APPARATUS FOR PRODUCING FIBERS BY ELECTROSPINNING

FIELD OF THE INVENTION

[001] The present invention relates to an electrospinning apparatus. More particularly, the invention relates to an apparatus for producing nanofibers with desirable and controlled characteristics.

BACKGROUND OF THE INVENTION

[002] Electrospinning or electrostatic spray processes, which produce superfine fibers on the nanoscale through the action of an external electric field imposed on a polymer solution or molten polymer solution, have been in use for many years and are well known. The principle behind the electrospinning process is to provide a driving force generated by an electrical field between a positive electrode and a negative electrode, so as to overcome surface tension and viscosity of a polymer solution or a molten polymer solution. Due to their large surface area to volume ratio and their unique nanometer-scale architecture, polymer nanofibers have been applied successfully to many fields, such as healthcare, biotechnology, environmental engineering, filtration, energy storage, tissue scaffolding, drug delivery, defense, and security applications.

[003] In view of the varied applications of nanofibers, there have been many attempts to industrialize or produce nanofibers on a larger scale. In particular, a common approach is to use multiple nozzles in the electrospinning process to increase the rate of production of nanofibers.

[004] For example, U.S. Patent No. 6,616,435 discloses a multiple nozzle configuration wherein an electrospinning apparatus comprises a base and a base conductor board having an inlet pipe to receive polymer solution from a pump. A charge distribution board is mounted to a lower portion of a base conductor

board, and a conductor board is mounted to the lower portion of the charge distribution board. However, the exposed conductor boards are capable of transferring electric charges. As a result, the electrospinning apparatus, with a multiple nozzle configuration and strong electric fields from the exposed conductor boards, produces irregular discharges of solution. This can result in mutual interference and repulsion between the discharged nanofibers, producing fibers having irregular diameters. Further, the close distance between the nozzle tips and a collector results in excess electrostatic ion discharge on the fibers, which may cause a high electric potential, thereby creating an unsafe production environment.

[005] U.S. Patent No. 7,351,052 also discloses an apparatus for producing nanofibers by an electrospinning apparatus comprising a supply unit for supplying polymer materials in the liquid state, a spinning unit having a plurality of spinning nozzles for discharging the polymer materials supplied by the supply unit in a charged filament form, and a collector positioned below the spinning unit in a specific location. A control unit charged to have a voltage of the same polarity as at least one of the charged filaments is located between the spinning unit and the collector to guide the stream of the charged filaments to prevent repulsion and dispersion of the charged filaments discharged from each spinning nozzle. However, the resultant polymer web formed is uneven with varying diameters and uneven distribution, and it is not possible to control the direction and alignment of the collected nanofibers.

[006] High voltages used in a multi-nozzle electrospinning apparatus may also lead to unnecessary damage to the mechanical parts of the apparatus due to the high leakage of current from the apparatus. This can lead to high repair and replacement costs of these mechanical parts.

[007] Also, it is well known that for an electrospinning apparatus with multiple nozzles, there are difficulties in controlling the alignment or the arrangement of the electrospun nanofibers. Controlling the alignment of the fibers may be

desirable for specific applications, particularly in biomedical or filtration applications.

[008] There is, therefore, a need to resolve the problems of lack of uniformity of the nanofibers and poor repeatability and control of the production process. There is also a need to resolve safety issues associated with high voltages and leakage of current from the apparatus.

[009] Any discussion of documents, devices, acts or knowledge in this specification is included to explain the context of the invention. It should not be taken as an admission that any of the material forms a part of the state of the art or the common general knowledge in the relevant art anywhere on or before the priority date of the disclosure and claims herein. All statements as to the date or representation as to the contents of these documents is based on the information available to the applicants and does not constitute any admission as to the correctness of the date or contents of these documents.

OBJECTS OF THE INVENTION

[010] It is an object of the present invention to overcome, or at least substantially ameliorate, the disadvantages and shortcomings of the prior art.

[011] It is also an object of the invention to provide an improved electrospinning apparatus.

[012] It is a further object of the invention to provide an improved nozzle system for an electrospinning apparatus.

[013] It is a further object of the invention to provide a capillary tube for use in an electrospinning process, wherein the capillary tube is made of non-conductive material.

[014] It is a yet further object of the invention to provide an electrospinning apparatus for preparing nanofibers, comprising:

a supply unit for supplying polymer material in a liquid state;

a spinning unit that receives the polymer material and generates charged filament forms;

a collector that receives the charged filament forms; and

a high voltage power supply for charging the polymer material;

wherein the spinning unit further comprises at least one nozzle rack with non-conductive capillary tubes.

[015] It is yet a further object of the invention to provide a nozzle for an electrospinning apparatus comprising a non-conductive capillary tube.

[016] These and other objects and advantages of the present invention will become more apparent from the description below.

SUMMARY OF THE INVENTION

[017] According to the present invention, an electrospinning apparatus comprises a supply unit or system for supplying polymer material to a spinning unit, a spinning unit for transforming the polymer material into thin fibers, a collector for collecting the fibers, and a high voltage power supply. The supply unit comprises one or more storage or supply containers that are in fluid communication with one or more pumps. Alternatively, a source of pressure may pressurize polymer material in one or more storage containers and force the polymer material to the spinning unit.

[018] Each storage container contains polymer material in a liquid state such as a polymer solution or melt polymer. One storage unit may be in fluid

communication with one pump or one pressurizer, two or more storage containers may be in fluid communication with one pump, two or more storage containers may be in fluid communication with two or more pressurizers, respectively, or a combination of the foregoing. The polymer material, whether from one source or combined sources, is supplied to the spinning unit, particularly to a distributor or charging chamber for each nozzle rack.

[019] The spinning unit comprises a distributor of the polymer material, a charging chamber for each nozzle rack having at least one electrode electrically communicating with at least one high voltage power supply, and two or more nozzles with non-conductive capillary tubes. Polymer material in a liquid state is injected through two or more charged nozzles, the high voltage power supply providing electric charge for charging the polymer materials discharged through the nozzles.

[020] Within the spinning unit one or more nozzle racks comprise a multitude of nozzles comprising non-conductive capillary tubes. One end of each capillary tube extends into a charging chamber to receive charged polymer material whereas the other end extends toward the collector. The non-conductive capillary tubes are received in the nozzle packs in such a way that the non-conductive capillary tubes are electrically isolated.

[021] According to one embodiment of the invention, a capillary tube adapted for use in an electrospinning process from which a polymer solution is drawn from the capillary tube is made from a non-conductive material.

[022] According to another embodiment of the invention, the capillary tube is made from a polymer material or a ceramic material.

[023] According to another embodiment of the invention, a capillary tube further comprises a pressing pin member including a cavity through the pressing pin

member, the pressing pin member being adapted for receiving the capillary tube through the cavity.

[024] According to another embodiment of the invention, a capillary tube is substantially cylindrical, and the inner diameter of the capillary tube is from about 20 to about 500 microns.

[025] According to another embodiment of the invention, a capillary tube is transparent or translucent.

[026] According to another embodiment of the invention, an electrospinning apparatus comprises:

a supply unit for supplying polymer material in a liquid state for producing fibers;

at least one nozzle rack for mounting a plurality of capillary tubes for discharging the polymer material supplied by the supply unit from the capillary tube;

a power supply for applying a predetermined voltage to the apparatus; and

a collector opposite to the at least one nozzle rack for collecting the fibers,

wherein each of the plurality of capillary tubes is made of non-conductive material.

[027] According to another embodiment of an electrospinning apparatus of the invention, the capillary tubes are made of a ceramic material or a polymer material.

[028] According to another embodiment of an electrospinning apparatus of the invention, at least one nozzle rack is adapted for receiving the plurality of capillary tubes in a grid array configuration.

[029] According to another embodiment of an electrospinning apparatus of the invention, at least one nozzle rack comprises a base plate, a cover plate, and an electrode interposed between the base plate and the cover plate.

[030] According to another embodiment of an electrospinning apparatus of the invention, the base plate includes a plurality of receptacles, wherein each receptacle is adapted for receiving a capillary tube.

[031] According to another embodiment of an electrospinning apparatus of the invention, the pitch between the capillary tubes varies from about 2 mm to about 50 mm.

[032] According to another embodiment of an electrospinning apparatus of the invention, the pitch between the capillary tubes is about 10 mm.

[033] According to another embodiment of an electrospinning apparatus of the invention, the capillary tubes are substantially cylindrical, and the inner diameter of each capillary tube is from about 20 to about 500 microns.

[034] According to another embodiment of an electrospinning apparatus of the invention, the capillary tubes are transparent or translucent.

[035] According to another embodiment of the invention, an electrospinning apparatus for preparing nanofibers comprises:

a supply unit for supplying polymer material in a liquid state,

a spinning unit that receives the polymer material and generates charged filament forms,

a collector that receives the charged filament forms, and

a high voltage power supply for charging the polymer material,

wherein the spinning unit further comprises at least one nozzle rack comprising nozzles with non-conductive capillary tubes.

[036] According to another embodiment of the invention, a nozzle rack adapted for use with an electrospinning apparatus comprises:

a base plate including a plurality of receptacles adapted for receiving a plurality of capillary tubes;

a cover plate; and

an electrode interposed between the base plate and the cover plate, wherein each of the capillary tubes is made of a non-conductive material.

[037] This invention may also be said broadly to consist in the parts, elements and features referred to or indicated in the specification of the application, individually or collectively, and any or all combinations of any two or more of said parts, elements or features, and where specific integers are mentioned herein which have known equivalents in the art to which this invention relates, such known equivalents are deemed to be incorporated herein as if individually set forth.

BRIEF DESCRIPTION OF DRAWINGS

[038] In order that the invention may be better understood and put into practical effect, reference will now be made to the accompanying drawings, in which:

[039] Figure 1 is a cross-sectional view of an apparatus for producing nanofibers utilizing an electrospinning process according to one preferred embodiment of the present invention;

[040] Figure 2 is a cross-sectional view of an apparatus for producing nanofibers according to another preferred embodiment of the present invention;

[041] Figure 3 is an elevation view of the arrangement of the nozzle racks according to an embodiment of the present invention.

[042] Figure 4A is an elevation view of a nozzle rack according to a preferred embodiment of the present invention;

[043] Figure 4B is a cross-sectional view of the nozzle rack shown in Figure 3A;

[044] Figure 5 is a perspective view of a portion of an embodiment of an apparatus of the invention showing how capillary tubes are connected to a nozzle rack;

[045] Figure 6 is a cross-sectional view of a nozzle rack with the capillary tubes connected to the nozzle rack according to one embodiment of the present invention;

[046] Figure 7A is a cross-sectional view of a capillary tube according to one embodiment of the present invention;

[047] Figure 7B is a cross-sectional view of a capillary tube with a nozzle rack according to one embodiment of the present invention;

[048] Figure 8 is an enlarged perspective view of the capillary tube according to one embodiment of the present invention;

[049] Figure 9 represents a Scanning Electron Microscope (SEM) printout of a polymer web produced by an apparatus comprising an embodiment of the present invention; and

[050] Figure 10 represents yet another SEM printout of a sample polymer web produced by an apparatus comprising yet another embodiment of the present invention.

[051] Figure 11 represents yet another SEM printout of a sample polymer web produced by an apparatus comprising yet another embodiment of the present invention.

DETAILED DESCRIPTION OF INVENTION

[052] The present invention will now be described in detail in connection with preferred embodiments with reference to the accompanying drawings.

[053] Figure 1 is a cross-sectional view of a representation of an apparatus according to a preferred embodiment of the invention for producing nanofibers utilizing an electrospinning process. In Figure 1, an electrospinning apparatus 10 for producing nanofibers according to a preferred embodiment of the present invention comprises at least one supply unit 12 for supplying polymer material in a liquid state, such as a polymer solution or melted polymer, for making fiber, a spinning unit 14 having at least one nozzle rack 16 comprising a plurality of capillary tubes 18 for discharging the polymer material supplied by supply units 12, and a collector 20 spaced apart from nozzle racks 16 to collect the discharge (not shown) from capillary tubes 18 deposited onto collector 20.

[054] As shown in Figures 1 and 2, each supply unit 12 comprises a storage container 22 for holding polymer material in the liquid state used to manufacture

nanofibers. The supply unit 12 further includes a pressurizer or pump 24. In Figure 1, each pressurizer 24 pressures polymer material in storage container 22 through lines 26 into spinning unit 14. In Figure 2, polymer material from each storage container 22 is pumped by pump 30 through lines 26' into spinning unit 14'.

[055] Each storage container 22 may be used for storing polymer material in the liquid state, such as melted polymer or polymer solution. The type of polymer material used may be dependent on the desired characteristic of the nanofiber to be produced. Such polymer materials used for the process or method may be polymer materials, for example, such as the nylon series such as Nylon 6, Nylon 6/6, Nylon 12, poly-vinyllidene fluoride (PVDF), polyacrylonitile (PAN), polysulfone (PS), polyimide, polyethylene, polypropylene, polyvinylalcohol, cellulose, cellulose acetate, butylate, polyvinyl, pyrrolidone-vinyl acetates, and the like. Copolymers and blends of the above polymers may also be used. Alternatively, a blend of these polymer materials together with emulsions or organic or inorganic powders may be used. The polymer materials can be used in melted form or dissolved in a solvent. Useful solvents include formic acid, hexafluoroisopropanol, and any other suitable solvents or a mixture thereof to provide the desired characteristic of the nanofiber produced.

[056] In a preferred embodiment of the invention there may be more than one storage container 22. Two or more storage containers 22 may be used for the storage and supply of the same or different polymer materials, whose quantity and mix may be decided based on the desired characteristic of the nanofiber to be produced. Each storage container 22 may be made of a suitable material, preferably a material that can withstand pressure as high as 10 bars and having high electrical insulative properties, such as polyetheretherketone (PEEK). A regulator (not shown) attached to a pressurizer 24 or a pump 30 may control the speed and output of the polymer material to the supply unit.

[057] The apparatus 10 comprises two supply units 12, each having a storage container 22 for storing polymer solutions. Each of the supply unit 12 is operatively connected to a voltage unit 32 and 34 to positively or negatively charge each of the polymer solutions contained in the storage container 22. Separating the polymer solutions into two different supply units 12 provides an advantage of controlling the neutralizing of the positive and negative ions when the polymer solutions are being discharged from nozzle racks during the electrospinning process.

[058] Each nozzle rack 16 is preferably easily detachable from apparatus 10 for producing nanofiber. The nozzle racks 16 may be made in modular units of varying sizes to suit the needs and capacities of the electrospinning apparatus. This also allows for easy installation of the nozzle racks on apparatus 10. Further, nozzle racks 16 may be adapted for use on a different apparatus (not shown) that utilizes the electrospinning process.

[059] A high voltage unit 32 or 34 outputs direct current voltage in the range of from about 5 kV to about 50 kV, preferably from about 5 kV to about 25 kV, to apparatus 10. An example of a useful high voltage power supply is Model 30C24-P60 available from UltraVolt. Collector 20 is grounded at ground 36. The application of current through the voltage unit 32 or 34 to the polymer solutions can influence the diameter of the nanofibers produced by the electrospinning process. A higher current applied will decrease the diameter of the nanofibers produced by the electrospinning process. It is therefore possible to control the diameter of the nanofibers by controlling the current applied to the apparatus. The current applied to the apparatus may be in the range of 50 μA to 80 μA, producing a corresponding range of nanofibers having a diameter of approximately 700 nm to 320 nm.

[060] Each nozzle rack 16 is adapted to receive a plurality of non-conductive capillary tubes 18. The number of capillary tubes 18 in a nozzle rack 16 may be determined by considering the size, thickness and production speed of the

nanofibers to be produced. Each single nozzle rack 16 may comprise tens, hundreds, or thousands of capillary tubes 18 depending on the desired characteristics of the nanofiber to be produced. An advantage of using non-conductive capillary tubes is that it is possible to have a higher density of capillary tubes 18 within each nozzle rack 16. Preferably, each nozzle rack 16 comprises of capillary tubes 18 arranged in an array like manner. The number of capillary tubes used in each nozzle rack is in the range of 2-10000, preferably, 10-6000. Since there is minimal electric field interference between the discharge streams of nanofiber from each nozzle 16, the pitch length or the interval between each of the capillary tubes 18 may be in the range of from about 2 to about 50 mm. A pitch length of about 10 mm is preferred.

[061] An advantage of having a high density array of capillary tubes 18 within a single nozzle rack 16 is reduction of weight of the nozzle rack, leading to increased speeds during the nanofiber production process. Another advantage advantage of high density array of capillary tubes 18 within a single nozzle rack 16 is finer alignment of the nanofibers, increasing the density of the nanofiber produced.

[062] Figure 2 is a cross-sectional view showing an apparatus for producing nanofiber according to another embodiment of the present invention. As shown in Figure 2, a collector 20' may be in the shape of a rotating drum, as shown. The rotating drum collector 20' may have a diameter of from about 20 to about 300 cm, preferably from about 30 to about 200 cm, and a speed of rotation of from about 5 to about 50 rpm, preferably from about 10 to about 40 rpm (or a rotational velocity/conveyor belt speed of from about 2 to about 50 m/min, preferably from about 3 to about 40 m/min) to enable a stable discharge of filaments. Nozzle racks 16' have an arced configuration to correspond to the curvature of the rotating drum on collector 20'. Other parts of apparatus 10'are similar to those shown in Figure 1. Collector 20' is grounded at ground 36'.

[063] The apparatus of Figures 1 and 2 may also include an ion neutralizer 82. An ion neutralizer 82 controls the diameter and uniformity of nanofibers produced by the electrospinning process, in turn controlling the quality of nanofibers produced. An example of an ion neutralizer 82 may include a Data Acquisition (DAQ) device. Some examples of DAQ devices utilize an analog to digital (A/D) or digital to analog (D/A) modules in a programmable logic controller (PLC). Typically, the ion neutralizer 82 is connected to the high voltage unit 32 or 34 to monitor and control the current used for the electrospinning process. The ion neutralizer 82 may be controlled remotely by controlling the output current of the high voltage supply unit 32 or 34. A control system 84 may be operatively connected to the apparatus for monitoring and controlling the parameters for the electrospinning process. It provides feedback to the controller so that the parameters may be adjusted accordingly to adapt to the needs and requirements of the process.

[064] Figure 3 shows the top view of a spinning unit 14 of the apparatus and the arrangement of the nozzle racks 16 for the electrospinning process. The nozzle racks 16 may be arranged such that one nozzle rack 16 is perpendicular to another, and this combination is repeated throughout the spinning unit. Other repeating combinations are possible. The nozzle racks 16 may also be arranged in a manner such that one of the nozzle racks 16 in each array is moving or stationary. This configuration enables a variety of nanofiber patterns to be achieved. (Please provide other reasons and advantages, if any, for the arrangement laid out in Figure 3)

[065] Figures 4A and 4B show a bottom and side view of the nozzle rack 16 in Figure 1. A base plate 40 has holes or receptacles 42 in an upper surface 44 of base plate 40. With regard to the modified, slightly exploded, cross-sectional view of Figure 4B, nozzle rack 16 comprises base plate 40, a cover plate 46, an electrode 48, and capillary tubes 18. Cover plate 46 is adapted for connection to base plate 40 once a plurality of capillary tubes 18 are mounted onto base plate 40, to form a charging chamber 50. Base plate 40 may be connected to cover

plate 46 by means of male or female connecting members (not shown). The male member may be attached to cover plate 46, and the female member may be attached to base plate 40, or vice versa. Other alternative means of connection include pressure fit or conventional bolts and screws.

[066] Electrode 48 is mounted in between base plate 40 and cover plate 46 and is adapted to be connected to base plate 40. Electrode 48 may be connected to base plate 40 by the use of male-female connecting members (not shown). When voltages are applied to electrode 48 via the positive high voltage supply 32, the solution in the charging chamber 50 is charged by the applied voltage. Electrode 48 may be made of an electrochemically inert material. Examples of electrochemically inert material include platinum, gold, carbon-graphite, stainless steel, or other similar materials. The advantage of using an electrochemically inert material for the electrode is to prevent the electrode from dissolving during the nanofiber production process.

[067] Base plate upper surface 44 includes a plurality of receptacles 42, each receptacle 42 being adapted for engagement with a capillary tube member 52, as shown in the perspective view in Figure 5. The capillary tube members 52 may be arranged in a grid like manner. Alternatively, they may be arranged in a series or a parallel grid array.

[068] Base plate 40 and cover plate 46 are preferably made of a non-conductive material. Such a material may include ceramic or polymeric materials having corrosion resistance characteristics. Examples of suitable types of polymeric materials include polypropylene, polyethylene, polyvinylidene-fluoride, polytetrafluoroethylene series and polyetheretherketon, polyamide series.

[069] Figure 6 is a sectional view of components of a nozzle rack 16 with the plurality of capillary tubes 18 attached according to one embodiment of the invention. Nozzle rack 16 comprises base plate 40 with capillary tubes 18, a

charging chamber 50 with an electrode 48, and a cover plate 46. Charging chamber 50 receives polymer solution from lines 26 connected to supply units 12, and electrode 48 is connected to high voltage units 32 or 34. Capillary tubes 18 extend from charging chamber 50 through base plate 40 toward collector 20. Electrode 48 may be connected to base plate 40 by the use of male-female connecting members (not shown). When voltages are applied to electrode 48 via the positive high voltage supply 32, polymer solution in charging chamber 50 is charged by the applied voltage.

[070] With reference to Figure 1, collector 20 may be grounded at ground 36 to have electric potential difference with the voltage applied to each nozzle rack 16. Collector 20 is used for the purpose of piling the charged streams of nanofiber from capillary tubes 18. Collector 20 is also capable of moving continuously by a web in the form of a conveyor belt 62.

[071] With reference to Figure 6, an operator can adjust the distance (X) between the ends of the capillary tubes 18 and collector 20 for the piling of nanofibers on collector 20 to be optimum. The distance between the ends of each capillary tube 18 and collector 20 may be in the range of from about 20 to about 50 mm.

[072] There may be more than one nozzle rack 16 adapted for connecting with apparatus 10. Alternatively, nozzle rack 16 may be adapted for connecting to another apparatus for producing nanofiber. Each nozzle rack 16 may be made of various sizes, depending on requirements.

[073] Figures 7A and 7B show a preferred embodiment of the capillary tube 18 and its supporting members. In Figure 7A, a preferred embodiment of a capillary tube member 52 comprises a capillary tube 18 and a pressing pin member 68 adapted for receiving a capillary tube 18 and supported by an O-ring 70. Capillary tube 18 may be fitted through pressing pin member 68 by tight fit or

pressure fit means which enable pressing pin member 68 to remain fixed on capillary tube 18. Capillary tube 18 may be made of a non-conductive material, the advantages of which will be elaborated on below. Pressing pin member 68 allows for the pressing pin member 68 to be easily inserted into and/or detached from nozzle rack base plate 40. Pressing pin member 68 may be made of a non-conductive material, for example, polymer or other non-conductive, resilient materials. Preferably, pressing pin member 68 is made of a resilient material so that it can be inserted into the nozzle body by pressure fit means. It is desirable that the capillary tube 18 has an inner diameter of from about 20 to about 1000 microns, preferably from about 100 to about 500 microns, an outer diameter of from about 100 to about 4000 microns, preferably from about 200 to about 2000 microns, and a length of from about 0.5 to about 50 mm, preferably from about 10 to about 40 mm. The dimensions of each capillary tube 18 are dependent upon the desired characteristics of the nanofiber to be produced. For example, a capillary tube 18 having a larger inner diameter will very likely produce a nanofiber having a greater thickness, other factors being substantially the same.

[074] Figure 7B shows a preferred embodiment of capillary tube 18 of Figure 7A when in use. A portion of the nozzle rack base plate 40 is shown. Pressing pin member 68 is adapted for insertion into a receptacle 42. Pressing pin member 68 may be inserted by pressure fit means. A cover or pressing plate 72, which is adapted to be received by nozzle rack base plate 40 is then inserted over the plurality of capillary tubes 18.

[075] For the purpose of achieving control and uniformity in the production of nanofibers, capillary tubes 18 may be made of non-conductive materials. Examples of non-conductive materials that may be used for this purpose are ceramic, fused silica tubes, glass, carbon tubes, etc. Fused silica tubes, in particular, provide the advantage of greater chemical resistance. The advantages of using non-conductive capillary tubes 18 for the discharge of filaments of nanofiber in the electrospinning setup include, but are not limited to, the following:

1. Ability to form a compact grid array configuration of a plurality of tubes in a small area without electric field interference between the filament discharges;

2. Enabling a smaller distance from the capillary tube and the collecting section for better control and alignment of nanofibers on the collecting section;

3. Achieving greater speeds of production than is conventionally known for a typical setup;

4. The discharge of nanofibers from the capillary tubes is better aligned on the collector due to the elimination of the mutual interference effects between the discharged streams of nanofiber.

5. The apparatus can produce nanofibers having a more uniform diameter, providing greater control of the nanofibers produced.

[076] Figure 8_shows an embodiment of a non-conductive capillary tube 18. At the end of the capillary tube 18 where the polymer solution flows through for the formation of nanofibers, the end comprises a plurality of pores 19 for the polymer solution to flow through. The non-conductive material capillary tube allows a multiple pore configuration since the electrostatic discharge between the nanofibres is reduced significantly. Alternatively, a sieve member 17 comprising of a plurality of pores 19 may also be attached separately to the capillary tube 18.

[077] The capillary tubes 18 according to the invention may also be transparent or translucent. This allows the melted polymer material to be seen through the tubing. Such transparent tubing may allow for easier troubleshooting during the process, for example, to identify which of the tubes may be experiencing problems discharging or whether the melted polymer materials are unable to flow due to problems in the tubing.

[078] The apparatus according to the invention can produce nanofibers having a uniform diameter of from about 10 to about 700 nm.

[079] The method for manufacturing the polymer web by the electrospinning process will be described through embodiments having different conditions.

EXAMPLE

[080] Nylon 6/6 was chosen as the polymer to use since nylon is extensively used in the fabric industry and Nylon 6/6 has higher mechanical stress as compared to Nylon 11 and Nylon 12. Hexafluoroisopropanol (HFP) was used to dissolve the Nylon 6/6. The polymer blend was stored in a storage container and quantitatively measured by a pump. The polymer blend was supplied to a nozzle rack through distributors, and once a voltage was applied, the charged filaments were produced and piled onto the collector to produce a polymer web.

[081] There were 2 nozzle racks on the apparatus. The nozzle rack comprised 236 capillary tubes, and the distance between the ends of the capillary tubes and the collector was 150 mm.

[082] The diameter of nanofibers electrospun from Nylon-HFP was approximately 700 nm.

[083] The concentration of the HFP-Nylon solution was 20 % (v/v), which is almost the highest concentration that can be electrospun so as to minimize the electrospinning speed. The reason for this is that conventional electrospinning speed is a few tens of meters per second, while the collector speed for the electrospinning setup is less than 5 meters per second. The electrospinning speed should be controlled to be slow enough to match the collector speed.

[084] The nanofibers collected at different collector speeds are detailed below.

[085] Figure 7A shows a polymer web produced when the collection speed was increased to 3 m/s. There is some alignment in the nanofibers, but bending coils can be observed along the collector moving direction. A better alignment was achieved by increasing collection speed to 4 m/s. This is shown in Figure 8.

[086] The diameters of electrospun nanofibers can be adjusted by changing the current applied. From the tests conducted, the diameters of nanofibers decrease from approximately 700 nm to approximately 320 nm when the current applied increases from 50 μA to 80μA.

[087] Although the invention has been herein shown and described in what is conceived to be the most practical and preferred embodiment, it is recognized that variations can be made within the scope of the invention, which is not to be limited to the details described herein but is to be accorded the full scope of the appended claims so as to embrace any and all equivalent devices and apparatus.

[088] 'Comprises/comprising' when used in this specification is taken to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other features, integers, steps, components or groups thereof.

CLAIMS:

1. A capillary tube adapted for use in an electrospinning process in which a polymer solution is drawn from the capillary tube, wherein the tube is made from a non-conductive material.

2. The capillary tube according to claim 1, wherein the tube is made from a polymer material.

3. The capillary tube according to claim 1, wherein the tube is made of a ceramic or glass material.

4. The capillary tube according to claim 1, wherein the capillary tube has a first and second end, the first end for receiving the polymer solution into the tube, the second end for drawing the polymer solution out of the tube, wherein the second end includes a plurality of pores for allowing the solution to flow through the pores.

5. The capillary tube according to claim 1, further comprising a pressing pin member having a cavity therein for receiving the capillary tube.

6. The capillary tube according to claim 1, wherein the tube is substantially cylindrical with an inner diameter in the range of from about 20 to about 500 microns.

7. The capillary tube according to claim 1, wherein the tube is substantially transparent.

8. The capillary tube according to claim 1, wherein the tube is translucent.

9. An electrospinning apparatus comprising:

at least a supply unit for supplying a polymer material in a liquid state for producing fibers;

a nozzle rack for mounting a plurality of capillary tubes;

a plurality of capillary tubes mounted in the nozzle rack for discharging the polymer material supplied by the supply unit;

a power supply for applying a predetermined voltage to the polymer material; and

a collector disposed opposite to the nozzle rack for collecting fibers of polymer material discharged from the capillary tubes;

wherein each of capillary tubes is made of a non-conductive material.

10. The apparatus according to claim 8, wherein each of the capillary tubes is made of a ceramic or glass material.

11. The apparatus according to claim 8, wherein each of the capillary tubes is made of a polymer material.

12. The apparatus according to claim 8, wherein the nozzle rack is adapted for receiving the plurality of capillary tubes in a grid array configuration.

13. The apparatus according to claim 10, wherein the nozzle rack further comprises a base plate, a cover plate and an electrode, interposed between the base plate and the cover plate, coupled to said power supply.

14. The apparatus according to claim 12, wherein the base plate includes a plurality of receptacles, wherein each receptacle is adapted for receiving a capillary tube.

15. The apparatus according to claim 8, wherein the pitch between adjacent capillary tubes varies from about 2 mm to about 50 mm.

16. The apparatus according to claim 14, wherein the pitch is about 10 mm.

17. The apparatus according to claim 8, wherein the capillary tubes are substantially cylindrical with an inner diameter in the range of from about 20 to about 500 microns.

18. The apparatus according to claim 8, wherein the capillary tubes are substantially transparent.

19. The apparatus according to claim 8, wherein the capillary tubes are translucent.

20. An electrospinning apparatus for preparing nanofibers, said apparatus comprising, in combination:

at least a supply unit for supplying polymer material in a liquid state;

a spinning unit that receives the polymer material and generates charged filament forms;

a collector that receives the charged filament forms;

a high voltage power supply for charging the polymer material; and

wherein the spinning unit comprises at least one nozzle rack having a plurality of nozzles with non-conductive capillaries.

21. A nozzle rack adapted for use with an electrospinning apparatus, said nozzle rack comprising:

a base plate including a plurality of receptacles adapted for receiving a plurality of capillary tubes;

a plurality of capillary tubes each mounted in one of said receptacles;

a cover plate; and

an electrode interposed between the base plate and the cover plate; wherein each of the capillary tubes is made of a non-conductive material.