Review of Polymer Solutions for Near-Field Electrospinning with Spatial Control

Antonio Osamu Katagiri Tanaka, Héctor Alán Aguirre Soto

# Abstract

Near-field electrospinning (NFES) is identified to be a technique able to fabricate polymer nano and micro fibers with accurate placement. In the past years (2006-2019), several polymer solutions have been successfully electrospun into fibers through several variants of the conventional NFES process. Each NFES variant intents to tailor the process parameters in order to improve the fibers’ properties. This paper presents a review on the research and related development of electrospun fibers, emphasizing the used polymers, solvents, and fiber characteristics. Relevant summary of polymer solutions and near-field electrospinning processing conditions is provided in this paper.

*Keywords:* polymer, solvent, near-field electrospinning, NFES, fibers, spatial control

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# Introduction

Even though electrospinning is an old inven- tion [1], it is currently a trending topic among researchers [2–4]. One of the reasons electrospin- ning is to be studied is its potential to fabricate polymer nano-fibers from a variety of polymers.

The technique allows the production of thin con- tinuous fibers with ease, with diameters down to 3 *nm* in some cases, which is something difficult to achieve by other techniques. Furthermore, the basic setup can be modified with ease to fabri- cate different fibers with diversified functionalities with different materials. The produced fibers can be aligned or unaligned. Besides, the electrospin- ning equipment is inexpensive and of small size, compared to the equipment of standard spinning techniques. On the other hand, the understand- ing of the electrospinning process has improved in the last years [5].

The main components of the electrospinning technique are the fluid control unit (e.g. syringe pump) and a voltage power supply. The process also requires a target electrode or combination of electrodes on which the fibers can be collected. Figure 1 describes a typical near-field electrospin- ning set-up [5]. Two sub-techniques can be de- rived from electrospinning depending on the dis- tance between the dispensing electrode and the collector. The process in which the electrospun jet can be controlled near the tip is called NFES or near-field electrospinning [6]. Moreover, if the distance between the collector and the dispensing needle is greater, the configuration is known as FFES or far-field electrospinning [7].

Near-field electrospinning is considered to be an outstanding technique to fabricate polymer fibers with spatial control and it has suffered several modifications to improve the precision and accu- racy of the fiber deposition. This paper intents to collect the NFES variants of electrospunable polymer solutions with spatial control in recent research.

# Polymer Solution

In electrospinning, it is generally agreed that with higher concentration, the diameter of the fibers increased due to greater viscosity which re- sist stretching. In near field electrospinning, sim- ilar observations have been reported where con- centration increases, fiber diameter increased [9, 10]. However, in separate studies by Pan et al. [11, 12] using poly(*γ*-benzyl *α*, l-glutamate)

and polyvinylidene fluoride (PVDF) reported re- duction in fiber diameter with increasing con- centration. Pan et al. [12] attributed this to a higher charge accumulation in higher concentra- tion PVDF solution. However, more studies need to be carried out to verify this.

* 1. *Polymers*

The polymer selection is in function on the in- tended application. For example, a fast dissolv- ing hydrophilic polymer such as poly(ethylene ox- ide) (PEO) is used for fast drug delivery sys- tems. Otherwise, slow dissolving polymers such as poly(*ε*-caprolactone) (PCL) or poly(lactic-co- glycolic acid) (PLGA) are implemented. [13]

The polymer molecular weight along with the polymer concentration and solvent selection have a direct effect on the solution viscosity, conductiv- ity and surface tension, hence the solution behav- ior in the electrospinning process. The spunable viscosity range varies with the polymer and sol- vent.

Solutions with low viscosity are prone to insuf- ficient polymer chain entanglements to produce fibers. [13] On the other hand, if the solution is too viscous, then the surface tension cannot easily be overcome by the electric field. In both cases, the result can be droplets or particles forming rather than fibers; see Table 1.

* 1. *Solvents*

The solvent used must be capable of dissolving the polymer of interest at an appropriate concen- tration to form fibers, and must posses a suitable volatility. A low-volatility solvent like water may fail to evaporate completely over the distance be- tween the spinneret and the collector. When the fibers form, they will hence contain residual wa- ter owing to this incomplete evaporation. The residue solvent will subsequently evaporate from the fibers upon storage, resulting in ribbon-like (flattened) fibers, wrinkles on the fiber surface or fused fibers. On the other hand, a high-volatility solvent may evaporate very quickly, leading to larger fiber diameters (less time for elongation be- fore solidification) and clogging of the spinneret (due to drying of the liquid at the spinneret before

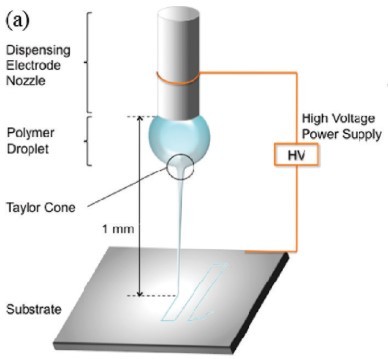


Figure 1: Typical near-field electrospinning set-up [8] .

Table 1: Approximation process to estimate the critical polymer concentration. Several polymer concentrations are tried and the resulting jets are observed until a continuous stream is achieved.

Observation Concentration Adjustement

Dripping, no stream Increase Splitting small droplets Increase slightly

Steady stream No concentration adjustment Splitting large globs Decrease slightly

Nozzle clogging Decrease

jetting, or drying of the Taylor cone during jet- ting). Solvents commonly used for electrospinning include ethanol, chloroform, dichloromethane and hexafluoroisopropanol.

Mixtures of miscible solvents can be used to ensure that sufficient polymer can be dissolved to give a solution of appropriate viscosity and volatility with suitable dielectric constant range to allow fiber formation. However, care must be taken because using a mixture of solvents with very different volatilities can result in porous fiber structures, as reported by Katsogiannis et al. for organic solvent mixtures with dimethyl sulfox- ide (DMSO). [14] DMSO evaporates much more

slowly than the organic solvents used, which re- sults in its incorporation into the fibers. The DMSO will eventually evaporate, yielding porous fibers.

It is also important to take into account the surface tension of the solution. Solvents with very high surface tensions (e.g. water) can result in in- stability arising during the spinning process, and a broad range of fiber diameters in the products. If necessary, a surfactant can be added to reduce the surface tension, but this will be incorporated into the fibers produced.

# NFES Parameters

To spin nano fibers at close distances, the initial diameter of the jet is required to be as small as possible since stretching of the thread is limited. Kameoka et al. [15] demonstrated that a small initial spinning radius can be achieved using an atomic force microscope tip with a small polymer solution drop at the tip.

Near-field electrospinning, has exhibited to be capable fabricate nano fibers over and nano fiber patterns [16]. Nevertheless, having a small poly- mer solution drop at the nozzle tip limits the length of the fibers that can be fabricated in a con- tinuous manner. Using a spinneret with a reser- voir (e.g. syringe) of solution generally produces fibers with diameter of a few micrometers [17, 18], since it creates a limit to which the nozzle inner diameter can be reduced to allow the solution to flow through.

Coppola et al. [19] have showed a NFES variant that allows polymer nano fibers to be deposited directly from a polymer drop, averting the is- sue of nozzle clogging. The fibers are also prone soaking after deposition thus giving the fibers a semi-circular cross-section as depicted in Xue et al.’s [18] work.

* 1. *Nozzle spinneret*

The thinnest nozzles in literature so far are about 100 *µm* in diameter, for instance Chang et al. [9] used a 100 *µm* inner diameter needle tip to electrospin poly(ethylene oxide) (PEO) and Camillo et al. [20] used a micro-diameter tip Tungsten spinneret in a 26G needle to electrospin co-polymer, poly[2-methoxy-5-(2- ethylhexyloxy)-1,4-phenylenevinylene] (MEH- PPV) with poly(ethylene oxide) (PEO). The noz- zle most commonly comprises a simple narrow- bore, blunt-end metal needle. The diameter of the needle can vary, but most commonly re- searches work with internal diameters below 1 *mm* . This translates to needles of gauge 18–22. In general, this simple spinneret design can be used to achieve successful spinning. A blunt- end rather than a tapered-end for the needle exit is important as the size distribution of the

products increase with an increase in needle tip angle. However, it should be noted that there will be some interactions between the solvent and polymer molecules in the solution and the metal surface of the spinneret. There will exist some attractive forces between the polar groups in the polymer and the electropositive metal surface, which can act counter to the drawing force of the electric field and can pull the polymer solution back into the spinneret. It has been found that coating the spinneret exterior in a non-conductive and non-stick polymer such as Teflon can reduce these interactions. [21] As a result, the electrical energy can be more efficiently used to elongate and narrow the polymer jet, and narrower fibers can be produced. In addition, strong attractive forces between the polymer jet and the metal spinneret can result in fibers becoming attracted to the needle, leading to lower yields and po- tentially to blocking of the exit orifice. This effect too can be ameliorated using an epoxy coating. [22]

* 1. *Applied Voltage*

In recent literature, near field electrospinning has been studied to reduce the fiber diameter and to improve the fiber deposition accuracy. Camillo et al. [20] demonstrated that the application of a modified fine tip nozzle enables the fabrication of 100 *nm* diameter fiber at a nozzle-to-substrate distance of 500 *µm* and an applied voltage of 1.5 *kV* . On the other hand, Bisht et al. [8] and Chang et al. [9] came to the conclusion higher voltages yield thicker micro-fibers with a loss in jet stabil- ity.

This discrepancy in literature between the ap- plied voltage and resulting fiber diameter is due to the relationship with other variables such as nozzle-to-substrate distance and solution deposi- tion rate. For instance, if a high voltage is applied at a low deposition rate then electrospraying is achieved, meaning the formation of several non- continuous fibers. The applied voltage shall be sufficient to break the surface tension and initiate the jet, but low enough to avoid multiple jets at the nozzle tip.

Bisht et al. [8] achieved the fabrication of thin- ner fibers with spatial control by reducing the ap- plied voltage to 200-600 *V* at a nozzle-to-substrate distance of 0.5-1 *mm*. The low voltage setting does not create enough charge to break the poly- mer solution surface tension to initiate the elec- trospinning process.

Bisht et al. [8] and Chang et al. [9] initiated the electrospun fibers by mechanically pull the poly- mer solution at the nozzle tip using a micro-probe tip. Chang and coworkers reduced the applied voltage from 1.5 *kV* to 600 *V* with a nozzle-to- substrate distance of 500 *µm* to yield a fiber diam- eter between 3 *µm* and 50 *nm* . With an applied voltage of 200 *V* and a nozzle-to-substrate dis- tance of 1 *mm* , PEO nano fibers were deposited with a diameter about 20 *nm*.

In near-field electrospinning, the applied volt- age has an impact on the produced fiber morphol- ogy. For instance, a voltage higher or lower to the optimum voltage will translate into an increase in fiber diameter. Song et al. [23] demonstrated that a decrease in voltage from 400 to 500 *V* can reduce the fiber diameter from 160 to about 60 *nm*with a nozzle-to-substrate distance of 20 *µm*. The optimum voltage is achieved when a balance is attained between the stretching of the jet and the speed at which it hits the substrate. The in- crease of voltage yields thinner fibers as it causes greater stretching, and a greater jet acceleration. Another workaround to break the polymer so- lution surface tension is to initialize the NFES process with a higher voltage and then lower the voltage once the jet is created. Huang et al. [24] implemented the previous and yield ordered fibers with a distance between adjacent fibers of 50 *µm*.

In most cases, a positive voltage is applied to the

spinneret.

* 1. *Nozzle-to-substrate distance*

In NFES, the fiber morphology can be altered by the control of the height between the nozzle and the substrate (collector). With the decrease of the nozzle-to-substrate distance, the electric field strength increases; however it can cause in- complete solvent volatilisation and possible short circuits between the collector and the nozzle tip.

An optimal nozzle-to-substrate distance shall be defined to ensure the fabrication of dry contin- uous fibers. If the solvent is not well evaporated, the produced fibers are prone to defects; on the other hand if solidification happens too fast, the solids can block the spinneret which can prevent a continuous fiber yield. Furthermore, the poly- mer jet will discharge itself as soon as possible, therefore long distances can result in low yields.

Typically, metal nozzle tips are used, with small inner diameters. From literature, needles with small diameters produce thinner fibers. A thin nozzle tip can help the reduction of the fiber diam- eter, but also it is more likely to become blocked.

* 1. *Electric field*

Recent literature suggests that the fiber mor- phology depends on the electric field profile cre- ated by the applied voltage during NFES. Since the electric field is an induced force that at- tracts the solution jet towards the desired location within the collector.

Bisht et al. [8] and Min et al. [25] have reported the ability to electrospin nano fibers with high accuracy. Min et al. [25] implemented a NFES setup with multiple "field-effect transistors" on a flexible polyacrylate collector with an x-y stage velocity of 13.3 *cm/s* to fabricate fibers with a diameter about 289 *nm* and a distance between adjacent fibers of 50 *µm*.

On the other hand, Bisht et al. [8] showed evi- dence of fabricated fibers with low-voltage NFES with high accuracy and precision. Bisht et al.’s suspended fibers were deposited over carbon posts with a distance between adjacent fibers of 100 *µm* with diameter of 30 *µm* [8].

The employment of guided electrodes in NFES, adapts the fabrication process to yield a more accurate fiber deposition. For instance, Kim et al. [26] manufactured ink patterns on a paper with silver nano particles. The printed patterns aid the fibers to land on the desired location. Kim et al. [26] electrospun the fibers with a distance between adjacent fibers of 150 *µm*.

Xu et al. [27] created a straight jet from the nozzle tip to the substrate using a guiding elec- trode underneath the collector. The purpose of

the guiding electrode is to adjust the path of the NFES jet. With the guiding electrode implemen- tation, the fiber’s spread was reduced from 74 *µm* to 7 *µm*.

* 1. *Substrate*

Due to the close distance between the grounded substrate and the charged spinneret in NFES, the set up is prone to electrical shorts. In NFES, when a short circuit takes place, the electrospinning process is interrupted resulting in the fabrication of discontinuous fibers. Two workarounds to avoid electrical shorts is to lower the applied voltage and to install less conductive substrates [28, 29].

Liu et al. [28] discovered that the fiber align- ment is improved by using a glass-cooper foil substrate, however the well aligned fibers are spoiled after prolonged depositions due to resid- ual charges. Additionally, the effect of resid- ual charges is amplified with the used collector substrate contains a conductive layer and a non- conductive layer [28].

On the other hand, Choi et al. [29] implemented a hydrophobic substrate to deposit the fibers with plasma treatment to increase the conductivity of selected areas. NFES was carried put with precise deposition as the fibers were placed as per the desired design within the hydrophilic substrate.

Table 2: Electrospun Polymer Solutions - Solution and Process Parameters

Polymer(s) Solvent(s) NFES Variant Process Parameters and Fiber Characterization Ref.

Poly(ethylene ox- ide) (PEO; MW = 4,000,000)

Poly[2- methoxy-5-(2-

ethylhexyloxy)-1,4- phenylenevinylene] (MEH-PPV; MW

= 380,000) with Poly(ethylene ox- ide) (PEO; MW = 300,000)

Deionized wa- ter

acetonitrile toluene mixture (65/35); acetic acid toluene (17/83); pure toluene

Low-Voltage NFES (LV NFES)

Typical NFES pro- cess

**Solution Concentration:** 1, 2, and 3 *wt*% PEO **Nozzle:** 27 gauge type 304; stainless steel needle **Solution deposition rate:** lower than 1*µL/h* **Nozzle-to-substrate distance:** 1*mm*

**Substrate composition:** Pyrolyzed SU-8 carbon and Si **Applied voltage:** polymer jet initiated at 400-600 *V* and dispensed at 200-400 *V*

**x-y stage velocity:** 10-40*mm/s*

**Fiber Diameter:** 50-425*nm*

**Distance between adjacent ftbers:** *Not determined*

# Solution Concentration:

10*mg* of MEH-PPV in 2*mL* of toluene; 500*mL* of MEH-PPV solution with 250*mg* of PEO in 3.5*mL* of acetonitrile; 500*mL* of MEH-PPV solution with 250*mg* of PEO in 3*mL* of acetic acid / toluene (17 / 83). The resulting MEH-PPV/PEO concentration is 1:100

**Nozzle:** mm-diameter tip Tungsten spinneret in a 26 gauge needle

# Solution deposition rate: 50*µL/h*

**Nozzle-to-substrate distance:** 500*µm*

**Substrate composition:** SiO2/Si (oxide thickness = 800 nm)

**Applied voltage:** around 1.3*kV* **x-y stage velocity:** 50*cm/s* **Fiber Diameter:** 100*nm*

**Distance between adjacent ftbers:** around 100*µm*

[8]

[30]

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*Continued on next page*

*Table 2 continued*

Poly(ethylene oxide) (PEO)

Water Scanning Tip Elec- trospinning and NFES

**Solution Concentration:** 7*wt*% PEO

**Nozzle:** Needle outer diameter of 200*µm* and inner diame- ter of 100*µm*

**Solution deposition rate:** 0.1*µL/h* **Nozzle-to-substrate distance:** 500*µm* **Substrate composition:** *Not determined*

**Applied voltage:** polymer jet initiated at 1.5 *kV* and dis- pensed at 600*V*

**x-y stage velocity:** 120*mm/s*

**Fiber Diameter:** 709 131*nm*; 49-74*nm* when applied volt- age is 800*V*

*±*

**Distance between adjacent ftbers:** *Not determined*

**Notes:** 108*m* yield in 15*min* with a fiber diameter of

[9]

709*±*131*nm*

Poly(vinylidine flu- orid) (PVDF)

N,N Dimethyl- formamide (DMF)

Helix Electrohydro- dynamic Printing (HE-printing)

**Solution Concentration:** 1.8*g* PVDF in 4.1*g* of DMF and 4.1*g* of acetone. The resulting concentration is 18% PVDF. **Nozzle:** Needle outer diameter of 510*µm* and inner diameter of 260*µm*

**Solution deposition rate:** 400*nL/min*

# Nozzle-to-substrate distance: 10-50*mm*

**Substrate composition:** Poly(dimethylsiloxane) (PDMS) on Ecoflex

**Applied voltage:** 1.5–3*kV*

**x-y stage velocity:** 0-400*mm/min*

**Fiber Diameter:** about 1.5-3*µm*

**Distance between adjacent ftbers:** *Not determined*

[31]

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*Table 2 continued*

Polyhedral Oligomeric Silsesquioxane- Poly(Carbonate- Urea)Urethane (POSS-PCU)

and Polyhe-

dral Oligomeric Silsesquioxane Poly(Caprolactone- Poly(Carbonate- Urea)Urethane) (POSS-PCL-PCU)

Dimethyl acetamide (DMAC) and 1-Butanol

Electrohydro- dynamic 3D Print- patterning or Electrohydro- dynamic Jetting

**Solution Concentration:** POSS-PCU and POSS-PCL- PCU used in 20%*w/w* concentration in DMAC

**Nozzle:** needle of 750 *µm* in diameter

**Solution deposition rate:** less than 1*µL/min*

**Nozzle-to-substrate distance:** about between 500*µm* to 2*mm*

**Substrate composition:** *Not determined*

**Applied voltage:** 8.0-10.0*kV* **x-y stage velocity:** 10*mm/s* **Fiber Diameter:** 5-50*µm*

# Distance between adjacent ftbers: 250*µm*

[17]

Poly(ethylene oxide) (PEO)

Distilled water Electrohydro-

dynamic Writing or Mechanoelectro- spinning (MES)

**Solution Concentration:** 6*wt*% PEO

**Nozzle:** *Not determined*

**Solution deposition rate:** 1200*nL/min* **Nozzle-to-substrate distance:** 7.5*mm* **Substrate composition:** *Not determined*

**Applied voltage:** polymer jet initiated at 2 *kV* and dis- pensed at 0.8-1*kV*

**x-y stage velocity:** around 400*mm/s*

**Fiber Diameter:** 200-350*nm*

# Distance between adjacent ftbers: 5*µm*

[24]

Poly(ethylene oxide) (PEO)

Deionized wa- ter and ethanol with a volume ratio of 3:1

Airflow-assisted Electrohydro- dynamic Direct- writing (EDW)

**Solution Concentration:** 8*wt*% PEO

**Nozzle:** Outer airflow passage diameter: 1*mm* Airflow gas pump pressure: 25*kPa* Inner liquid passage diameter: 0.21*mm*

**Solution deposition rate:** 30*µL/h* **Nozzle-to-substrate distance:** 2*mm* **Substrate composition:** Silicon **Applied voltage:** about 2*kV*

**x-y stage velocity:** 1-20*mm/s*

**Fiber Diameter:** 3.73 *±* 1.37*µm*

[32]

**Distance between adjacent ftbers:** 5.13 *±* 6.67*µm*

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*Continued on next page*

*Table 2 continued* Poly(Vinylidene Fluoride) (PVDF)

Acetone and Dimethyl Sul- foxide (DMSO)

3D Electrospinning **Solution Concentration:** 17*wt*% PVDF; 1.7*g* of PVDF, 5*g* of acetone, 0.5*g* of Capstone FS-66, 5*g* of DMSO **Nozzle:** Needle inner diameter of 100*µm*

**Solution deposition rate:** 14 *nL/min*

# Nozzle-to-substrate distance: 750*µm*

**Substrate composition:** A4 size commercial printing pa- per (Double A)

**Applied voltage:** 1.9*kV*

**x-y stage velocity:** 10*mm/s*

**Fiber Diameter:** *Not determined*

**Distance between adjacent ftbers:** *Not determined*

[26]

Poly(9-Vinyl Car- bazole) (PVK)

Styrene Typical NFES pro- cess

**Solution Concentration:** 3.96*wt*% PVK in styrene

**Nozzle:** Needle inner diameter of 100*µm* **Solution deposition rate:** 500*nL/min* **Nozzle-to-substrate distance:** around 2.5*mm* **Substrate composition:** Si/SiO2

**Applied voltage:** 3-4*kV*

x-y stage velocity: 13.3*cm/s*

**Fiber Diameter:** 289.26 35.37*nm* **Distance between adjacent ftbers:** 50*µm* **Notes:** 15*m* yield in 2*min*

*±*

[25]

Polystyrene (PS) 1,2,4-Trichloro

benzene

Electrohydro- dynamic (EHD) jet printing

**Solution Concentration:** 1 to 5*wt*% PS

**Nozzle:** Glass nozzle inner diameter of 2*µm* and outer di- ameter of 2.66*µm*

# Solution deposition rate: Si

**Nozzle-to-substrate distance: 20, 30, 40***µm* **Substrate composition:**

**Applied voltage:** 500 to 400*V* in 25*V* increments

**x-y stage velocity:** 0.01-10*mm/s*

**Fiber Diameter:** about 60-170*µm*

**Distance between adjacent ftbers:** *Not determined*

[23]

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*Continued on next page*

*Table 2 continued*

Poly(ethylene oxide) (PEO)

*Not determined* Typical NFES pro-

cess

**Solution Concentration:** 3*wt*% PEO

**Nozzle:** *Not determined*

**Solution deposition rate:** *Not determined* **Nozzle-to-substrate distance:** 500*µm* **Substrate composition:** Si

**Applied voltage:** 1000*V*

**x-y stage velocity:** 20*cm/s*

**Fiber Diameter:** 300*nm*

# Distance between adjacent ftbers: 25*µm*

[16]

Poly(ethylene oxide) (PEO)

Poly(ethylene oxide) (PEO)

Distilled water Multinozzle NFES **Solution Concentration:** 5*wt*%

**Nozzle:** four-nozzle and six-nozzle array with needle spacing changes from 1.5*mm* to 3.5*mm*

**Solution deposition rate:** 1-3*µL/min* **Nozzle-to-substrate distance:** 2*mm* **Substrate composition:** *Not determined* **Applied voltage:** 1.7-2.7*kV*

**x-y stage velocity:** *Not determined*

**Fiber Diameter:** 5.47*µm*

# Distance between adjacent ftbers: 3-5 *mm*

Distilled water Multinozzle NFES **Solution Concentration:**5*wt*%

**Nozzle:** Dual-28G-needle array with needle inner diameter of 0.18*mm* and outer diameter of 0.36*mm*; with needle spac- ing changes from 2.0*mm* to 3.0*mm*

**Solution deposition rate:** 0.2*µL/min* **Nozzle-to-substrate distance:** 3.0-4.0*mm* **Substrate composition:** *Not determined* **Applied voltage:** 2.0-3.0*kV*

**x-y stage velocity:** 20*mm/s*

**Fiber Diameter:** *Not determined*

**Distance between adjacent ftbers:** 218-326*µm*

[33]

[34]

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*Continued on next page*

*Table 2 continued*

Poly(ethylene oxide) (PEO)

Distilled water Multinozzle NFES **Solution Concentration:**5 *wt*%

**Nozzle:** Dual-28G-needle array with needle inner diameter of 180*µm* and outer diameter of 360*µm*; with needle spacing changes of 2.0*mm*

**Solution deposition rate:** 0.2*µL/min*

**Nozzle-to-substrate distance:** 4.0*mm* **Substrate composition:** chromium-plated glass **Applied voltage:** 2.5*kV*

**x-y stage velocity:** 20*mm/s*

**Fiber Diameter:** *Not determined*

**Distance between adjacent ftbers:** 2.3002-2.7224*mm*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Poly(ethylene | *Not determined* | Typical | NFES | pro- | **Solution Concentration:** 2*wt*% | [27] |
| oxide) (PEO) |  | cess |  |  | **Nozzle:** G30 needle with inner diameter of 0.15*mm* |  |
|  |  |  |  |  | **Solution deposition rate:** *Not determined* |  |
|  |  |  |  |  | **Nozzle-to-substrate distance:** 1-3*mm* |  |
|  |  |  |  |  | **Substrate composition:** Silicon |  |
|  |  |  |  |  | **Applied voltage:** 1250*V* |  |
|  |  |  |  |  | **x-y stage velocity:** *Not determined* |  |
|  |  |  |  |  | **Fiber Diameter:** *Not determined* |  |
|  |  |  |  |  | **Distance between adjacent ftbers:** 20*µm* |  |
| Gelatin | Acetic Acid and | Typical | NFES | pro- | **Solution Concentration:** 11*wt*% gelatin, 30*wt*% water, | [18] |
| (porcine skin) | Ethyl Acetate | cess |  |  | 35.4*wt*% acetic acid, 23.6*wt*% ethyl acetate |  |
|  | | | | | **Nozzle:** 19G needle tip with outer diameter of 1.08*mm* |  |
| **Solution deposition rate:** *Not determined* |  |
| **Nozzle-to-substrate distance:** 1.25*mm* |  |
| **Substrate composition:** Poly(Dimethylsiloxane) (PDMS) |  |
| films |  |
| **Applied voltage:** 1000*V* |  |
| **x-y stage velocity:** *Not determined* |  |
| **Fiber Diameter:** around 2-3*µm* |  |
| **Distance between adjacent ftbers:** 40*µm* |  |

[35]

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*Continued on next page*

*Table 2 continued*

Poly(ethylene oxide) (PEO)

Poly(ethylene oxide) (PEO)

Poly(ethylene oxide) (PEO)

Water/Ethanol (v/v = 60/40)

Water/Ethanol (v/v = 3/1)

Deionized wa- ter

Typical NFES pro- cess

Electrohydro- dynamic Direct- Write (EDW)

Mechano- Electrospinning

**Solution Concentration:** PEO concentrations of 16% adn 18%

**Nozzle:** 40*µm*

# Solution deposition rate:

**Nozzle-to-substrate distance:** 1*mm* **Substrate composition:** Planar silicon **Applied voltage:** 1.7*kV*

**x-y stage velocity:** 0.36*m/s*

**Fiber Diameter:** 5.15*µm*

**Distance between adjacent ftbers:** *Not determined*

**Solution Concentration:** 14*wt*% PEO

**Nozzle:** Stainless needle with inner diameter of 210*µm* and outer diameter of 400*µm*

# Solution deposition rate: 50*µL/h*

**Nozzle-to-substrate distance:** 2*mm*

**Substrate composition:** Poly(ethylene terephthalate) (PET)

# Applied voltage: 3*kV*

**x-y stage velocity:** 700*mm/s*

**Fiber Diameter:** 15-35*µm*

# Distance between adjacent ftbers: 70*µm*

**Solution Concentration:** 3*wt*% PEO

**Nozzle:** Stainless steel nozzle with inner diameter of 160*µm* and outer diameter of 310*µm*

**Solution deposition rate:** 50*nL/min* **Nozzle-to-substrate distance:** 2-5*mm* **Substrate composition:** Silicone

**Applied voltage:**polymer jet initiated at 2*kV* and dis- pensed at 1*kV*

**x-y stage velocity:** 200-400*mm/s*

**Fiber Diameter:** from 344 32 to 214 27*nm*

*± ±*

**Distance between adjacent ftbers:** *Not determined*

[36]

[37]

[38]

13

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*Continued on next page*

*Table 2 continued*

Poly(co-Glycolic) acid (PLGA)

Poly(ethylene ox- ide) (PEO) with Tetrabutylammo- nium tetrafluorob- orate (TBF) and SU-8 2002

Dimethyl Car- bonate (DMC)

N,N Dimethyl- formamide (DMF)

Tethered Pyro- Electrohydro- dynamic Spinning (TPES)

Typical NFES pro- cess

**Solution Concentration:** *Not determined*

**Nozzle:** nozzle-free

**Solution deposition rate:** The drop reservoir is placed directly on a flat substrate

**Nozzle-to-substrate distance:** Taylor’s cone is focused and put in direct contact with the collector

**Substrate composition:** Poly(tetrafluoroethylene) (PTFE) coated glass slide

**Applied voltage:** pyro-electric field of between 2.7

*x*107 *V/m* and 5.5*x*107 *V/m*

**x-y stage velocity:** *Not determined*

**Fiber Diameter:** 304.7*nm*

**Distance between adjacent ftbers:** *Not determined* **Solution Concentration:** SU-8/PEO/TBF blend with 0.75*wt*% PEO, 1*wt*% TBF; the blend is diluted with 30*vol*% DMF

*µmµm*

**Solution deposition rate:** *Not determined*

**Nozzle-to-substrate distance:** *Not determined* **Substrate composition:** Brass disk with a diameter of 38*mm*

# Applied voltage: 980*V*

**x-y stage velocity:** *Not determined*

**Fiber Diameter:** *Not determined*

**Distance between adjacent ftbers:** *Not determined*

[19]

[6]

14

*August 15, 2019*

*Continued on next page*

*Table 2 continued*

Poly(ethylene oxide) (PEO)

Water:Ethanol (3:2)

Suspension NFES **Solution Concentration:** 14*wt*% PEO

**Nozzle:** stainless steel needle (25 G) with inner diameter of 0.25*mm*

# Solution deposition rate: 3*nL/s*

**Nozzle-to-substrate distance:** between 0.5 and 10*mm* with 0.5*mm* increments

**Substrate composition:** Planar silicon electrodes

**Applied voltage:** 1.6*kV*

**x-y stage velocity:** 50, 150, and 250*mm/s*

**Fiber Diameter:** 300*nm*

**Distance between adjacent ftbers:** 0.1 and 0.5*mm*

[39]

Poly(ethylene oxide) (PEO)

Deionized wa- ter

Typical NFES pro- cess

**Solution Concentration:** 10*wt*% PEO

**Nozzle:** 32G metal needle

**Solution deposition rate:** (Jet impact speed of 5*mm/s* )

**Nozzle-to-substrate distance:** 0.5*mm* **Substrate composition:** p-type silicon wafer **Applied voltage:** 400*V*

# x-y stage velocity: 5*mm/s*

**Fiber Diameter:**

**Distance between adjacent ftbers:** 50*µm*

[40]

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# NFES Variants

[SECTION UNDERWORK]

* 1. *Low-Voltage NFES (LV NFES) [8]*

Some differences have been discovered between LV-NFES and conventional NFES. Low voltage near field electrospinning produces thinner fibers with lower voltages. Moreover, when implement- ing a moving stage, the fibers are affected by the mechanical stretching. Bisht et al. (2011) re- ported that thinner diameters are yield with the increase of the x-y stage velocity, and larger di- ameters by decreasing the stage velocity.

* 1. *Scanning Tip Electrospinning [9]*

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* 1. *3D Electrospinning [26]*

*Electrohydro-dynamic 3D Print-patterning or Electrohydro-dynamic Jetting [17]*

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* 1. *Multinozzle NFES [33–35]*

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* 1. *Electrohydro-dynamic Writing or Mechano- electrospinning (MES) [24]*

*Electrohydro-dynamic Direct-Write (EDW) [37]*

*Mechano-Electrospinning [38]*

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* 1. *Suspension NFES [39]*

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* 1. *Helix Electrohydro-dynamic Printing (HE- printing) [31]*

*Electrohydro-dynamic (EHD) jet print- ing [23]*

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* 1. *Airflow-assisted Electrohydro-dynamic Direct-writing (EDW) [32]*

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* 1. *Tethered Pyro-Electrohydro-dynamic Spin- ning (TPES) [19]*

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# Conclusion

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