Co. This method was capable of producing nanofibers from PVA aqueous solutions at a rate of around 1.5 g min^{-1} m^{-1} (Table III). Although no clogging occurred, there was no precise control on the solution feeding.

In a research work [27] three different electrospinning methods including the single needle electrospinning, Jirsak's method (spider spinning) and Yarin & Zussman's method (two–layer–fluid electrospinning) were compared.

Nanofibers were produced from polyacrylonitrile/dimethyl sulfoxide solutions using theses electrospinning methods. It has been found that it is possible to increase the production rate by spider spinning and two-layer-fluid electrospinning, where the nanofibers are electrospun from multiple jets.

Generally, the solution concentration, the distance between electrodes, and the applied voltage control the fiber diameter in each method investigated. If the concentration is too low, the solution can form droplets instead of fibers, and if the concentration increases, the fiber diameter also increases irrespective of which method is applied. It was also observed that the character of relation between the fiber diameter, applied voltage and distance between electrodes depends on the solution concentration. Moreover, it was observed that in spider spinning method the diameter of nanofibers decreases with increasing the speed of the rotating cylinder. Another obtained result was the possibility of producing fibers at a 10 wt% polymer concentration by two-layer-fluid electrospinning, leading to much finer fibers than in single needle electrospinning and spider spinning. Moreover, higher voltage values (higher than 20 kV) were necessary for two-layer-fluid electrospinning, while voltage values such as 10, 15, and 20 kV were enough for single needle electrospinning and spider spinning [27].

D. Ball Electrospinning

Ball electrospinning is a technique which increases the production rate of nanofibers. Like spider spinning, electrospinning jet erupts from the surface of a ball dipped in solution, by applying the high voltage electric field. To further increase the solution spinning surface area, an array of balls is arranged on a solution reservoir. However, as a spherical ball has greater surface area compared to a cylindrical drum, more electrospinning jets should erupt from the spinning surface.

A comparison of the average fiber production rate between single needle electrospinning and single ball electrospinning gives an output of 0.37 mg min^{-1} and 32 mg min^{-1}, respectively. Using a 6 wt% polyacrylonitrile solution, the average number of jets from a ball was 24 and with a higher concentration of 8 wt%, the number increased to 38. This setup is used commercially by Stellenbosch Nanofiber Company to fabricate their nanofibrous products [23]. To further increase the solution spinning surface area, an array of balls was arranged on a solution reservoir (Table III).

E. Disc Electrospinning

In this process when the applied voltage was high enough, a number of jets were generated mainly from the edge of the disc. The disc electrospinning process was very stable and showed little dependence on its environment. Fiber diameters and productivities among cylinder, ball, and disc spinnerets were compered by Niu *et al.* using polyvinyl alcohol (PVA) [28]. In comparison with the needle electrospinning, these spinnerets had much higher productivities (cylinder 8.6 g h^{-1}, disc 6.2 g h^{-1}, and ball 3.1 g h^{-1}). Under the same working conditions, the disc produced finer nanofibers (257 ± 77 nm) with a narrower diameter distribution compared to the ball (344 ± 105 nm)

TABLE III
NEEDLELESS ELECTROSPINNING SETUPS FOR MASS PRODUCTION OF NANOFIBERS

nanofiber formation setup	throughput	advantage	disadvantage
electro-spinning based on a two-layer system [22]	26 jets cm^{-2}	no clogging	very wide distribution of nanofiber diameter, magnetic field required
bubble electro-spinning [24]	not available	no clogging	large beads formation, process stability depends very largely on gas pressure
spider spinning [25]	1.5 g min^{-1} m^{-1} - 8.6 g h^{-1}	no clogging	lack of solution feeding control
ball electro-spinning [23]	32 mg min^{-1}	no clogging	lack of solution feeding control, higher applied voltage
disc electro-spinning [23]	6.2 g h^{-1}	finer nanofiber, narrower diameter distribution	higher applied voltage
cleft electro-spinning [29]	6 – 15 mL h^{-1}	no clogging	complex spinneret
porous tube electro-spinning [30]	4.2 g min^{-1} m^{-1}	easy to be scaled up	possible clogging due to quite small holes, very wide distribution of nanofiber diameter, compressed air required
porous electro-spinning with drilled hole [31]	0.3–0.5 g h^{-1} for a 13 cm long tube with 20 holes on the bottom surface of the tube	relatively simple design compared to multi-needle spinneret, fibers with average diameters of 300–600 nm	fiber productivity is limited by number of holes and their distribution
ring electro-spinning [32]	not available	no clogging	higher applied voltage
stepped pyramid stage [33]	2.5-6 g h^{-1}	decrease of fiber diameter with simultaneous increase of productivity	higher applied voltage
wire electrode [34]	up to 0.9 mg min^{-1} cm^{-1}	no clogging	applied voltage dependency

and the cylinder (357 ± 127 nm) spinnerets (Table III) [23].

F. Cleft Electrospinning

Lukas *et al.* presented a one-dimensional electro-hydrodynamic theory to describe the electrospinning of liquids from linear clefts even without being aided by a magnetic fluid underneath. Its throughput was nearly 6–15 mL h^{-1} by flow rate (Table III) [29].

G. Porous Tube Electrospinning

Reneker *et al.* presented a method for the electrospinning of multiple polymer jets into nanofibers. In this work, a polymer solution was electrified and pushed by air pressure through the walls of a porous polyethylene tube with a vertical axis. Multiple jets formed on the porous surface and were electrospun into nano-scale fibers. The mass production rate was reported to be 250 times greater than that of a typical single jet. However, the porous tube produced fibers with a broad distribution (Table III) [30].

In another porous tube electrospinning (horizontal tube), drilled pores into the tube wall had low flow resistance; therefore polymer solution was pushed by low air pressure through the wall. However, there are a low number of holes because the distance between holes should not be smaller than a critical value. In fact, the smaller the distance, the bigger the electric field repulsion between the jets (Table III) [31].

H. Ring Electrospinning

Wang *et al.* obtained a high electrospinning rate by a novel electrospinning setup, which used a metal-wire coil as spinneret [32]. Single ring electrospinning is a hollow disc which could be able to fabricate large scale nanofibers [23]. Multiple interconnected rings would enhance the production rate of nanofibers. The latter approach is called wire coil electrospinning [32]. These methods are affected by experimental parameters such as applied voltage, spinning distance, and polymer concentration. It has been found that the PVA nanofibers diameter increased with increasing the solution concentration. Also, further increase in the solution concentration caused the productivity to decrease. When the PVA concentration was very high, only few jets were initiated from the ring top surface and the spinning process ran intermittingly. The possible reason for such a problem was that high solution viscosity caused insufficient stretching. However, these methods need much higher voltage than traditional electrospinning process, which limits their applications (Table III) [32].

I. Stepped Pyramid Stage

A simple and efficient free surface electrospinning setup has been developed by using a one-stepped pyramid stage. In this setup among the three operating parameters (e.g. polymer solution concentration, applied voltage and collecting distance), solution concentration demonstrated a direct effect on the fiber diameter regardless of the applied potential and working distance. The response surface analysis indicated that the applied potential had a significant effect on productivity. The interactive effect between the applied potential and the working distance on productivity has been also observed. The decrease in fiber diameter with simultaneous increase in productivity has been achieved by using this novel free surface electrospinning system. The nanofiber diameter and productivity were around 157–237 nm and 2.5–6 g h^{-1}, respectively [33].

J. Wire Electrode

A needleless electrospinning system was developed by Forward *et al.* in which a wire electrode was swept (in a rotary motion) through a bath containing a polymeric solution in contact with a high voltage, resulting in entrainment of the fluid, the formation of liquid droplets on the wire and electrostatic jetting from each liquid droplet.

The wire electrode spindle consisted of two Teflon disks 3.2 cm in diameter and 0.4 cm thick held into position 6.4 cm apart (center-to-center) with a threaded rod and nuts. Two stainless steel wires with a diameter of 200 µm were wrapped around the disks approximately 180° apart from each other. The wire spindle was rotated by a small DC motor to allow for variable speed control between 2.5 and 18 rpm. The wire spindle was placed in a solution bath with the center of rotation positioned approximately at the surface of the bath. Experimentally observed, the productivity for 30 wt% 55 kDa PVP in ethanol at different applied voltages and rotation rates varied by up to 0.9 mg min^{-1} cm^{-1}. Changes in rotation rate and applied voltage had little effect on the fiber diameters (from 711 to 898 nm) or standard derivations (from 138 to 258 nm). The highest productivity occurred at high applied potentials and high rotation rates [34].

VI. Centrifuge Spinning

Centrifuge spinning (Table IV) firstly presented by Sarkar *et al*. has been used to fabricate nanofibers from a wide range of materials. This method utilizes centrifugal force, rather than electrostatic force as in the electrospinning process. Centrifuge Spinning has the ability to fabricate nanofibers from both solutions and melted materials. It has been claimed that hazardous effect of polymer solvents on environment could be eliminated by using materials melt. This setup consists of a multiple orifice spinneret, thermal system, collecting devices, environmental chamber, control system, motor, and brake. There is an ability to increase the spinneret numbers as a 3-spinneret setup. The polymer solution is injected into the spinneret. When the spinneret starts to rotate, the polymer solution ejects from the orifice and elongates toward the collector [35]. Other setups based on utilizing centrifugal force are rotary jet spinning developed by Badrossamy *et al*. [36] and air-sealed centrifugal spinning invented by Valipouri *et al.* [37,38]. It is worth mentioning that in the latter the air drag has been deleted from the spinning setup. Therefore, the liquid jet has more time to stretch and elongate resulting in ultrathin nanofibers [37]. Some researchers have utilized centrifuge spinning to fabricate nanofibers from a number of ordinary materials such as

TABLE IV
CENTRIFUGE SPINNING SETUPS FOR MASS PRODUCTION OF NANOFIBERS

nanofiber formation setup	throughput	advantage	disadvantage
spin coater [40]	not available	using centrifugal forces, rather than electrical forces	very wide distribution of nanofiber diameter (25 nm to 5 μm), discontinuous nanofiber
three-plate spinning [35]	1g min^{-1} per spinneret orifice	using centrifugal forces, rather than electrical forces	relatively wide distribution of nanofiber diameter
rotary jet spinning [36]	not available	using centrifugal forces, rather than electrical forces	relatively wide distribution of nanofiber diameter and mostly high nanofiber diameter
air-sealed centrifuge spinning [37,38]	not available	using centrifugal forces, rather than electrical forces, finer nanofiber	relatively huge setup

PEO, bismuth, PP [39], PS, PC, PLA, ABS, PPV, PVP, TFP, CA, PAN, and nano-reinforced polymer composites [35].

VII. HYBRID ELECTROSPINNING METHODS

The possibility of developing hybrid electrospinning methods to increase the production rate of nanofibers has been studied by several researchers. To assist the electrospinning technique to scale up nanofiber fabrication, hybrid electrospinning methods utilize a secondary force like pressure, air-flow, magnetic, etc. However, the nanofibers produced through many of these methods can be highly irregular.

A. Magnetic Force Aided Method

As previously mentioned, Yarin and Zussman [22] reported a two-layer-fluid electrospinning setup that could fabricate nanofibers on a large scale. They utilized magnetic forces to induce electrospinning jets. In this method, a ferrofluid was placed at the bottom of the container as the lower fluid layer and the upper layer was the polymer solution. When the two-layer fluid was subjected to a normal magnetic field, steady vertical spikes were formed and acted as electrospinning jet initiation points (Table V).

B. Air-flow Force Aided Method

One such air-assisted method was developed by Medeiros *et al.* [41]. The solution blow spinning technique combined the elements of both electrospinning and melt blowing technologies for making nanofibers. In this method, a polymer solution was delivered to an apparatus consisting of concentric nozzles whereby the polymer solution was pumped through the inner nozzle while a constant, high velocity gas flow was sustained through the outer nozzle. Pressure at the gas/solution interface ejected multiple jets of polymer solution towards a collector. Having a fiber production rate of several times higher than that of single needle electrospinning is an advantage of solution blow spinning.

A comparison has been made between electrospun and solution blow spun nanofibers. The diameters of solution blow spun and electrospun fibers made from 10% PMMA, PLA, PS and PLA/PAni blends were similar. By comparison, the injection rate typically used for electrospinning is only 4–10 μL min^{-1}; roughly more than an order of magnitude lower than that obtained for the solution blow spinning technique (Table V) [41].

A recently developed hybrid electrospinning system is Zetta spinning (Zs) which is composed of electrospinning system and high-speed air blowing system. This technique is applicable for both polymer solutions and polymer melts. It has been reported that the Zs–solvent system can be applied for polymer solutions with a maximum flow rate from nozzle of 2 mL min^{-1} for producing nonwoven fabrics, and the Zs–melt system can be applied for polymer melts with a molten polymer rate of about 1 to 2 kg h^{-1} for producing nanofiber wadding. It has been claimed that the development of the Zs system to produce mass nanofibers has expanded their potential applications, which include filters for air pollution, water treatment, battery separators, medical separation, etc. [42].

Porous tube electrospinning is another method which utilizes air pressure to increase nanofiber production rate [30, 31]. This method has been described previously.

C. Centrifugal Force Aided Method

Weitz *et al.* [40] developed a simple and efficient procedure enabling the fabrication of nanofibers. Their fiber forming technique was the basis for the design of the hybrid electrospinning. In nozzle-free centrifugal spinning, a drop of polymer solution is applied onto a standard spin coater. When the chuck rotates fast, the centrifugal force creates many fluid exit points from the disk surface. This technique allows the electrospinning jets to form as the polymer solution reaches the edge of the disk. The fiber formation relies on the instability of the liquid film that tends to create liquid fingers. The finger instability arises due to a competition between the centrifugal force and the Laplace force induced by the surface curvature. Fine liquid jets emerge from the polymer solution on the edge of the disk, and yield solid nanofibers after evaporation of the solvent. Although this technique has much higher productivity in comparison to single nozzle electrospinning, the diameter of the fibers fabricated in this way is not uniform, varying from 25 to 5000 nm (Table V) [43].

In another centrifugal-force based approach, an electriferous rotating cone is used as spinneret. This high-throughput electrospinning system consists of a high-voltage power supply, a metallic cone, a direct-current (DC) electromotor, and a collector. Polymer solution is

TABLE V
HYBRID ELECTROSPINNING METHODS FOR MASS PRODUCTION OF NANOFIBERS

nanofiber formation method	throughput	advantage	disadvantage
		magnetic force aided method	
electro-spinning based on a two-layer system [22]	26 jets per cm^2	no clogging	very wide distribution of nanofiber diameter, magnetic field required
		air-flow force aided method	
solution blow spinning [41]	not available	having a polymer injection rate several times higher	relatively wide distribution of nanofiber diameter and mostly high nanofiber diameter, high-pressure gas required
Zetta spinning [42]	2 mL min^{-1} solution from nozzle, 1-2 kg h^{-1} molten polymer	applicable for both polymer solutions and polymer melts, mass production	high-pressure gas required
		centrifugal force aided method	
rotary cone electro-spinning [44]	nearly 10 g min^{-1}	superhigh-throughput electro-spinning, continuous nanofiber	higher applied voltage and high rotation speed required
electro-centrifuge spinning [46]	2.7185 mL h^{-1} per nozzle	continuous and aligned nanofiber	thicker nanofibers due to exposing the ejected liquid jet to the high velocity airflow
air-sealed centrifuge electro-spinning (ASCES) [50, 51]	not available	ultrafine nanofiber	relatively huge setup

disposed to the cone surface, followed by rotation of the cone. Upon the coactions of gravity, the moment of inertia, and the electric force, the charged liquid droplet flow along the rotating surface. Electrospinning jets are formed as the polymer solution reaches the lower edge of the cone. It has been found that the typical production throughput of this approach is nearly 10 g min^{-1}, which is 1000 times more than that of the single needle electrospinning technique. Whilst microscopy investigation show that the morphology of nanofibers prepared by the cone-spinneret setup are nearly the same as those prepared by the single needle electrospinning technique (Table V) [44].

Electro-centrifugal spinning is another fabrication method for scaling up nanofibers production. In this technique a nozzle for supplying the polymer solution is placed on a circular plate. The polymer solution runs through the nozzle while the circular plate is rotating. The centrifugal force overcomes the surface tension and a jet of the fluid is ejected from the tip of the nozzle. An electric field is applied between the nozzle and cylindrical collector. The traveling jet is stretched by electric force as well as centrifugal force to become very fine and solidifies through solvent evaporation. Dried nanofibers deposit on the cylindrical collector. Although this method could be able to increase production rate of nanofibers, it suffers from a stream of rotating air surrounding the nozzle. Exposing the ejected liquid jet to the high velocity airflow causes the jet to lose its solvent rapidly and as a consequence, the extension of the jet becomes more difficult, resulting in thicker nanofibers. The diameter of fibers varied from 300 to 500 nm [45-47]. The production rate of electro-centrifuge spinning was 12 times larger than that of the conventional electrospinning approach at the concentration of 13 wt% polyacrylonitrile solution (Table V).

Valipouri *et al.* [48-51] enhanced the latter nanofiber fabrication method [46, 47] to obtain high quality ultrafine nanofibers. A schematic of this setup called air-sealed centrifuge electrospinning (ASCES) is shown in Fig. 1. These enhancements included isolating the electro-centrifuge spinning from surrounded air and using a rotating collector. Because the fabrication process was skillfully sealed from the ambient airflow, the jet could be able to propagate and elongate much higher than in the previous technique before solidification, resulting in thinner fibers. The results extracted from FESEM observations revealed that nanfibers produced by air-sealed centrifuge electrospinning had good uniformity and high fineness, as compared with the previous centrifugal force based technique and the single nozzle electrospinning. The average fiber diameter (std) was 134 nm (20 nm) at a concentration of 13 wt% polyacrylonitrile solution and the average fiber diameter (std) of nylon (ssp) was 60 nm (19 nm). Moreover, air-sealed centrifuge electrospinning facilitated the fabrication of finer fibers from polymer solutions containing high volatile solvent (Table V).

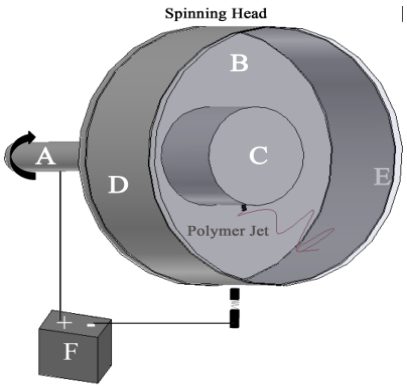

Fig. 1. Schematic of air-sealed centrifuge electrospinning system. (A) rotating drive shaft, (B) insulated plate, (C) rotating cylindrical receptacle, (D) rotating metallic cylindrical collector, (E) transparent door, (F) high-voltage power supply [51].

VIII. Conclusion

Nanofibers have been considered as an important class of materials that is useful in a variety of applications. Therefore, during two recent decades, many efforts have been done to increase nanofibers productivity; however, innovations are still improving these days. There are many reports that have claimed to increase nanofibers production, while some strategies have proven to be extremely powerful for scaling up nanofiber productivity. For example, multi-nozzle electrospinning, needleless electrospinning, centrifugal spinning, and hybrid electrospinning methods are the main classifications of scale up techniques. Among them, spider spinning, centrifuge spinning, or any approach based on utilizing centrifugal force could scale up productivity and had high efficiency.

References

[1] F. K. Ko and Y. Wan, *Introduction to Nanofiber Materials*, Cambridge: Cambridge University Press, 2014, pp. 1-5.

[2] Dashtbani and E. Afra, "Producing Cellulose nanofiber from Cotton wastes by electrospinning method", *Int. J. Nano Dimens.*, vol. 6, pp. 1-9, 2015

[3] S. Thomas, S. Rafiei, S. Maghsoodlou, and A. Afzali, *Foundations of Nanotechnology*, vol. 2, Ontario: CRC Press, 2014, pp. 300-304.

[4] A. Martins, R. L. Reis, and N. M. Neves, "Electrospinning: processing technique for tissue engineering scaffolding", *Int. Mater. Rev.*, vol. 53, pp. 257-274, 2008.

[5] A. K. Haghi, *Electrospun Nanofibers Research: Recent Developments*, 1st ed., New York: Nova Science Publishers, Inc., 2009, pp. 1-18.

[6] Raghvendra and A. Mishra, "Review on potential applications of carbon nanotubes and nanofibers", *Int. J. Pharm. Rev. Res.*, vol. 3, pp. 12-17, 2013.

[7] J. Lin, B. Ding, J. Yang, J. Yu, and G. Sun, "Subtle regulation of the micro- and nanostructures of electrospun polystyrene fibers and their application in oil absorption", *Nanoscale*, vol. 4, pp. 176-182, 2012.

[8] I. S. Chronakis, "Novel nanocomposites and nanoceramics based on polymer nanofibers using electrospinning process—A review", *Journal of Materials Processing Technology*, vol. 167, pp. 283-293, 2005.

[9] D. Li and Y. N. Xia, "Electrospinning of nanofibers: Reinventing the wheel? ", *Adv. Mater.*, vol. 16, pp. 1151-1170, 2004.

[10] F-L. Zhou, R-H. Gong, and I. Porat, "Mass production of nanofibre assemblies by electrostatic spinning", *Polymer Internatinal*, vol. 58, pp. 331–342, 2009.

[11] D. R. Salem, *Electrospinning of nanofibers and the charge injection method*, Cambridge: Woodhead Publishing, 2007, pp. 3–21.

[12] C. Burger, B. S. Hsiao, and B. Chu, "Nanofibrous Materials and Their Applications", *Annu. Rev. Mater. Sci.*, vol. 36, pp. 333-368, 2006.

[13] Y. Yamashita, F. Ko, A. Tanaka, and H. Miyake, "Characteristics of Elastomeric Nanofiber Membranes Produced by Electrospinning", *J. Text. Sci. Eng.*, vol. 53, pp. 137-142, 2007.

[14] A. Vaseashta, "Controlled formation of multiple Taylor cones in electrospinning process ", *Appl. Phys. Lett.*, vol. 90, pp. 093115-3, 2007.

[15] S. A. Theron, A. L. Yarin, E. Zussman, and E. Kroll, "Multiple jets in electrospinning: experiment and modeling", *Polymer*, vol. 46, pp. 2889-2899, 2005.

[16] Y. Yamashita, H. Miyake, A. Higashiyama, and A. Tanaka, "Practical Use of Nanofiber Made by Electrospinning Process," In: Proceedings of *the 9th Asian Textile Conference*, Taiwan, 2007.

[17] W. Tomaszewski and M. Szadkowski, "Investigation of Electrospinning with the Use of a Multi-jet Electrospinning Head", *Fibers Text. East. Eur.*, vol. 13, pp. 22-26, 2005.

[18] Y. Yang, Z. Jia, Q. Li, L. Hou, H. Gao, L. Wang *et al.*, "Multiple jets in electrospinning," presented at the 8th International Conference on Properties and Applications of Dielectric Materials, Bali, 2006.

[19] B. Ding, E. Kimura, T. Sato, S. Fujita, and S. Shiratori, "Fabrication of blend biodegradable nanofibrous nonwoven mats via multi-jet electrospinning", *Polymer*, vol. 45, pp. 1895–1902, 2004.

[20] F. L. Zhou, R. H. Gong, and I. Porat, "Three-jet electrospinning using a flat spinneret", *J. Mater. Sci.*, vol. 44, pp. 5501– 5508, 2009.

[21] Y. Yamashita, F. Ko F, H. Miyake, and A. Higashiyama, "Establishment of nanofiber preparation technique by electrospinning", *Sen'i Gakkaishi,* vol. 64, pp. 24–28, 2008.

[22] A. L. Yarin and E. Zussman, "Upward needleless electrospinning of multiple nanofibers", *Polymer*, vol. 45, pp. 2977-2980, 2004.

[23] T. Lin and X. Wang, *Needleless Electrospinning of Nanofibers: Technology and Applications*, Singapore: Pan Stanford, 2013, pp. 67-68.

[24] Y. Liu and J.-H. He, "Bubble Electrospinning for Mass Production of Nanofibers", *Int. J. Nonlin. Sci. Num.*, vol. 8, pp. 393-396, 2007.

[25] O. Jirsak, F. Sanetrnik, D. Lukas, Z. Na, V. Koteck, L. Martinova, *et al.*, "A method of nanofibres production from a polymer solution using electrostatic spinning and a device for carrying out the method," US patent, 2005.

[26] T. Lin, *Nanofibers–Production, Properties and Functional Applications*, 1st ed., Croatia: InTech, 2011, pp. 1-30.

[27] F. Cengiz, I. Krucińska, E. Gliścińska, M. Chrzanowski, and F. Göktepe, "Comparative Analysis of Various Electrospinning Methods of Nanofibre Formation", *Fibers Text. East. Eur.*, vol. 17 pp. 13-19, 2009.

[28] H. Niu, T. Lin, and X. Wang, "Needleless electrospinning. I. A comparison of cylinder and disk nozzles", *J. Appl. Polym. Sci.*, vol. 114, pp. 3524–3530, 2009.

[29] D. Lukas, A. Sarkar, and P. Pokorny, "Self-organization of jets in electrospinning from free liquid surface: A generalized approach", *J. Appl. Phys.*, vol. 103, pp. 084309-7, 2008.

[30] O. O. Dosunmu, G. G. Chase, W. Kataphinan, and D. H. Reneker, "Electrospinning of polymer nanofibres from multiple jets on a porous tubular surface", *Nanotechnology*, vol. 17, pp. 1123–1127, 2006.

[31] J. S. Varabhas, G. G. Chase, and D. H. Reneker, "Electrospun nanofibers from a porous hollow tube", *Polymer*, vol. 49, pp. 4226–4229, 2008.

[32] X. Wang, H. Niu, X. Wang, and T. Lin, "Needleless Electrospinning of UniformNanofibers Using Spiral Coil Spinnerets", *J. Nanomater.*, vol. 2012, pp. 1-9, 2012.

[33] G. Jiang, S. Zhang, and X. Qin, "Effect of processing parameters on free surface electrospinning from a stepped pyramid stage", *J. Ind. Text.*, vol. 45 pp. 483-494, 2016.

[34] K. M. Forward and G. C. Rutledge, "Free surface electrospinning from a wire electrode", *Chem. Eng. J.*, vol. 183, pp. 492–503, 2012.

[35] K. Sarkar, C. Gomez, S. Zambrano, M. Ramirez, E. d. Hoyos, H. Vasquez, *et al.*, "Electrospinning to forcespinning™", *Mater. Today*, vol. 13, pp. 12-14, 2010.

[36] M. R. Badrossamay, H. A. McIlwee, J. A. Goss, and K. K. Parker, "Nanofiber Assembly by Rotary Jet-Spinning", *Nano Lett.*, vol. 10, pp. 2257–2261, 2010.

[37] A. Valipouri, S. A. Hosseini Ravandi, A. Pishevar, and E. I. Părău, "Experimental and numerical study on isolated and non-isolated jet behavior through centrifuge spinning system", *Int. J. Multiph. Flow.*, vol. 69, pp. 93–101, 2015.

[38] [38] A. Valipouri, S. A. Hosseini Ravandi, A. Pishevar, and E. I. Parau, "Numerical Study on the Jet Dynamic through Centrifuge Spinning: Influence of Angular Velocity", *J. Text. Polym.*, vol. 3, pp. 20-25, 2015.

[39] B. Raghavan, H. Soto, and K. Lozano, "Fabrication of Melt Spun Polypropylene Nanofibers by Forcespinning", *J. Eng. Fiber. Fabr.*, vol. 8, pp. 52-60, 2013.

[40] R. T. Weitz, L. Harnau, S. Rauschenbach, M. Burghard, and K. Kern, "Polymer Nanofibers via Nozzle-Free Centrifugal Spinning", *Nano Lett.*, vol. 8, pp. 1187-1191, 2008.

[41] E. S. Medeiros, G. M. Glenn, and A. P. Klamczynski, "Solution Blow Spinning: A New Method to Produce Micro- and Nanofibers from Polymer Solutions", *J. Appl. Polym. Sci.*, vol. 113, pp. 2322-2330, 2009.

[42] A. Tanioka and M. Takahashi, "Highly Productive Systems of Nanofibers for Novel Applications", *Ind. Eng. Chem. Res.*, vol. 55, pp. 3759–3764, 2016.

[43] C. J. Luo, S. D. Stoyanov, E. Stride, E. Pelan, and M. Edirisinghe, "Electrospinning versus fibre production methods: from specifics to technological convergence", *Chem. Soc. Rev.*, vol. 41, pp. 4708-4735, 2012.

[44] B. Lu, Y. Wang, Y. Liu, H. Duan, J. Zhou, Z. Zhang, *et al.*, "Superhigh-Throughput Needleless Electrospinning Using a Rotary Cone as Spinneret", *small*, vol. 6, pp. 1612–1616, 2010.

[45] F. Dabirian, "Experimental and Theoretical Investigation on the Nanofiber Production by Electrocentrifuge Spinning," PhD dissertation, Department of Textile Engineering, Isfahan University of Technology, 2012.

[46] F. Dabirian, S. A. Hosseini Ravandi, and A. R. Pishevar, "Investigation of Parameters Affecting PAN Nanofiber Production Using Electrical and Centrifugal Forces as a Novel Method ", *Curr. Nanosci.*, vol. 6, pp. 545-552, 2010.

[47] F. Dabirian, S. A. Hosseini Ravandi, and A. R. Pishevar, "The Effects of Operating Parameters on the Fabrication of Polyacrylonitrile Nanofibers in Electro-Centrifuge Spinning", *Fiber Polym.*, vol. 14, pp. 1497-1504, 2013.

[48] A. Valipouri, S. Hosseini, and A. R. Pishevar, "Effect of electric field intensity on nanofiber morphology," presented at the 44th International Symposium on Macromolecules (MACRO 2012) - IUPAC World Polymer Congress, Virginia Tech, USA, 2012.

[49] A. Valipouri, S. A. H. Ravandi, and A. Pishevar, "A Novel Method for Manufacturing Nanofibers," Iran, Patent,73734, 2012.

[50] A. Valipouri, S. A. H. Ravandi, and A. Pishevar, "A novel method for manufacturing nanofibers", *Fiber Polym.*, vol. 14, pp. 941-949, 2013.

[51] A. Valipouri, S. A. H. Ravandi, and A. Pishevar, "Optimization of the Parameters Involved in Fabrication of Solid State Polymerized Polyamide (SSP PA66) Nanofibers via an Enhanced Electro-centrifuge Spinning", *J. Ind. Text.*, vol. 45, pp. 368-386, 2015.