Electrospun uniform fibres with a special regular hexagon distributed multi-needles system

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Abstract: A special design for the multi-jets electrospinning system is presented. In this work, a 6 (g/ml) % polyethylene oxide (PEO) water solution was electrified and pushed by air pressure through a spinneret. The spinnerets were built-up with needles with a regular hexagon distribution and each 3 needles have been designed as a regular triangle distribution. The outside needles modified the electrical field to uniform the electrical field strength on the inside nozzles and restrict the path of the inside jets. A coaxial iron ring was used in order to uniform the electrical field strength on the outside nozzles and restrict the collection area. In this paper, a 7 cm diameter ring was used in the 7 needles system, a 9 cm diameter ring was used in the 19 needles system and a 11 cm diameter iron ring was used in the 37 needles system test. The results demonstrated that the special design setup can produce uniform nanoscale fibres and the spinning process is insensitive with the atmosphere disturbance. The distribution of needles shows a possibility design for improving the production rate of nanofibres manufacturing.

1. Introduction

Electrospun fibres have recently become an object of intensive experimental research due to potentially broad markets for the fibres as small as 100 nm. Such small scale fibres have numerous potential applications including filtration [1], tissue engineering [2], drug delivery [2], superhydrophobic surfaces [3] and composite materials [4].

The mass rate of fibre deposition from a single jet is typically 0.1-1.0 g/h with single needle electrospinning system. The low efficiency of single needle electrospinning process and the non-uniform fibres received on the collection with the multiple needles spinning process may limit the industrial use of electrospinning. The repulsion from the neighborhood jets and the non-uniform electrical field on each nozzle at different position of the spinneret were the most difficult work in multi-jets electrospinning field. The multi-jets were always unstable and easily affected by environmental factors.

For receiving a stable electrospinning jet, Deitzel et al. [5] demonstrated a controlling system using 3 power supplies and 8 rings, which could dampen the instability of electrospinning. Kim designed an electrospinning process with a cylindrical auxiliary electrode connected to a spinning nozzle to stabilize the initially spun solution with a parallel-plate electrode as a collector to generate an alternating current electric
field for collecting the spun jets [6]. Yang et al. design a novel system using a PVC insulator tube to modify the electrical field distribution controlling the jet path [7] [8].

Renker and his group demonstrated a model that under comparable conditions 9 jets could be electrospun steadily from separate nozzles located with a pitch of 1 cm on a square of 4 cm² [9]. Yarin and his group provided a new approach employing a ferromagnetic liquid sub layer that yields about 26 jets/cm² upwards. But the fibre diameters were broader in distribution from 200 nm to 800 nm [10]. Recently their group did an experiment with 9 needles and a modeling of multiple jets during the electrospinning of polymer solutions [11]. Tomaszewski et al. compared 3 types of multi-jets electrospinning heads and found that the 10 spinning pipes arranged in a circle with a diameter of 50 mm is the best arrangement in their work[12]. Dosunmu et al. produced electrospun fibres using a porous tube. The mass production rate from the porous tube is 250 times greater than from a typical single jet but the fibre diameter distribution was larger [13]. Kim et al. used a cylindrical electrode to stable the 5 jets electrospinning [14]. Yang et al. reported 3 kinds of spinneret in order to get a stable electrospinning process with 7 needles [15].

To meet high liquid throughput requirements and uniform fibres in a relative small area, a regular hexagon distribution multi-jets system has been designed. Each 3 needles have been designed as a regular triangle distribution in this system in order to uniform the electrical field strength on the inside nozzles and restrict the path of the inside jets. A coaxial iron ring was used in order to uniform the electrical field strength on the outside nozzles and restrict the collection area. In this paper, the spinneret was built-up with 7 needles and 37 needles. The distance between each two needles is 1 cm. The results demonstrate that the special design setup can produce uniform nanoscale fibres and the process is stable.

2. Experimental

500,000 average molecular weight PEO was dissolved in de-ionized water to make solutions with 6 % (g/ml) concentration in our experiments.

The schematic illustrations of the experimental setups used in this study were shown in Figure 1. In this design, PEO water solution was electrified and pushed by air pressure through a spinneret to improve the insulting property of the setup. The polymer solution is forced with a syringe pump through a 2 mm inner diameter silicone rubber tube, resulting in formation of drops of polymer solution at syringe tips when using 7 needles system and 19 needles system. The polymer solution is forced through a reservoir holding PEO solution that connected with a syringe pump through a 2 mm inner diameter silicone rubber tube, resulting in formation of drops of polymer solution at syringe tips when using 37 needles system in order to protect the pump. Needles used in this test having 0.55 mm inside and 0.6 mm outside diameters. Iron rings range form 7 cm to 11 cm were concentrically fastened with the needles at the height of the nozzles. The needles and the iron ring were linked with a copper wire connected with the power supply. The electrospun fibres were collected on a flat 30 cm×30 cm target. The distance between the nozzle and target was varied from 25 cm to 38.5 cm. The solution was prepared and all experiments were performed at about 25 ºC in air at 40 %-60 % RH.

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**Fig.1 (a) the schematic illustration of the experimental setup; (b) the schematic illustrations of the experimental 37 needles spinneret distribution**
Electrospun fibres were observed with a scanning electron microscope (JSM-5910LV, Japan). The IMAGEJ image analysis software was used to measure the fibre diameters. The segments shown in the images are parts of very long fibres. About 300 fibre diameters and segment diameters were measured from multiple SEM images for each group of fibres distribution.

3. Experimental results and discussion

3.1. Results of 7 needles system
To explain the design in depth, 7 needles system was used as it is the simplest distribution for this structure. The 7 needles were distributed as 0# needle and 1# needles in Figure 1(b). A 7 cm diameter iron ring in the test was coaxial with the 7 needles. The spinning process is stable for 4 hours with the 7 cm diameter ring. The stability of the normal 7 needles is not as good as the ring system. The stable spinning always keeps for 1 hour and the balance is easy to be broken by some environmental factors.

Figure 2 and Figure 3 showed the electrospinning results. The diameter of the large mat is 15cm and the boundaries of the small mats were clear with the normal 7 needles system. The diameter of the fibre mat is 12 cm and the boundaries of the small mats were disappearing when using an iron ring. The distributions of the fibres diameters are ranging from 200 nm to 600 nm and the mean diameters are all about 400 nm at 22.5 kV with the ring. The distributions of the fibre diameters are ranging from 300 nm to 500 nm and the mean diameters are all about 400 nm at 25 kV with the ring. The fiber diameter distribution is smaller with 7 needles system with a 7 cm diameter iron ring than that with the normal 7 needles system. The distributions of the fibre diameters of the ring system were almost the same with the distributions of the fibre diameters of single needle system [16].

The calculated electrical field distributions of the 7 nozzles in the two systems are shown in Figure 4(a) and Figure 4(b). The electrical field strength values on the nozzles and 5mm under the nozzles were listed in table 1. The results show that the angle away from z axis is larger without ring. The difference between the needles E value was about 10000 V/m in the ring system and was 20000V/m in the normal system. The larger electric field strength needs a larger solution rate for the outside needle so the solution rate is a little smaller for the outside ones. That caused the larger distribution of the fibres in the outside hexagon and made the process sensitive to be interrupted. According to Figure 4(c), larger electric field strength on the nozzle of single needle system with a constant solution rate causes a larger distribution of fiber diameters. The HSC images show that the range of the bending point of the jet is larger with the higher voltage power supply, which can be considered as the reason for the larger fiber diameter distributions of the outside needles. The outside jets formed a secondary electric field to affect the jet in the middle. The affection is instable for the instability of the outside jets. So, the fibre diameters distribution of the inside needle is larger than single needle system.

![Image](image_url)

Fig.2 electrospinning fibres with 7 needles system without a ring at 22.5 kV, 0.7ml/h, 25 cm (a) photo image of fibre mat; (b) SEM result of 0# needle in the middle; (c) SEM result of the outside circles; (d) electrospinning fibre diameter distribution with PEO-water solution
Fig. 3 electrospinning fibres with 7 needles system with a 7 cm diameter ring at 25 kV, 0.7ml/h, 25 cm (a) photo image of fibre mat; (b) SEM result of 0# needle in the middle; (c) SEM result of the outside circles; (d) electrospinning fibre diameter distribution with PEO-water solution.

Fig. 4 (a) electric field distribution of the normal 7 needles system; (b) electric field distribution of the 7 needles with a 7 cm diameter ring system; and (c) Fiber diameter distribution of single needle system at 30 cm, 0.1 ml/h.

Table 1 electric field strength of the 7 needles system

| Height (mm) | system   | Needle Position | E Value (V/m) | angle from z axis |
|------------|----------|----------------|---------------|-------------------|
| 250        | With ring| Middle         | 3710554       | 0                 |
|            |          | Outside        | 5241897       | 0                 |
|            | Normal   | Middle         | 10796387      | 0                 |
|            |          | Outside        | 13106015      | 0                 |
| 245        | With ring| Middle         | 301744.6      | 9.4               |
|            |          | Outside        | 325722.7      | 0                 |
|            | Normal   | Middle         | 557523.5      | 23                |
|            |          | Outside        | 596161.3      | 0                 |

3.2. Results of 37 needles system

Based on the analysis above and the regular triangle distribution can be extended out endlessly with the largest number of needles per area, keeping the distance between the nearest ones the same, 19 needles system and 37 needles system were used in the test. The collected fibers were show in Figure 5.

Take 37 needles for example. The boundaries of the 37 round mats are clear at the beginning and disappear after about 1 hour. The spinning process is stable for more than 4 hours with the ring and is insensitive with the environmental disturbance. But the output mass of the 4# needles is larger than input mass which causes zero flow some times when the spinning last for a long time as the electrical field distribution is not uniform without the ring.

The mat diameter was 34 cm with the 11 cm iron ring when the distance between the nozzle and target was 38.5 cm and the voltage is 57.4 kV. The polymer solution is forced by air pressure at 18.5 ml/h. The mat
diameter was 28 cm without iron ring when the distance between the nozzle and target was 35 cm and the voltage is 46.8 kV. The polymer solution is forced by air pressure at 6 ml/h. It is a hard work to make the conditions all the same because the system was too complicated.

The diameters of mats on the outside circle (3# hexagon) are about 5.5 cm to 6 cm and the diameters of mat on the inside circles (0#, 1# and 2# hexagon) are about 4 cm to 5 cm with ring system. With the normal 37 needles system, the diameters of mats on the outside circle (4# hexagon) are about 5 cm and the diameters of mat on the inside circles (0#, 1# and 2# hexagon) are about 4 cm.

Fig. 5 fibres collected on the target with 37 needles system (a) electrospinning with 19 nozzles at 28.5 kV, 2.9ml/h, 30 cm; (b) electrospinning with 19 nozzles at 43 kV, 2.9ml/h, 30 cm; (c) with a 11 cm diameter iron ring at 57.5 kV, 18.5 ml/h, 38.5 cm and (d) without a ring at 46.8 kV, 6 ml/h, 35 cm.

Figure 6 and Figure 7 showed the SEM results of electrospun fibres and the fibre diameter distributions with PEO-water solution at different position. The results show that the fibre distributions are almost the same although the needles positions are different. The distributions of the fibre diameters are all ranging from about 200 nm to 450 nm. The mean diameters of the two systems at different conditions are all about 300 nm shown in Figure 7 and Figure 8. It can be seen that the difference of fibre diameters distributions between the two systems disappear when using 37 needles forming 4 hexagons in different size.

Fig. 6 SEM results of electrospinning fibres with 37 needles system without a ring at 46.8 kV, 6 ml/h, 35 cm (a) 0# needle in the middle of the needles; (b) 1# needles in the first circle; (c) 2# needles in the second circle; (d) 3# needles in the third circle; (e) fibre diameter distribution with PEO-water solution
Fig. 7 SEM results of electrospinning fibres with 37 needles system with a 11 cm diameter iron ring at 57.5 kV, 18.5 ml/h, 38.5 cm (a) 0# needle in the middle of the needles; (b) 1# needles in the first circle; (c) 2# needles in the second circle; (d) 3# needles in the third circle; (e) electrospinning fibre diameter distribution with PEO-water solution

The system with a ring was more stable for the smaller difference among the electric-field intensities on the nozzles at different positions. The ring could concentrate the jets when the number of needles is smaller. With the increase of the needles, the effect of the ring is mostly on uniform electric field on the nozzles. The special aligned needles formed a concentrated electric field to concentrate the jets inside. The secondary electric field by the outside needles caused that a larger space was needed for jet stretching of the inside nozzles for longer straight part of the jet. The larger collection area with the ring system in the experiment is caused by the different heights in the two experiments.

4. Conclusion

The special design that each 3 needles have been deposed as a regular triangle distribution and the outside needles are formed a regular hexagon is demonstrated in this paper. The results show that stable uniform fibres were received with the struction of 37 needles and a ring spinneret. It was demonstrated that the more nozzles of the spinneret were used, the larger space was needed for jet stretching. It was also shown that the larger spinning solution mass needs higher voltage. The results show that there were two ways to match the different electric-field intensities on the nozzle at different position. One is making the solution rate match the nozzles of the spinneret were used, the larger space was needed for jet stretching. The other is uniforming the electric-field intensities on the nozzle at different positions. The design and the results provide a useful idea to obtain a more needles system for multi-needles electrospinning setups.

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