Effect of Nozzle Shapes on the Formation of Taylor Cone and the Oscillation of Fibers During Electrospinning Process

Bussarin Ksapabutr*, Tanapol Chalermkiti and Manop Panapoy

Department of Materials Science and Engineering, Faculty of Engineering and Industrial Technology, Silpakorn University, Sanamchandra Palace Campus, Nakorn Pathom 73000, Thailand

**Corresponding author. E-mail: bussarin@su.ac.th*

ABSTRACT

The purpose of this work was to investigate the effect of nozzle shapes on the formation of Taylor cone and the oscillation of fibers during the preparation of polyacrylonitrile nanofibers via an electrospinning process. Electrospun polyacrylonitrile fibers were obtained, using high-voltage DC power supply rated 20 kV at a distance between nozzle and target (or substrate) of 15 cm. The experimental results showed that the nozzle in sawtooth shape gave higher length of Taylor cone than that in flat shape having angle of 180o and in standard nozzle. At high flow rate of polymer solution, it was found that the standard nozzle generated the splitting of Taylor cone. However, this phenomenon had not occurred in the case of other nozzles. In addition, we also found that the use of nozzle in flat shape provided the lowest oscillation of fibers.

Key words: Electrospinning, Taylor cone, Electric field, Electrospun polyacrylonitrile

INTRODUCTION

Polymeric material processing is an area which is receiving increasing attention as progress is made towards tailoring the morphology and porosity of constructs for a variety of applications, including filters, membranes, biomimetic materials and composites (Zheng et al., 2003; Jing et al., 2005; Robinette and Palmese, 2005; Tan et al., 2005). Towards this end, electrospinning represents an attractive approach to the fabrication of fibrous materials for these applications. Electrostatic fiber spinning, or “electrospinning”, is a technology for fabricating fibers with nanoscale diameters, one to two orders of magnitude smaller than fibers produced by conventional extrusion techniques, through the action of electrostatic forces. The fibers are derived by charging a liquid from the electrode. The charged liquid is attracted to the electrode of opposite polarity, forming a so-called Taylor cone at the tip of nozzle and, eventually, a fiber jet as the electric field strength exceeds the surface tension of the solution (David, 2000; Cory et al., 2004; Eugene et al., 2005; Seong et al., 2005; Veli et al., 2005).

The properties of the nanofibers produced depend on many process parameters including the properties of polymer precursor, the solvent, the magnitude of the applied voltage, and the distance and geometrical relationship between the nozzle and the collector (Myung et al., 2004; Won et al., 2004; Bumsu et al., 2005). However, most of earlier investigations on polymeric nanofibers have been focused on the viscosity of polymer solution, the type of solvent, the field strength and the working distance of the system (the nozzle tip-to-target distance). The shape of nozzle requires a special attention leading to a homogeneous spinning and a control of deposition area. Therefore, the present work is devoted to investigate the influence of nozzle shapes on the formation of Taylor cone and the oscillation of fibers during electrospinning process.

MATERIALS AND METHODS

Polyacrylonitrile (PAN) was dissolved in *N,N*-dimethylformamide (DMF) at concentration of 12 % w/v. The polymeric nanofibers were produced directly by electrospinning technique. The typical experimental set-up for electrospinning is shown in Figure 1. A benchtop fume hood housed the equipment to ensure protection from hazardous solvent fumes as well as electric field. In the electrospinning set-up, the as-prepared polymer solution was stocked in a syringe. A positive high-voltage power supply charged a polymer solution which contained in a syringe with a voltage of around 20 kV. The charge on the polymer solution eventually overcame the surface tension of the solution and a jet was ejected from the needle tip in the direction of the grounded collector plate (or target). Electrostatic charging of the polymer solution at the apex of a nozzle led to the formation of Taylor cone, from the tip of which a single fluid jet was ejected. The jet ran continuously, producing nanofibers that may be many kilometers in length.

To study the effect of the nozzle geometry on Taylor cone formation, three types of nozzles with different outlet shapes were employed for PAN electrospinning. Typical nozzles were varied into three different nozzle configurations including flat tip (180°), standard tip and sawtooth tip (30°) as demonstrated in Figure 2. The flow rate of the polymer solution was varied in the range of 0.1 to 2.0 ml/min. The positive-high voltage at 20 kV was applied to the nozzle. The nozzle-to-target distance was 15 cm.

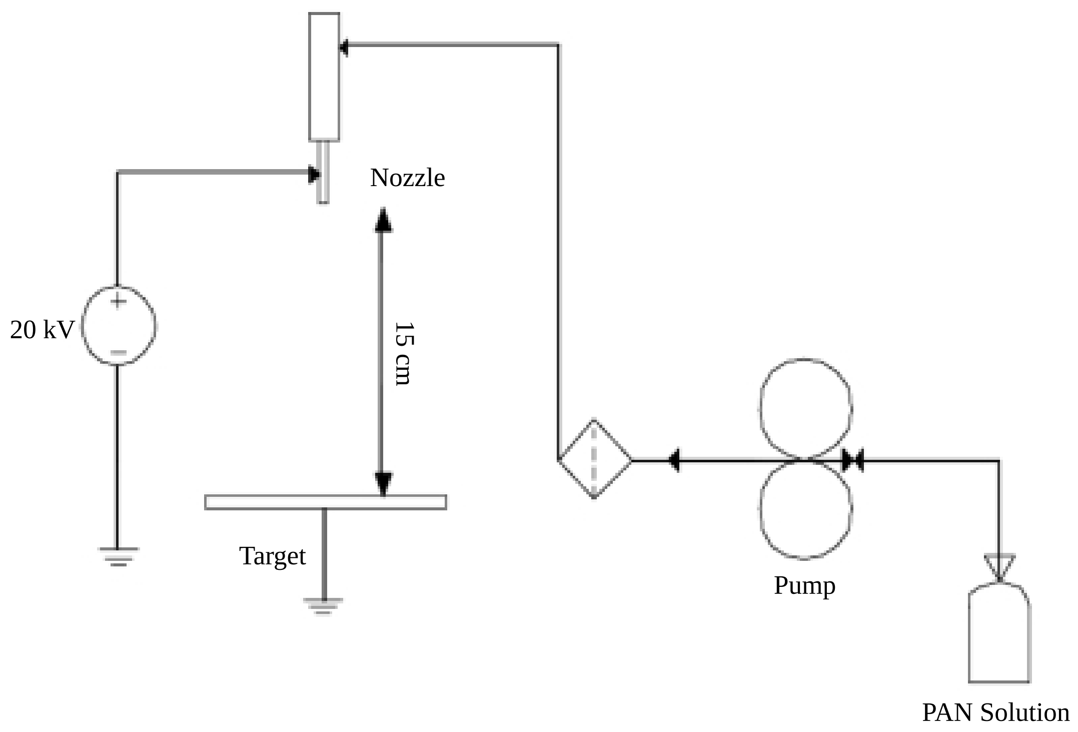

Figure 1. Schematic view of the electrospinning setup.

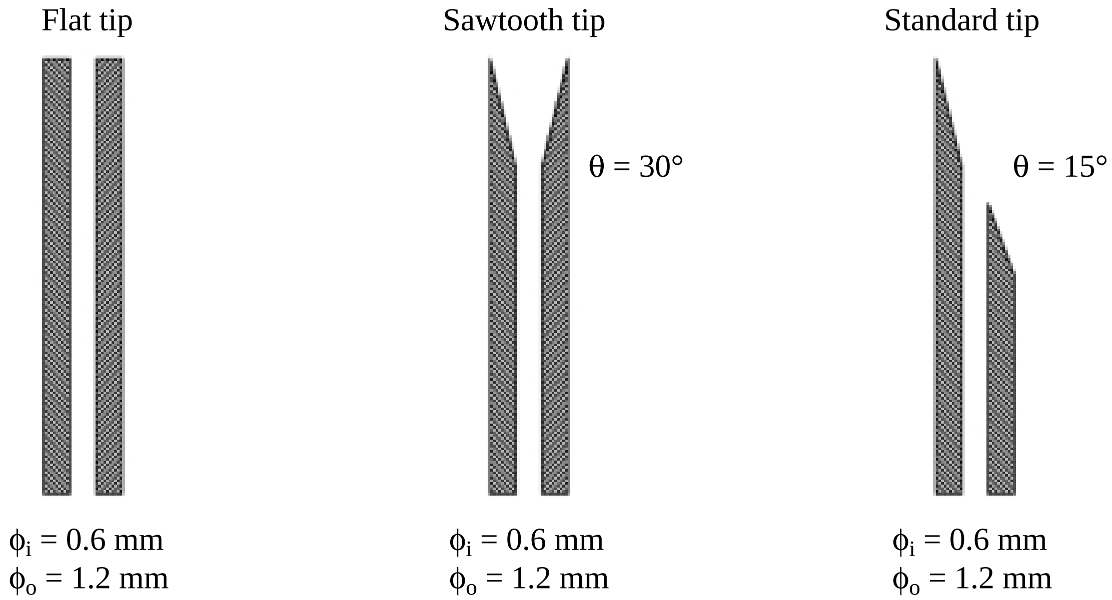

Figure 2. Geometry of three nozzles for the feeding of PAN solution. (ϕ_i = inner diameter, ϕ_o = outer diameter).

RESULTS AND DISCUSSION

For polyacrylonitrile electrospun at the liquid flow rate of 0.1 ml/min and the distance between the nozzle and the target of 15 cm is demonstrated in Figure 3. The use of nozzle with sawtooth outlet gave higher length of Taylor cone than those with flat outlet and with standard outlet, respectively. It might be due to the symmetry and the support of two protruding teeth of the nozzle in sawtooth shape. The shape of sawtooth outlet is similar to the joining of two standard nozzles. One standard outlet leads to Taylor cone at one position. By using sawtooth nozzle, the combination of two Taylor cones can be achieved. Moreover, two protruding zones in sawtooth outlet help support the resulting Taylor cone, leading to higher length of Taylor cone compared with other nozzles. Although the flat outlet has the highest symmetry in shape, it exhibits lower length of Taylor cone than sawtooth outlet.

Additionally, it was also found that the use of flat tip provided the lowest oscillation of fibers emerging from Taylor cone, as illustrated in Figure 3(b). It might be due to the symmetry in shape of flat outlet. This leads to the axial-symmetrical Taylor cone and the stability of fluid jet emitted from the nozzle tip with low oscillation of fibers.

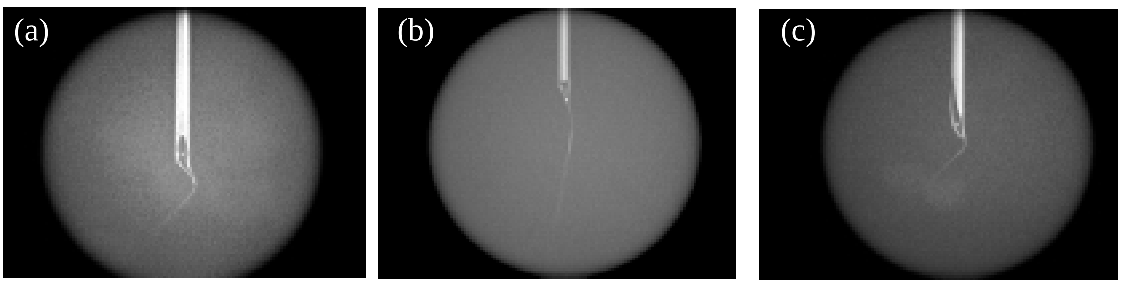

Figure 3. The formation of Taylor cone at liquid flow rate of 0.1 ml/min in (a) sawtooth tip, (b) flat tip and (c) standard nozzle.

At higher flow rate of polymer solution (2 ml/min), it can be obviously seen that the standard nozzle generated the splitting of Taylor cone, as exhibited in Figure 4. However, this phenomenon did not occur in the case of other nozzles. It might be due to the evolution of another Taylor cone in the flow direction of the polymer solution at higher liquid flow rate during spinning process with the vertical configuration. At low liquid flow rate, with the use of the standard nozzle, polymer solution that emerged from the nozzle flowed into the apex of the nozzle. Then Taylor cone took place at the tip of the nozzle as described above. Upon increasing the liquid flow rate, the polymer solution has higher pressure, leading to the driving force for the occurrence of Taylor cone at two positions, one at the apex of the nozzle and another in the axial-flow direction of polymer solution. As spinning time passes, another cone generates (Figure 4(a)-(c)).

After spinning, the microstructures of these fibers were analyzed with a scanning electron microscope. Figure 5 shows a scanning electron micrograph (SEM) of one sample of submicron-diameter fibers of polyacrylonitrile (PAN), obtained from an organic solution by electrospinning. Such fibers were deposited in the form of a nonwoven fabric when a charged fluid jet was accelerated down an electric field gradient, solidified and deposited onto a ground collector.

Figure 4. The evolution of the formation and splitting of Taylor cone in standard nozzle at a liquid flow rate of 2 ml/min.

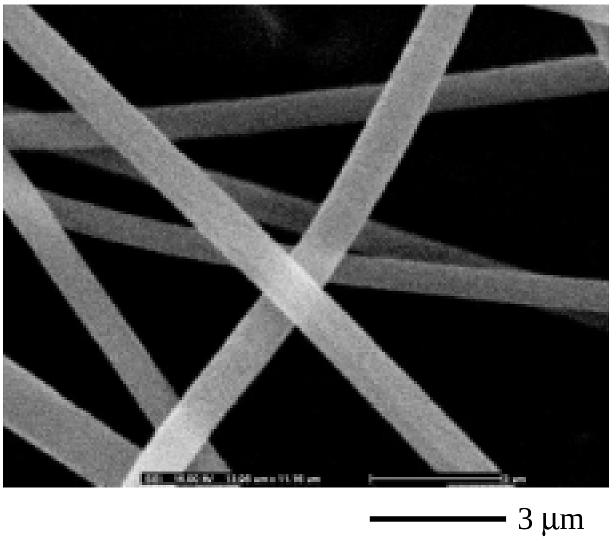

Figure 5. SEM micrograph of electrospun PAN fibers. The fibers were spun from a 12 wt% solution of PAN in *N,N*-dimethylformamide at a flow rate of 0.1 ml/min and a voltage of 20 kV with a flat nozzle.

CONCLUSION

The results show that electrospinning is a very promising, facile and effective technique for fabricating nanofibers. The geometry of the nozzle influenced the length of Taylor cone and the oscillation of fiber. For feeding polyacrylonitrile solution, the standard nozzle provided the lowest oscillation of fiber due to the symmetry in outlet shape. Meanwhile, the highest length of Taylor cone was demonstrated in the sawtooth nozzle which might be due to the support of protruding zone in the apex of nozzle. It has been illustrated that it is possible to control the spinning of electrospun fibers through the design of nozzle.

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