

EFFECT OF BUBBLE SIZE ON NANOFIBER DIAMETER IN BUBBLE ELECTROSPINNING

by

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Polymer bubbles are widely used for fabrication of nanofibers. Bubble size affects not only bubble's surface tension, but also fiber's morphology. A mathematical model is established to reveal the effect of bubble size on the spinning process, and the experiment verification shows the theoretical analysis is reliable.

Key words: bubble electrospinning, bubble diameter, fiber diameter

Introduction

Bubble electrospinning [1-9] is a powerful technology to mass-produce nanofibers. Its output mainly depends up the bubble number produced and bubble size. The surface tension of a bubble depends upon its size; a smaller bubble requires a smaller electronic force for fabrication of ultrafine fibers during bubble electrospinning. The electronic field triggers rupture of polymer bubbles to eject jets. In this paper, a single bubble is formed during the spinning process to study the effect of bubble size on the spinning process.

Experiment

The experiment set-up for single bubble electrospinning is shown in fig. 1. Many bubbles can be formed on the surface of solution, which will be interacted with each other, and form a single bubble on the tube exit. The tube diameter should be as small as possible to guarantee only a single bubble form for spinning. In our experiment, the inner diameter of the tube is

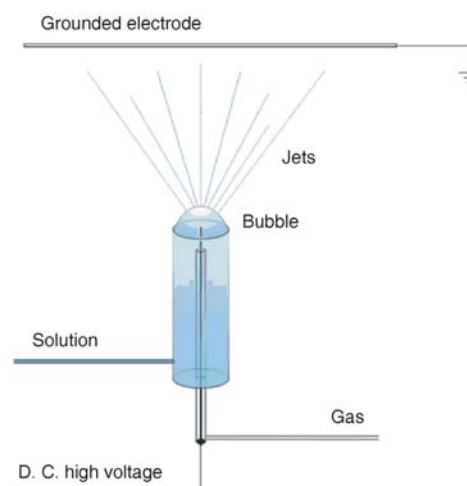


Figure 1. Experiment set-up for single bubble electrospinning

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controllable. Five bubble sizes are used in experiment, they are 1.05 cm, 1.5 cm, 1.9 cm, 2.4 cm, and 3.5 cm, respectively.

The mixture of polyvinyl alcohol (PVA), average molecular weight 1,750 50 g/mol, powder and deionized water with a weight ratio 1:9 was magnetically stirred at 80 °C for two hours to prepare for uniform and transparent solution. We produced micro/nano fibers using the present experiment set-up with the prepared solution. The inner diameters of the tubes were 1.05 cm, 1.5 cm, 1.9 cm, 2.4 cm, and 3.5 cm, separately. The applied voltage was 35 kV, the distance from the top of the tube to the grounded electrode was 20 cm. The environment temperature was 20 °C, and the relative humidity was 52%.

The morphology of the electrospun PVA fibers was investigated using scanning electron microscope (SEM); the SEM micrographs are shown in fig. 2. In the figure we can find that the fiber diameters decrease with the increase of the bubble diameters.

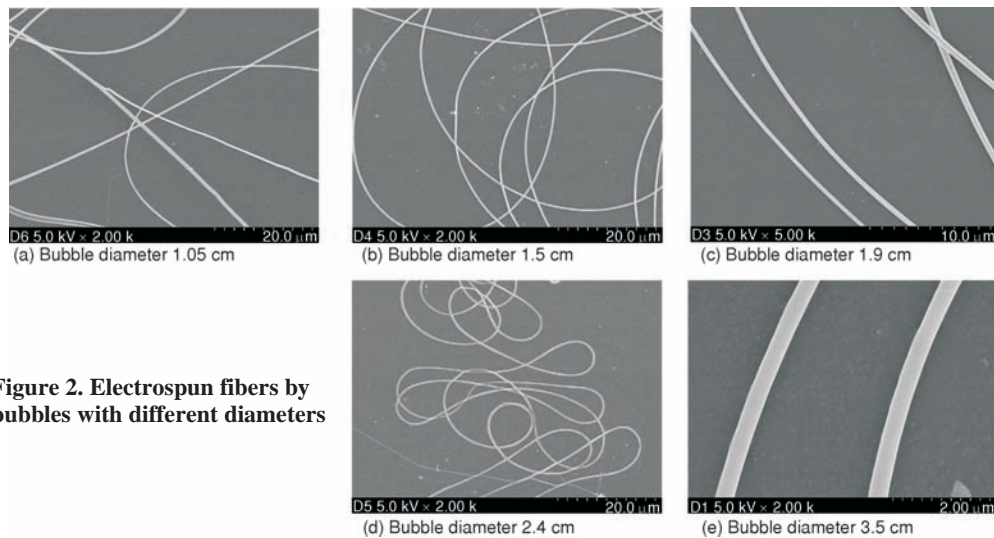


Figure 2. Electrospun fibers by bubbles with different diameters

Mathematical model

In bubble electrospinning process, the conduction current through bubble is an insignificant effect on the distribution of electric charge on the bubble. Generally, electric charge distributes only on jet surface since the electric conductance of the solution is not absolutely equal to 0. We take the bubble in fig. 1 as a sphere, the electric charge on the bubble surface can be written $q = 4\pi\epsilon_0 R_b U$ [10], and the electric field on the bubble surface is:

$$E = \frac{U}{R_b} \quad (1)$$

where R_b is curvature radius of the bubble, and U is the electric potential of the bubble which is equal to anode voltage. When the anode voltage is kept constant:

$$E \propto \frac{1}{R_b} \quad (2)$$

the electric field E on the bubble surface is inversely proportional to the curvature radius R_b of the bubble.

The moving jet is assumed to be a laminar flow. The velocity distribution is [11]:

$$v(r) = g \frac{2\sigma E}{\rho R} t - \frac{\sigma E}{2\eta R} r^2 \quad (3)$$

here σ , ρ , R , and η are mass density of the solution, viscosity coefficient of the solution, radius of the jet, and area density of electronic charge on the jet surface, respectively. At the time $t = 0$, the velocity is $v = (\sigma E / 2\eta R) r^2$. Section area of a flow layer with radius, r , and thickness, dr , is $dS = 2\pi r dr$, and mass flow in the flow layer is:

$$dM = \pi \rho r^3 \frac{\sigma E}{\eta R} dr \quad (4)$$

Then total mass flow through the cross-section of the jet can be written:

$$M = \pi \rho \frac{\sigma E}{\eta R} \int_0^R r^3 dr = \frac{\pi \rho \sigma E R^3}{4\eta} \quad (5)$$

We can see that the mass flow, M , in the jet is in proportion to the electronic field, E , on a bubble surface:

$$M \propto E \quad (6)$$

According to $E = (1/R_b)$, we can get the relation of the mass flow, M , with the bubble radius, R_b :

$$M \propto \frac{1}{R_b} \quad (7)$$

The mass flow and the radius of the jet have the relation:

$$M \propto R^2 \quad (8)$$

therefore

$$R \propto \frac{1}{\sqrt{R_b}} \quad (9)$$

Equation (9) reveals that the radius of fibers produced by bubble electrospinning is inversely proportional to the square root of the bubble radius, $(R_b)^{1/2}$. The radii, R , of the fibers and the, R_b , of the bubble can be displaced by the diameter, d , of the fibers and the diameter, D_b , of the bubble:

$$d \propto \frac{1}{\sqrt{D_b}} \quad (10)$$

In fig. 3 the small squares denote the diameters of the fibers electrospun through bubbles with different diameters, and the curve shows $d = 0.665/(D_b)^{1/2}$ in graphic form, the trend of the fiber diameters fits the curve approximately.

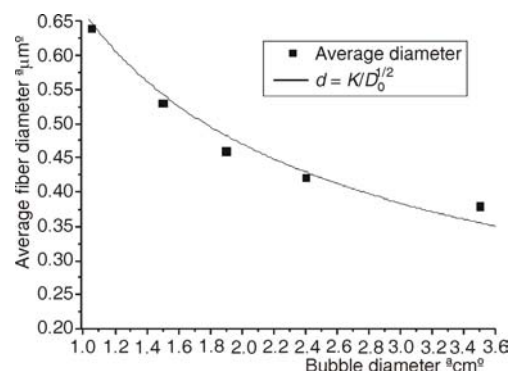


Figure 3. The trend of the diameters of the fibers electrospun through bubbles

Conclusion

This paper gives a mathematical analysis of effect of bubble size on fiber diameter during the bubble electrospinning. It reveals that smaller size results in bigger fibers, and the experimental data gives a good agreement. The present theory provides a useful tool for controlling fiber diameter by adjusting bubble size.

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References

- [1] Chen, R., et al., Bubble Rupture in Bubble Electrospinning, *Thermal Science*, 19 (2015), 4, pp. 1141-1149
- [2] Shen, J., et al., Effect of Pore Size on Gas Resistance of Nanofiber Membrane by the Bubble Electrospinning, *Thermal Science*, 19 (2015), 4, pp. 1349-1351
- [3] He, C. H., et al., Bubbfil Spinning for Fabrication of PVA Nanofibers, *Thermal Science*, 19 (2015), 2, pp. 743-746
- [4] Liu, H. Y., et al., A Novel Method for Fabrication of Fascinated Nanofiber Yarns, *Thermal Science*, 19 (2015), 4, pp. 1331-1335
- [5] Liu, Z., et al., Active Generation of Multiple Jets for Producing Nanofibres with High Quality and High Throughput, *Materials & Design*, 94 (2016), Mar., pp. 496-501
- [6] Shen, J., et al., Bio-Mimic Design of PM2.5 Anti-Smog Masks, *Thermal Science*, 18 (2014), 5, pp. 1689-1690
- [7] Li, Y., et al., Copper/PA66 Nanofibers by Bubbfil-Spinning, *Thermal Science*, 19 (2015), 4, pp. 1463-1465
- [8] Liu, Z., et al., Tunable Surface Morphology of Electrospun PMMA Fiber Using Binary Solvent, *Applied Surface Science*, 364 (2016), pp. 516-521
- [9] Liu, Z., et al., A Mathematical Model for the Formation of Beaded Fibers in Electrospinning, *Thermal Science*, 19 (2015), 4, pp. 1151-1154
- [10] Xu, L., et al., Numerical Simulation for the Single Bubble Electrospinning Process, *Thermal Science*, 19 (2015), 4, pp. 1255-1259
- [11] Ren, Z., et al., Thermal and Hydrodynamic Performance Analysis of Charged Jet in Electrospinning, *International Journal of Numerical Methods for Heat & Fluid Flow*, 24 (2014), 6, pp. 1260-1267