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Nano-web formation by the electrospinning at various electric fields

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Abstract Electrospinning is a process in which an electrified liquid jet is ejected by the interaction between the surface tension and the exerted electric force on the droplet surface. It is important to understand the effects of an electric field on the path of the ejected jet from the droplet to the opposite electrode in the electrospinning process. The effects of electric fields on the formation of nano-webs are presented in this paper. As the design of the electrodes varies, the ejected jets were deposit on the screen, exhibiting different or chareateristics. The design of the electric field is a significant parameter in the attempt to control nano-web formation.

Introduction

Electrospinning was introduced for the first time in 1930 with an electrospray that used a low viscosity polymer solution. This technique has had a lot of success as a nanofiber forming technology that uses a high viscosity solution [1–4]. There are several methods that can produce nanofibers. When considering the commercial possibilities, a variety of polymers and their commercial applications [5, 6], the simplicity of the manufacturing process and its applicability in various product technologies, nanofiber manufacturing by electrospining becomes the most efficient technology. This nanofiber web is a super thin film with a super light weight, creating a much higher surface area per volume than existing microfibers. This is due to the fact that the three-dimensional network porosity of the web can be formed with ultra fine nanofibers [7]. Electrospinning uses electric force, not mechanical force. The fiber diameter and shape of the deposited web must be controlled by various parameters. Electrospinning is the simplest and easiest method that can produce a fiber of nano dimension, but a method that can control shape, structure and uniformity of electrospun fibers is very difficult to produce with current technology [8]. High voltage imposed on a polymer solution acts as the main force for electrospinning. The electrostatic force forms charges that accomplish repelling power; thus, as voltage increases, the polymer solution that is spurted in the tip is ejected as a fiber that has a thickness of fewer than a microdimension along the electric line of force [9, 10]. Voltage and electrospinning conditions change the shape of the polymer droplet, the amount of jet ejection and electric field density between the tip and collector. There are many factors that influence web characteristics [11]. Usually, the factors that affect electrospinning can be classified into two categories. The first factor is concerned with the solution parameters such as the concentration, viscosity, surface tension and conductivity of the polymer solution. The second factor is concerned with the processing of the inside and outside diameters of the nozzle, applied voltage, as well as tip and collector distance (TCD). When processing electrospinning, the surrounding atmospheric conditions are also on important factor.

In the past, there have been many studies concerning the effects of the solution and processing parameters on electrospinning [9–15] and bicomponent electrospinning [16, 17]. However, little research on the electric field effect of electrospinning has been reported [18, 19]. In this study, the electric field effects on the shape of deposited webs

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have been investigated. The electric fields are designed by changing the shape of the tip and/or collector. The additional effects influencing the electric field have also been investigated.

Experimental

Materials and methods

The polymer used in this experiment was PVA (Poly vinylalcohol). Distilled water was used as a solvent to prepare 8 wt.% PVA solution. A CCD camera with an optical zoom lens of 30 cm focus length captured the droplet of the fluid at the exit of the needle.

A DC power source that can generate 0–50 kV was used for electrospinning. Negative electrodes were connected to the needle. The flow rate of the solution was kept constant by the constant hydrostatic pressure. Electrospinning was performed at a voltage of 20 kV. The ejected jets had been deposited on the thin black paper on an aluminum collector for 5 min.

A black box equipped with a ring light was used to capture images of the deposited web under uniform light intensity. The nano/microfiber structure of the deposited webs were analyzed by SEM (Scanning Electron Microscopy).

Electric field design

Four basic electric fields were designed by changing the shape of the electrodes. A common 20 Gage needle was used as the electrospinning nozzle. A single needle was assumed as a point electrode. A circular aluminum plate with a diameter of 20 cm was used in this experiment. Point to point, point to plate, plate to point and plate to plate electrodes were designed. When a plate was used as a tip, a needle penetrated through the center of the plate to supply the polymer solution. A square aluminum plate measuring 20 × 20 cm was used as an external conductor at the point to plate condition. For further applications, a betterfly-shaped aluminum plate was used as a collector. Various TCDs (Tip to collector distance) of 14 cm, 20 cm, and 26 cm were explored.

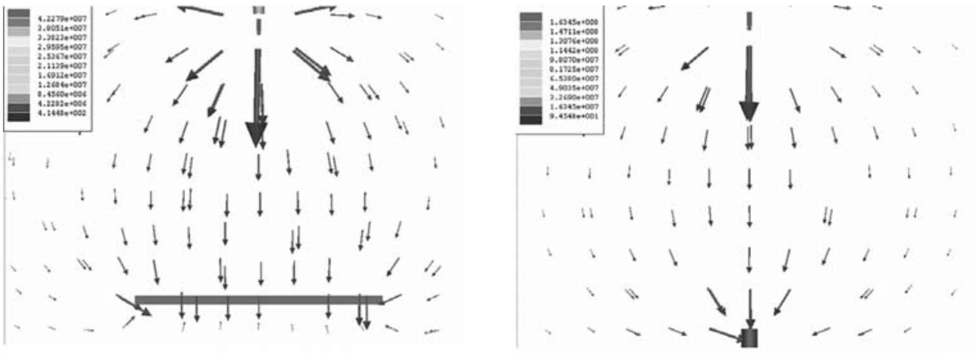
A Maxwell SV (Ansoft Corporation) program was used for modeling the electric fields. The software can model the electric fields of various designs in 2-dimension.

Results and discussion

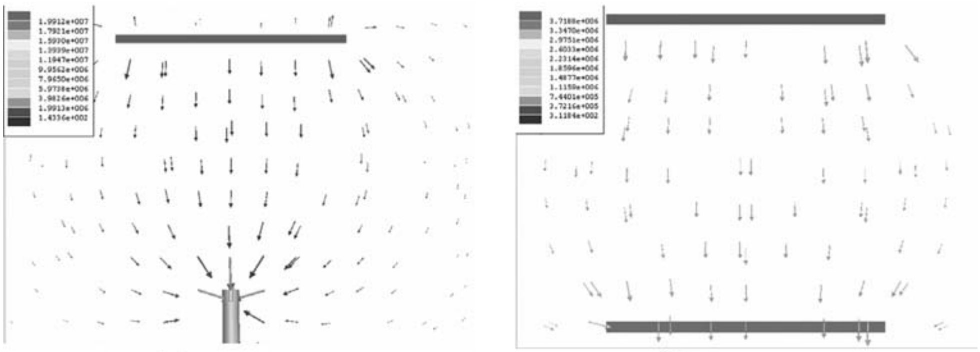
For basic electric field designs

Figure 1 shows the modeling of the four basic electric fields. The electric field was modeled for (a) point to point,

Fig. 1 Modeling of the four basic electric fields



(a) Point to Plate **(b) Point to Point**



(c) Plate to Point **(d) Plate to Plate**

(b) point to plate, (c) plate to point and (d) plate to plate electrodes with a fixed applied voltage of 20 kV. Since the electric field is a vector quantity, it is represented by a vector arrow. The arrows indicate the direction of the electric field and their length is proportional to the strength of the electric field at that location. The electric field vectors at the point electrode in the point to plate electric field corresponded not only to the center but also to the edges of the opposite plate electrode. However, in the case of plate to plate electric fields, uniform and vertical electric field vectors were produced between the two large charged plates. The direction of the electric forces acting on the surface of the polymer solution followed the direction at the electrode where the nozzle is attached. In point to plate or point to point electric fields, an electrospun web with a large diameter may be deposited if the ejected jet that has electrons on the droplet surface flies to the opposite electrode along the electric line of force. For the same reason, the plate to point field design may produce electrospun webs with a small diameter.

Figure 2 shows the electrospun web for 5 min at the point to plate electric field. The web separations were observed in the deposited webs at the TCD of 14 and 20 cm, respectively. In cases where there was a short TCD, the droplet retracted to the nozzle because of the relatively high electric force (in contrast to the long TCD). The strength of the electric field is inversely related to the distance between the two electrodes. The flow rate of the polymer solution was kept constant by the constant hydrostatic force. The large amount of jet ejection by the strong electric force causes the retraction of the polymer solution to the nozzle when the polymer throughput is kept constant. If the polymer solution is retracted to the nozzle, the polymer solution cannot form the stable Taylor cone (Fig. 3a, b). Therefore, the jets were ejected at the edge of the nozzle, resulting in web separation as shown in Fig. 2a and b. The direction of the jet ejection at the edge of the nozzle end may depend on the surface characteristics of the nozzle end. With a TCD of 26 cm, the electric force is smaller than the others because of the relatively long distance between the two electrodes. The amount of ejected jets with a long TCD was relatively small while the droplet formed a stable Taylor cone (Fig. 3c). The strength of the electric field of the short TCDs is too strong to form a stable Taylor cone.

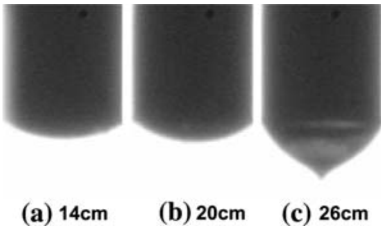


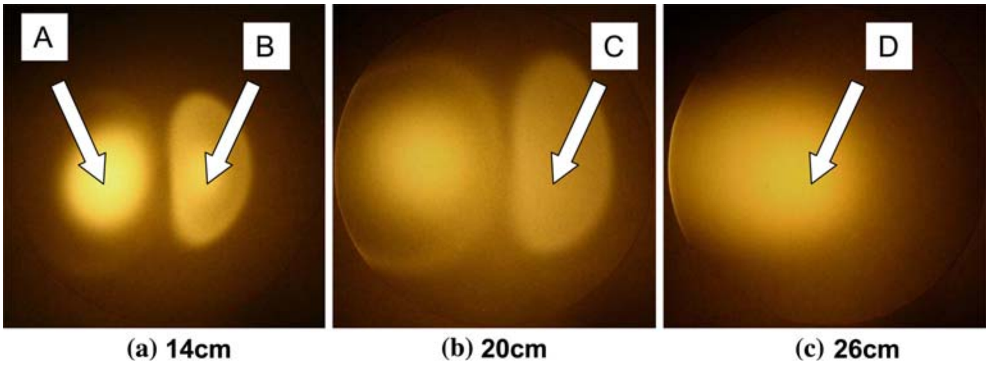
Fig. 3 Droplet images during the spinning process at the electric field of point to plate

Figure 4 shows SEM images at the indicated areas in Fig. 2. There were no significant differences in the fiber diameter and web density in areas A, B and C. The web density in area D (the case of a long TCD) is relatively low because of the weak electric field intensity. The fiber diameters in area D are a little bigger than the other cases.

Figure 5 shows an electrospun web produced at 20 kV for 5 min at the electric field of a point to point condition. Electrospun webs show different patterns when compared with the point to plate condition. Web separation was not observed in this case. The drop images shown in Fig. 6 do not show the retraction of the polymer solution resulting from the large amount of jet ejection compared to the amount of the polymer throughput with a constant hydrostatic pressure. Stable Taylor cones were observed. Relatively low electric fields, except in the direct direction of the vector from the charge source point of the tip to the point of the collector may be formed because there are only two charged source points. In weak electric fields, the diameter of the deposited electrospun web is bigger than in strong electric fields. The effect of the electron repulsion that causes the splitting of the jet in an electrospinline may be more dominant than in cases with a strong electric field in a short TCD.

Figure 7 shows an electrospun web in 20 kV for 5 min at the electric field of a plate to plate condition. The

Fig. 2 Electrospun web images at the electric field of point to plate at the TCD of (**a**) 14 cm (**b**) 20 cm (**c**) 26 cm



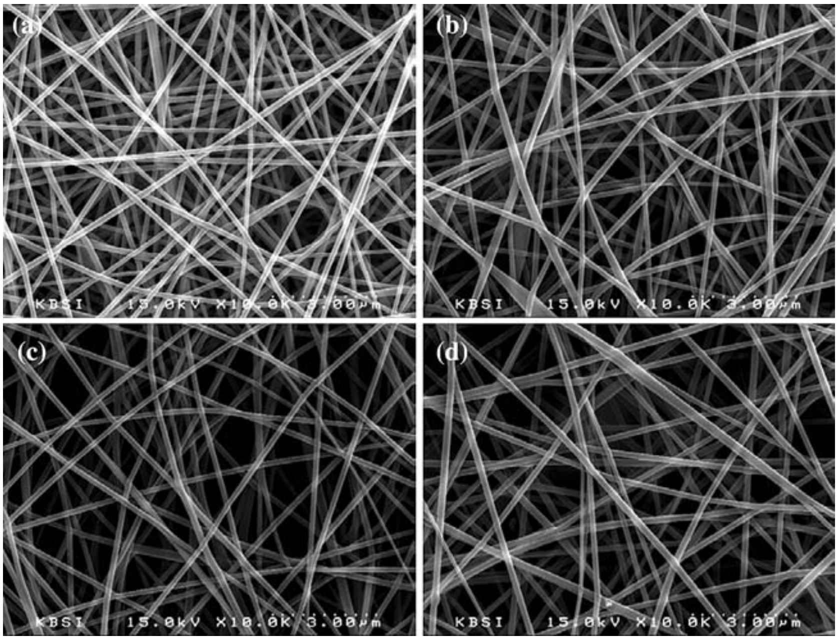


Fig. 4 SEM images of the indicated areas in Fig. 2

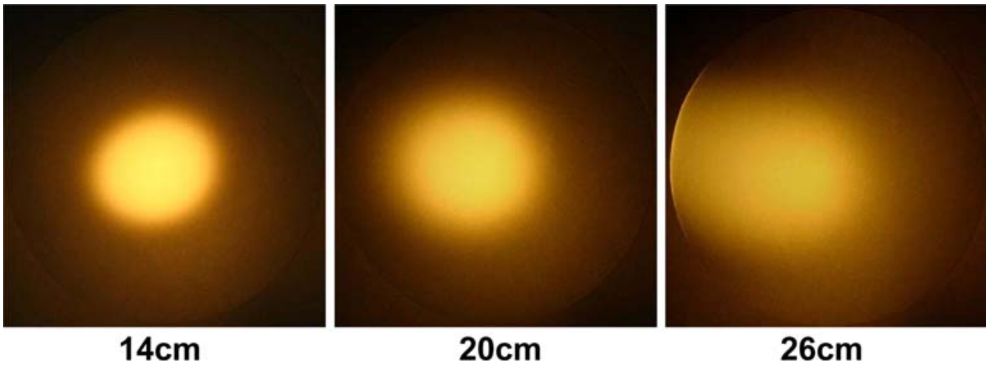


Fig. 5 Electrospun web images at the electric field of a point to point at the TCD of (**a**) 14 cm (**b**) 20 cm (**c**) 26 cm

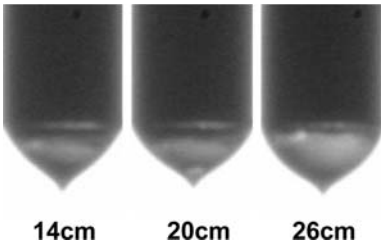


Fig. 6 Droplet images during the spinning process at the electric field of a point to point

diameters of the electrospun webs are smaller than the webs at the point to point and point to plate conditions. Similar web formations were observed in the electric field of a plate to plate condition. Electric field vectors are not formed in various directions around the polymer solution except in the direct direction from the charged point of the tip to the center of the collector(the opposite electrode). The plate electrodes attached to the tip form a parallel or semi-parallel electric field down to the collector, while the electric field vectors in various direction around the surface of the polymer solution are formed in point to plate and point to point conditions (refer to Fig. 1). The electrospun web at the plate to point was expected to have a smaller diameter for its deposited web because all the charged tip plates form an electric field corresponding to the point of the opposite collector. However, there is almost no significant difference in the two cases. It may be due to the effect of the electron repulsion in the electrospinline that disturbs the integration of electrospun fibers in a point.

Figure 8 shows droplet images in an electric field of a plate to plate condition. The falling of the droplet was observed in a plate to plate condition while it was not observed in the electric fields of the point to point and point to plate conditions. The falling of the droplet could be expected from the droplet images in Fig 8c. Similar droplet formations were observed at the electric filed of a plate to point condition. It should be the case that the amount of jet

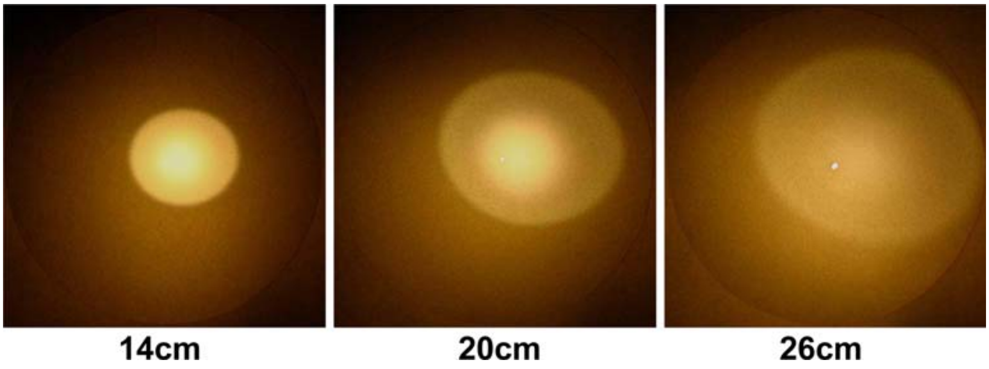


Fig. 7 Electrospun web images at the electric field of a plate to plate at the TCD of (**a**) 14 cm (**b**) 20 cm (**c**) 26 cm

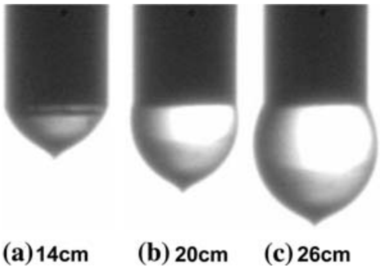


Fig. 8 Droplet images during the spinning process at the electric field of a plate to plate

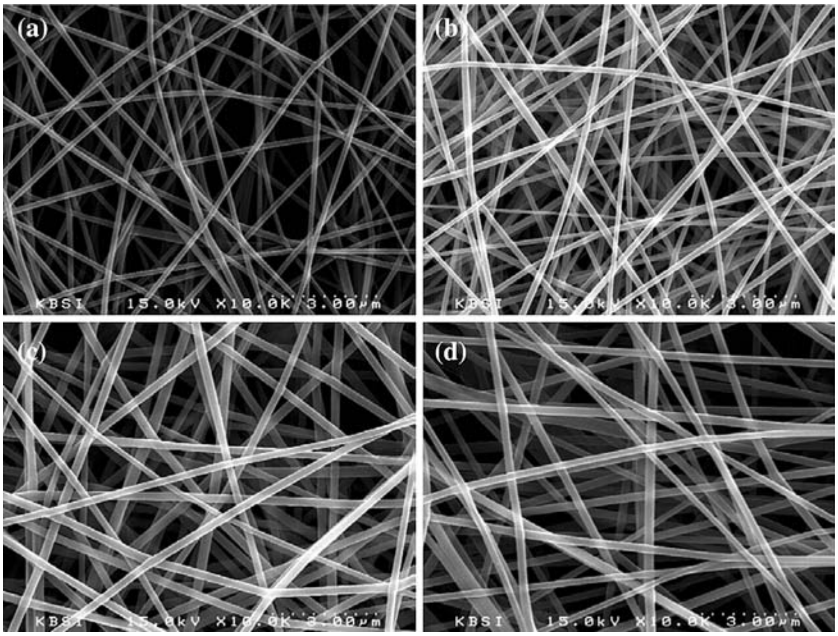
ejection by the weak electric field intensity is smaller than the throughput of the solution flow (Fig. 9).

Application of electric field

Figure 10 shows the schematic diagram of the charge distribution expected by the addition of an external conductor. A 20 × 20 cm square aluminum plate was used as the external conductor. The upside of the conductor is charged positively while the downside of the conductor is charged negatively by the effect of the charged electrodes, tip and collector. The conductor near the electric field affects the electrospinline of the jet. The (–) charged jet may be attracted by the (+) charged upside of the conductor. The (–) charged jet may be repulsed by the (–) charged downside of the conductor. The jet was ejected along the distorted electric field as shown in Fig. 11a.

Figure 11b shows the electrospun web image. Although the upside of the conductor attracts the jet, the electrospun web was deposited not near the conductor but around the center of the black sheet. The (–) charged jet may be repulsed before deposition by the (–) charged downside of the conductor, although the (–) charged jet may be attracted by the (+) charged upside of the conductor. Figure 12 shows the electrode around the nozzle. A butterfly-shaped aluminum plate was used. The arrows indicate the kind of

Fig. 9 SEM images of the electrospun web at the electric fields of (**a**) a point to plate, (**b**) a point to point, (**c**) a plate to point and (**d**) a plate to plate at the TCD of 20 cm



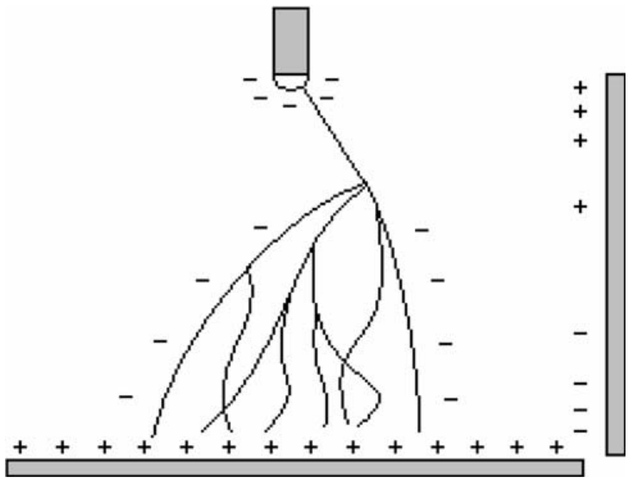


Fig. 10 Illustration of the expected charge distributions by adding an external conductor

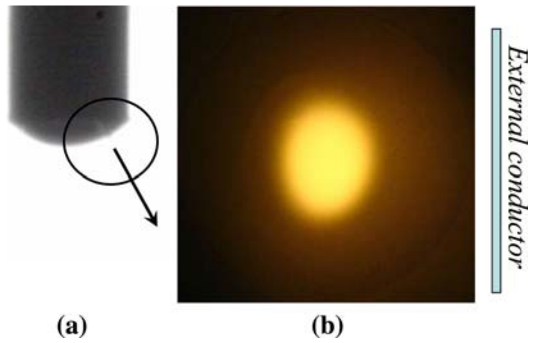


Fig. 11 (**a**) Droplet image emitting a jet toward the external conductor. (**b**) electrospun web image with the external conductor

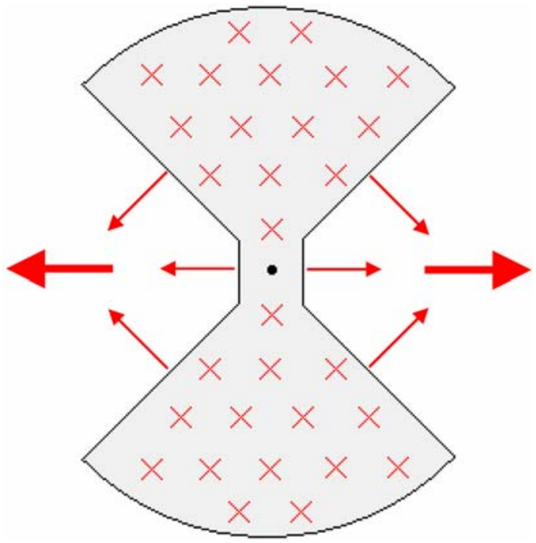


Fig. 12 Design of a butterfly-shaped tip plate

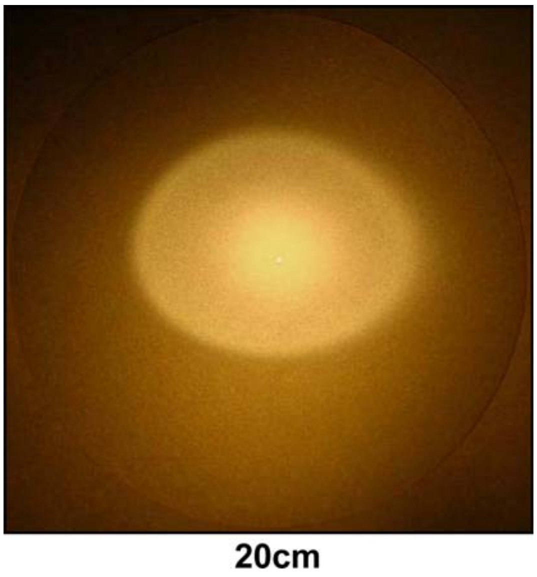


Fig. 13 Electrospun web image using the tip of a butterfly-shape plate

electric field expected such as in the electric field of a point to plate and ‘X’ represents the electric field directed to the backward opposite electrode. A regular circular plate was used as a collector. Figure 13 shows the electrospun web for 5 min. The electrospun web was elongated in a horizontal direction according to the distorted electric field as expected.

Using the directions from this study, the systems based on random jets will be investigated.

Conclusion

It is clear that the electric field design is one of the key parameters to control the formation of a web. The electric field for electrospinning should be designed carefully to avoid an unexpected web formation or to control web formation in the targeted way. It is thought that not only the direction but also the amplitude of the electric field vectors, which should be varied by the electric field design even under the same voltage applied, affect the formation of the electrospun web significantly.

The effect of the tip design is much more significant in web formation than the effect of the collector design. The electron repulsion causing the splitting of the jet in an electrospinline may reduce the effects by the various collector designs. The tip as a point electrode causes a higher charge density than that at the plate electrode. The plate electrode as a nozzle requires higher voltage to eject a jet than the tip as a point electrode. The tip as a point electrode allows for the creation of a web formation of a larger diameter along the well-distributed electric line of force than in cases where a tip acts as a plate electrode.

The addition of an external conductor near the electric field affects the electrospinline significantly. The charged jets are repulsed or attracted in the spinline by the partially charged external conductor. Therefore, an external conductor can be used as one of the methods to control web formation.

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