High-throughput multi-jet electrospinning for two fluids using a coaxial grooved nozzle

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Electrospinning is a simple and versatile technique for fabricating nanofibers and fibrous mats, capable of producing continuous nanofibers with various types of surface morphology. Because of its numerous advantages, the procedure has been widely employed with variety of polymers in various applications. To increase the throughput, we have introduced coaxial grooved nozzles. (Fig.1) By using a coaxial grooved nozzle and two fluids, including polyethylene oxide (PEO), we are able to achieve stable multi-jet operation and relatively high throughput. The multi-jets are initiated by the multi-jet mode of the inner fluid, and share the total flow rate of the polymer solution. We have investigated the operating conditions for various flow rate combinations of two fluids.

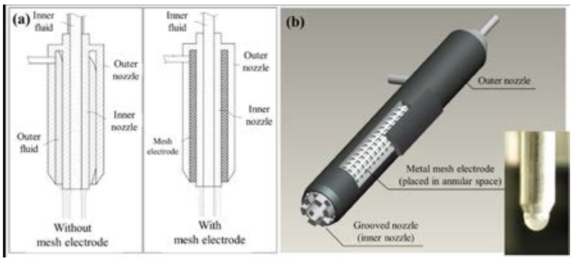

Figure 1. Schematics coaxial grooved nozzle.

The formation mechanism of multi-jet electrospinning with two fluids is described as follows. In previous research on electrospray, we observed that when the applied voltage reached a certain onset voltage, multi-jets became anchored in the grooves of the nozzle tip. In electrospinning, a single jet is similarly divided into multi-jets by the splitting of the electrified inner jet. In general, multi-jets can be formed from a polymer jet alone, but in the present case, it would be difficult to achieve because of the relatively high flow rates. To summarize the mechanism of multi-jet electrospinning for two fluids, the two liquids create two fluid layers, and the charged inner fluid is subjected to a repulsive force as it enters the functional domain of the multi-jet mode. This force is directly transferred in the outward direction along the two fluid layers. The exterior of the single jet becomes extremely unstable, and finally the two-layered jet divides into thinner multi-jets. To find the optimized number of multi-jets and flow rate of the inner fluid, we examined jet formation while adjusting the flow rate of the inner fluid. When the polymer solution was fed at 6 ml/h, three jets appeared at the tip of the nozzle for voltages close to 25 kV. When three jets formed, fiber deposition was observed on the collector. One or two multi-jets proved to be insufficient. In these cases, polymer solution was delivered to the collector, and fibers were not formed. This result shows that for fiber deposition to occur, the single jet must be divided into an adequate number of thinner multi-jets. As the flow rate of the polymer solution increased, the number of multi-jets required for stable operation also increased. In the 6-ml/h case, three jets were sufficient for stable operation, whereas in the 14-ml/h case, five jets were necessary for stable operation. When the flow rate of the inner fluid was inadequate, the additional jet was not formed. However when the flow rate of the inner fluid was excessive, there was interference between the inner fluid and the electrospun multi-jets, and the jets became intermittent. Using these results, we determined the optimized flow rate conditions. The results are summarized in Figure 2.

$Q_{ethanol}$	Q_{PEO}	1 jet	2 jets	3 jets	4 jets	5jets
0 ml/h	6 ml/h	12.5 kV	-	-	-	-
1 ml/h	6 ml/h	10.3 kV	15.7 kV	23.1 kV	-	-
2 ml/h	6 ml/h	5.5 kV	15.1 kV	21.3 kV	-	-
3 ml/h	6 ml/h	4.0 kV	14.0 kV	17.1 kV	21.8 kV	-
$Q_{ethanol}$	Q_{PEO}	1 jet	2 jets	3 jets	4 jets	5jets
1 ml/h	8 ml/h	8.0 kV	16.8 kV	21.5 kV	22.6 kV	-
2 ml/h	8 ml/h	7.2 kV	15.6 kV	20.4 kV	24.4 kV	-
3 ml/h	8 ml/h	6.0 kV	15.2 kV	20.3 kV	23.2kV	-
4 ml/h	8 ml/h	5.8 kV	15.1 kV	20.5 kV	-	-
$Q_{ethanol}$	Q_{PEO}	1 jet	2 jets	3 jets	4 jets	5jets
2 ml/h	10 ml/h	7.6 kV	18.3 kV	23.4 kV	-	-
3 ml/h	10 ml/h	7.1 kV	17.2 kV	18.5 kV	20.5 kV	23.9 kV
4 ml/h	10 ml/h	5.1 kV	16.3 kV	18.3 kV	19.5 kV	-
5 ml/h	10 ml/h	5.2 kV	16.9 kV	20.1 kV	21.8 kV	-
$Q_{ethanol}$	Q_{PEO}	1 jet	2 jets	3 jets	4 jets	5jets
3 ml/h	12 ml/h	7.8 kV	16.4 kV	18.4 kV	23.4 kV	-
4 ml/h	12 ml/h	7.5 kV	13.3 kV	20.4 kV	22.4 kV	24.0 kV
5 ml/h	12 ml/h	5.5 kV	15.1 kV	20.5 kV	22.4 kV	-
$Q_{ethanol}$	Q_{PEO}	1 jet	2 jets	3 jets	4 jets	5jets
4 ml/h	14 ml/h	7.5 kV	15.3 kV	20.9 kV	22.5 kV	23.8 kV
5 ml/h	14 ml/h	7.3 kV	15.2 kV	21.3 kV	23.2 kV	24.7 kV

Direct deposition
Unstable multi-jet
Stable multi-jet

Figure 2. Operating conditions for multi-jet electrospinning.

The morphology of the resulting nanofibers is uniform without bead formation. The fibers have an average diameter of about 350 nm.

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