INTERACTION OF MULTIPLE JETS IN BUBBLE ELECTROSPINNING

by

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Original scientific paper
https://doi.org/10.2298/TSCI211228083L

The bubble electrospinning is a peerless technology for mass-production of various functional nanofibers. During the spinning process, multiple jets are ejected, which might be interacted with each other. The interaction might result in mass transfer, energy transfer and force imbalance, all these factors will greatly affect the mechanical property and morphology of the resultant fibers. A theoretical model is established to study the two-jets combination during the spinning process, the mass conservation and momentum conservation are considered, and the combined fiber's diameter and moving velocity are theoretically elucidated. The present theory analysis can be easily extended to multiple jets interaction.

Key words: *bubble electrospinning, nanofiber yarn, multiple jets, mathematical model*

Introduction

Bubble electrospinning [1, 2] has attracted more and more attention in the last decade for its high production, it is a totally peerless technology after the electrospinning technology [3] for fabrication of various functional nanofibers. It uses an external force (*e.g.* the electrostatic force or a blowing air) to overcome the surface tension of the polymer bubble, which is then broken into millions of tiny jets, fig. 1. The multiple jets fly onto the receptor, and it will be solidified due to solvent evaporation [4]. The multiple jets in the spinning process have made it difficult to control the exact nanofibers' morphology and mechanical properties. It was already proved that the mechanical behavior of nanocomposite depends upon nanoscale structures [5].

Many researchers investigated the behavior of multiple jets in the traditional electrospinning [6-9], for example, Theron *et al.* [6] described the path of multiple jets in the process of electrospinning, and proposed a model by implementing Maxwell equation. Yang *et al.* [7] designed a special aligned multiple jets set-up to meet high liquid throughput requirements. Wu *et al.* [8] focused on the parameters influencing multiple jets especially the voltage. The double-switching voltage was adopted to manipulate multiple jets for enhanced throughput. Varesano *et al.* [9] tested several multiple electrospinning set-ups, and Li *et al.* [10] optimized the multiple

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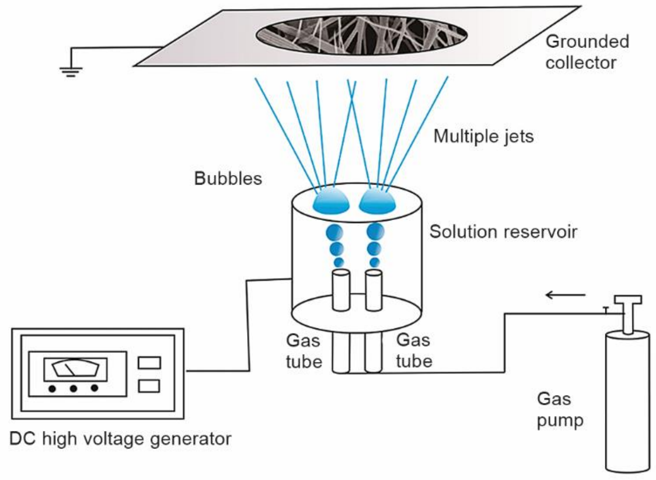

Figure 1. Bubble electrospinning set-up

needle electrospinning with great success. Wu and Liu [11] further improved the multiple electrospinning process and a fractal-like spinning process was proposed, however, neither experiment nor theory was carried out for multiple jets in bubble electrospinning. The interaction between the flying jets will greatly affect the morphology and properties of the obtained nanofiber membranes, this problem becomes even more serious in the bubble electrospinning, because millions and millions of flying jets are formed during the spinning process, and there is no way to control their trajectory when a jet was ejected from a broken bubble.

Bubble electrospinning can produce membranes with nanoscale thickness [12, 13]. Qian and He [12] reported that the fragments of a broken bubble can be directly received as a nanoscale membrane, no other technology can match this bubble spinning so far.

Thermodynamical model for the jets interaction

During the interaction of the moving jets, there happens the mass and energy transfer, this makes the problems much complex. Inspired by the work [14], the present authors give the following model as illustrated in fig. 2 to study their interaction.

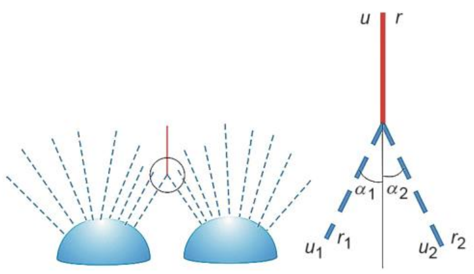

Figure 2. Scheme of combination of multiple jets in bubble electrospinning

This section considers only two-strand moving jets interaction. The law of mass conservation requires [14]:

$$\pi\rho_1 u_1 r_1^2 + \pi\rho_2 u_2 r_2^2 = \pi\rho u r^2 \tag{1}$$

where r_1, r_2, and r are the radiuses of the combing fibers and the combined fiber, respectively, ρ_1, ρ_2, and ρ – their densities, respectively, u_1, u_2, and u – their velocities, respectively. In case that $\rho_1 = \rho_2 = \rho$, we have the following relation:

$$u_1 r_1^2 + u_2 r_2^2 = u r^2 \tag{2}$$

The law of momentum conservation reads [14]:

$$\pi\rho_1 u_1 r_1^2 \vec{u}_1 + \pi\rho_2 u_2 r_2^2 \vec{u}_2 = \pi\rho u r^2 \vec{u} \tag{4}$$

where $\vec{u}_1$, $\vec{u}_2$, and $\vec{u}$ are velocity vectors, respectively. When $\rho_1 = \rho_2 = \rho$, eq. (4) becomes:

$$u_1^2 r_1^2 \cos\alpha_1 + u_2^2 r_2^2 \cos\alpha_2 = u^2 r^2 \tag{5}$$

where α_1 and α_2 are the inclined angles between the coming jets and the combined jet, respectively, fig. 2.

According to eqs. (2) and (5), the combined jet has the velocity:

$$u = \frac{u_1^2 r_1^2 \cos\alpha_1 + u_2^2 r_2^2 \cos\alpha_2}{u_1 r_1^2 + u_2 r_2^2} \tag{6}$$

and its radius can be calculated:

$$r = \frac{u_1 r_1^2 + u_2 r_2^2}{\sqrt{u_1^2 r_1^2 \cos\alpha_1 + u_2^2 r_2^2 \cos\alpha_2}} \tag{7}$$

We consider a special case that $u_1 = u_2 = u_0$, $r_1 = r_2 = r_0$, and $\alpha_1 = \alpha_2 = \alpha$, eqs. (6) and (7) deduce to, respectively, the following simple cases:

$$u = u_0 \cos\alpha \tag{8}$$

and its radius can be calculated:

$$r = \frac{2u_1 r_1^2}{\sqrt{2u_1^2 r_1^2 \cos\alpha_1}} = \frac{2r_0}{\sqrt{2\cos\alpha}} \tag{9}$$

From eq. (9), it is obvious that:

$$\lim_{\alpha\to 0} r \to \sqrt{2} r_0 \tag{10}$$

and

$$\lim_{\alpha\to \pi/2} r \to \infty \tag{11}$$

Equation (10) implies that when the two jets having same radius and same velocity move parallelly with mass and energy transfer, the final radius is $(2r_0)^{1/2}$. However, when the two jets are interacted perpendicularly $(\alpha = \pi/2)$, the resultant fiber tends to be infinitely large. This theoretical result can be used for designing a perpendicular bubble spinning for porous fibers.

When $u_1 = u_2 = u_0$, eq. (7) becomes:

$$r = \frac{r_1^2 + r_2^2}{\sqrt{r_1^2 \cos\alpha_1 + r_2^2 \cos\alpha_2}} \tag{12}$$

When $\alpha_1 = \alpha_2 = \alpha$, eq. (12) can be further simplified:

$$r = \frac{r_1^2 + r_2^2}{\sqrt{(r_1^2 + r_2^2)\cos\alpha}} \tag{13}$$

For multiple jets interaction, eqs. (1) and (4) are modified, respectively:

$$\pi\rho_1 u_1 r_1^2 + \pi\rho_2 u_2 r_2^2 + \cdots + \pi\rho_n u_n r_n^2 = \pi\rho u r^2 \tag{14}$$

$$\pi\rho_1 u_1 r_1^2 \vec{u}_1 + \pi\rho_2 u_2 r_2^2 \vec{u}_2 + \cdots + \pi\rho_n u_n r_n^2 \vec{u}_n = \pi\rho u r^2 \vec{u} \tag{15}$$

where the subscript n imply the n^{th} jet.

A dynamical model for the system can be established in a similar way as those in [15, 16], and an instability condition for the spinning process can be theoretically analysed like those in [17-20]. The stable property is the periodic motion, while the instable property is a chaotic one. Zhang and He [15] showed chaotic properties of Sirofil yarn spinning, if the uncertain properties due to environment change and solvent evaporation, an uncertain chaotic system [21-28] should be considered.

Experimental verification

An experiment was designed, the experimental set-up was shown in fig. 1, multiple bubbles were formed and broken simultaneously, and the jets are interacted with each other with different angles. The experimental process is similar to that in [1]. Figures 3 and 4 were the SEM illustrations of the obtained nanofibers.

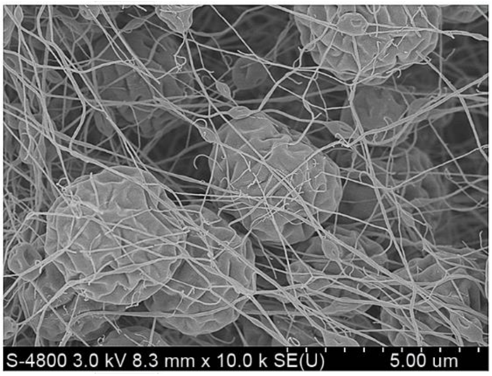

Figure 3. Fibers obtained by the bubble electrospinning using 23% polyvinylpyrrolidone (PVP) aqueous solution, the applied voltage was set at 35 kV and the bubble top to the collector distance was set as 20 cm

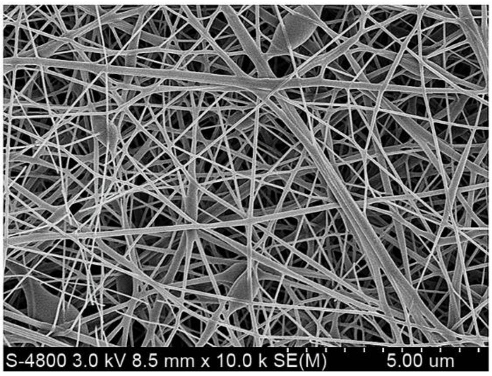

Figure 4. Fibers obtained by the bubble electrospinning using 8% polyacrylonitrile (PAN) solution with DMAC as solvent, the applied voltage was set at 20 kV and the bubble top to the collector distance was set as 20 cm

From fig. 4, we found a typical interaction, and the main parameters were given in fig. 5. We assumed that $u_1/u_2 = 1$, this results in a modification of eq. (7):

$$r = \frac{r_1^2 + r_2^2}{\sqrt{r_1^2\cos\alpha_1 + r_2^2\cos\alpha_2}} \tag{16}$$

From fig. 5 we have r_1 = 0.047 μm, r_2 = 0.041 μm, r = 0.075 μm, α_1 = 27.487, and α_2 = 21.965. By eq. (16), we have:

$$r = \frac{0.047^2 + 0.041^2}{\sqrt{0.047^2 \cos 27.487° + 0.041^2 \cos 21.965°}} = \\ = 0065579\ \mu\text{m} \quad (17)$$

While the experimental value is r = 0.075 μm, the 12.5% is reasonable, considering the assumption $u_1/u_2 = 1$ is very much approximate.

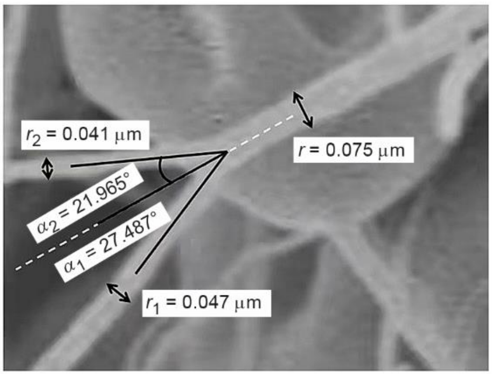

Figure 5. The geometrical relation of the two combined fibers

Discussion and conclusion

For the first time ever, we have proposed a theoretical model dealing with a complex combination process of the two moving jets in the bubble electrospinning. This model is able to predict the combined jet diameter and velocity, shedding a bright light on controlling the combined fibers in the practical spinning process.

Acknowledgment

The work is supported by Jiangsu R&D Center of the Ecological Textile Engineering & Technology, Yancheng Polytechnic College under grant No. YGKF202010.

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Paper submitted: December 28, 2021
Paper revised: March 8, 2022
Paper accepted: April 2, 2022