

## JET SPEED IN BUBBLE RUPTURE

by

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Original scientific paper

<https://doi.org/10.2298/TSCI151202149S>

*When a polymer bubble is broken in the bubble electrospinning process, thousands of thousands jets are produced with almost same initial ejecting speed, which plays a very important role on the formation of the nanofiber. In this paper, the nanofiber membranes were prepared by the bubble spinning with different air temperatures. This paper also gives a simple mathematical model to predict the initial speed of jets, and it is as high as 300 m/s.*

Key words: *nanofiber, bubble electrospinning, rupture, jet speed*

### Introduction

A polymer bubble can be used for production of nanofibers by the bubble electrospinning [1-3]. When a polymer bubble under an electrostatic field ruptures, the surface tension leads to surface minimization of some film fragments, and daughter bubbles are formed [4-6]. Ruptured film might be stripped upwards by an electronic force to form a very thin and long fiber. The nanofibers of polyvinyl alcohol (PVA), polyvinylpyrrolidone (PVP), polylactic acid (PLA), silk fibroin, and silk fibroin/chitosan have been prepared successfully by the bubble electrospinning [7-10]. Various researches have been taken out to find the main factors affecting the spinning process. Ren, *et al.* [11] studied the effect of bubble size on the nanofiber diameter, from theoretical results and the experimental data, they found that smaller size bubble results in bigger fibers. Yang, *et al.* [12] studied the effect of solution conductivity on the morphology of bubble electrospinning nanofibers. They changed electrical conductivities of the polymer solutions by adding different amounts of LiCl into the solutions. They found that when the mass fraction of LiCl is 0.5%, the smallest mean diameter and a uniform fineness of electrospinning nanofibers were obtained. Yang, *et al.* [13] investigated the effects of solution concentration and viscosity on diameter and morphology of bubble electrospinning PVA nanofibers. The result showed that the fibers change their morphology from few beads, smooth surfaces and finally to larger diameter fibers, when PVA solution concentration increases. Liu, *et al.* [14] focused on the effects of applied voltages on diameter, morphology, and structure of bubble electrospinning fibers. By theoretical analysis and experiments, they found that the average diameter of fibers increased with the increase of the applied voltage in bubble electrospinning; the number of

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beaded fibers decreased with increasing applied voltage. He and Liu [15] established a theoretical model of number of sub-daughter bubbles produced after bubble rupture during bubble electrospinning. They found that the size and number of sub-daughter bubbles mainly depended upon the applied voltage and the initial size of interacted bubbles. Liu and Dou [16] established an improved Young-Laplace equation for bubble electrospinning. The results showed that temperature and humidity can be used to control the surface tension of bubbles. However, the initial speed of the jets when a bubble is broken has not been studied so far [17].

### Experimental design

The polymer, PVA, was purchased from Nantong Keda Co., Ltd. The solvent was water. All the chemicals were used as received. The polymer was added into water, and then the mixture was stirred at 90 °C for 3 hours to get homogeneous and transparent solution. The PVA solution concentration was 10 wt.%.

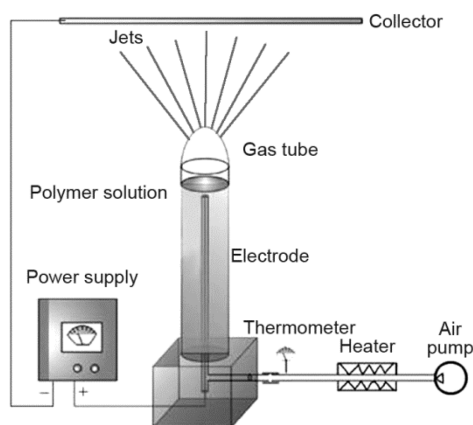


Figure 1. Bubble electrospinning equipment set-up

The spinning process was performed on the bubble electrospinning equipment (Nantong Bubbfil Nanotechnology Co., Ltd.). The bubble electrospinning equipment set-up was shown in fig.1. The bubbles of polymer solution were blown by the air, and the bubbles were stretched in the electric field. A flat piece of aluminum foil placed 10 cm above the nozzle was used for collecting fibers. The voltages applied to the electrode were set as 20 kV. The spinning time was 20 minutes for a sample. The air were heated by a heater, the air temperature was measured by a thermometer. The air temperature was set as 20, 30, and 40 °C. The temperature and humidity of the laboratory were 10 °C and 65%.

Figure 2 shows the morphology of the PVA nanofiber membrane. The air temperature great influences the PVA nanofiber membrane structure. As shown in fig. 2(a), when the air temperature was 20 °C, the nanofiber cannot be produced. Compare with the membrane prepared in 20 °C, We can see nanofiber in the membrane prepared in 30 °C, but the nanofibers bond together obviously. In fig. 2(c), the membrane exhibited a typical nanofiber structure. With the air temperature increase, the thinner nanofibers were produced.

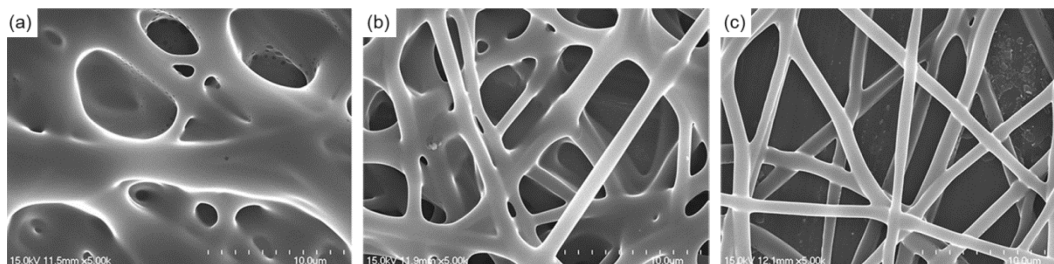


Figure 2. Micrographs of the PVA nanofiber membrane with different air temperature; (a) 20 °C, (b) 30 °C, (c) 40 °C

### Theoretical analysis

The bubble rupture is shown in fig. 3. During the bubble rupture, the jets are produced. Bernoulli equation for the jet's initial motion reads:

$$\frac{P_o}{\rho} + \frac{1}{2}u^2 = \frac{P_i}{\rho} + 0 \quad (1)$$

where  $P_i$  is the pressure inside of the bubble,  $P_o$  – the pressure outside of the bubble,  $u$  – the initial speed of the jets, and  $\rho$  – the density of air in the bubble.

By a simple calculation, we have:

$$u = \sqrt{\frac{2(P_i - P_o)}{\rho}} \quad (2)$$

If the differential pressure inside and outside is 1 atm, and the gas inside is air, we have:

$$u = \sqrt{\frac{2 \cdot 101325}{2.3381}} = 294.4 \text{ m/s} \quad (3)$$

The initial speed of jet is almost 300 m/s. According to eq. (2), the initial speed of jets can be controlled by the differential pressure inside and outside and the density of air in the bubble.

The density of an ideal gas is:

$$\rho = \frac{MP}{RT} \quad (4)$$

where  $M$  is the molar mass,  $P$  – the pressure,  $R$  – the universal gas constant, and  $T$  – the absolute temperature of air in the bubble. This means that the density of air can be adjusted by temperature, so the temperature inside and outside the bubble is one of the key factors to control the bubble spinning process.

With the increase of air temperature, the density of air decreases, the initial speed of jet increases, therefore the bubble film fragments were draw thinner. The experimental results conform to the theoretical analysis.

### Conclusions

In this paper, the nanofiber membranes were prepared by the bubble spinning with different air temperatures. With the air temperature increase, the thinner nanofibers were produced. The mathematical model was established, and the initial speed of jets produced in bubble rupture was calculated. From the model, we can conclude that the initial speed of jets can be controlled by the differential pressure inside and outside and the temperature inside and outside the bubble. The experimental results conform to the theoretical analysis.

### Acknowledgment

The work is supported by National Natural Science Foundation of China under grant No. 61303236, Production and Research Prospective Joint Research Project of Jiangsu Prov-

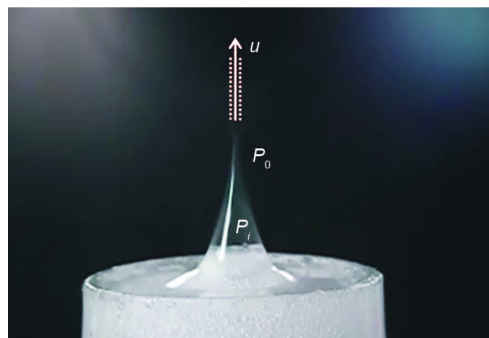


Figure 3. Photograph of the bubble rupture

ince under grant No. BY2015047-09, Nantong Science and Technology project under grant No. GY12015022.

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