A MATHEMATICAL MODEL FOR THE BLOWN BUBBLE-SPINNING AND STAB-PROOF OF NANOFIBROUS YARN

by

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Blown bubble-spinning is a one-step process for fabrication of nanofibrous yarns. A mathematical model is established to adjust spinning velocity. Due to high friction among nanofibers, the obtained yarns are extremely suitable for stab-proof fabrics.

Key words: *thermodynamic, nanofibers, mechanism, bubble, spinning*

Introduction

Recently, bubbfil spinning has been demonstrated as a fascinating and effective technology for mass production of nanofibers [1-3]. The technology was developed from bubble-electrospinning and blown bubble-spinning, and the latter can be used as a one-step process for producing nanofibrous yarns [4-6]. In general, controlled gas is injected into the spun solution to generate bubbles as well as high velocity air with certain temperature blows bubbles into ruptured fragments and provides a forwarding force to attenuate the polymer jets, leading to the final nanofibers [7]. Similar to the principles of two well-known technologies, melt-blowing and solution blowing [8, 9], blown bubble-spinning not only makes full use of air drawing force but also focuses on the form of polymer bubble instead of traditional solution or melt from a needle or an orifice die. This is because bubbles own an interesting property that the surface tension of a polymer bubble geometrically depends upon its size and the pressure difference [10]:

$$\sigma = \frac{1}{4} r(P_{\mathrm{i}} - P_{\mathrm{o}})$$

In this paper, the air drawing mechanism of bubble jets in the blown bubble-spinning process was established.

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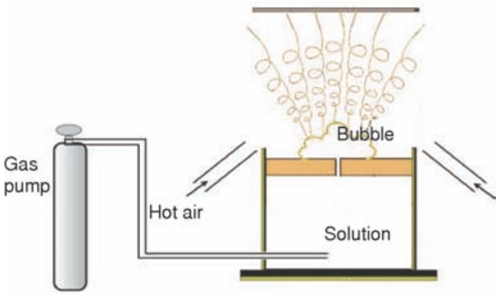

Figure 1. The schematic of the blown bubble-spinning

Mathematical model

The experimental set-up is shown in fig. 1. Polymer bubbles are produced on the solution surface, and they are acted by the hot blowing air. The moving jet during spinning process is assumed to be steady and viscous.

Continuity equation for the jet motion reads:

$$\rho uA \quad \rho\pi r^2 u \quad Q \tag{1}$$

where ρ is the jet density, u – the jet velocity, A – the jet cross area, r – the jet radius, and Q – the mass flux of jet.

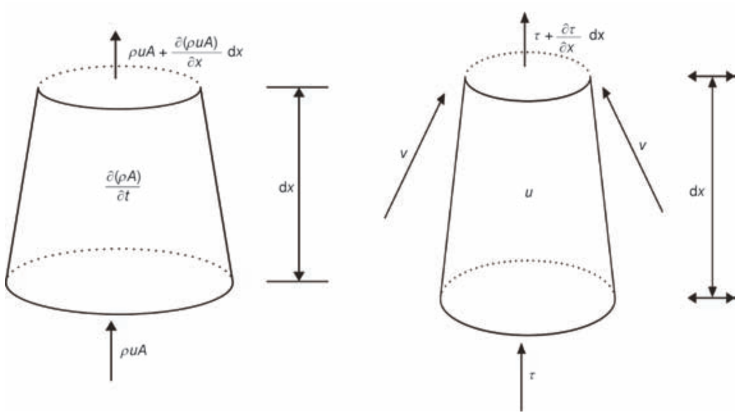

Figure 2. The schematic of motion and force analysis of jets

Moment equation should consider air drag, fig. 2, which is:

$$(\rho\pi r^2 \mathrm{d}x)\frac{\mathrm{D}u}{\mathrm{D}t} \quad \frac{\partial\tau}{\partial x}\mathrm{d}x \;\; \pi r^2 \quad \alpha\rho_\mathrm{a}(2\pi r\mathrm{d}x)(v \quad u)^2 j \tag{2}$$

where Du/Dt is the material derivative, τ – the viscous resistance, α – the coefficient of air resistance, ρ_a – the air density, and v – the air velocity. In this paper, its direction is assumed to be vertical, and j – the symbol factor. If v is bigger than u, j is +1 and if v is smaller than u, j is –1. By simplifying eq. (2), we have:

$$\rho u\frac{\partial u}{\partial x} \quad \frac{\partial\tau}{\partial x} \quad \frac{2\alpha}{r}\rho_\mathrm{a}(v \quad u)^2 j \tag{3}$$

Newtonian fluid is assumed for moving jets, the viscous resistance is:

$$\tau \quad \mu\frac{\partial u}{\partial x} \tag{4}$$

where μ is the viscosity.

By a simple calculation, we have:

$$r \quad \sqrt{\frac{Q}{\pi\rho u}} \tag{5}$$

and $$\rho u \frac{\mathrm{d}u}{\mathrm{d}x} \quad \mu \frac{\mathrm{d}^2 u}{\mathrm{d}x^2} \quad \sqrt{\beta u}(v \quad u)^2 j \tag{6}$$

where $$\beta \quad 2\alpha\rho_{\mathrm{a}}\sqrt{\frac{\pi\rho}{Q}} \tag{7}$$

Analytical solution

Equation (6) is of high non-linearity. This paper applies the weighting residual technology to solve jet velocity. Introducing $R(u)$ defined:

$$R(u) \quad \mu \frac{\mathrm{d}^2 u}{\mathrm{d}x^2} \quad \rho u \frac{\mathrm{d}u}{\mathrm{d}x} \quad \sqrt{\beta u}(v \quad u)^2 j \tag{8}$$

By experimental observation, the jet velocity can be expressed in the form:

$$u(x) \quad u_0 \mathrm{e}^{\mathrm{ax}} \tag{9}$$

where u_0 is initial jet velocity, and a is constant coefficient.

From eqs. (8) and (9), we could obtain:

$$R(x) \quad \mu a^2 u_0 \mathrm{e}^{ax} \quad \rho a u_0^2 \mathrm{e}^{2ax} \quad \beta u_0^{(1/2)} \mathrm{e}^{(1/2)ax}(v \quad u_0 \mathrm{e}^{ax})^2 j \tag{10}$$

Setting $R(0) = 0$:

$$R(0) \quad \mu a^2 u_0 \quad \rho a u_0^2 \quad \beta u_0^{1/2}(v \quad u_0 e^{ax})^2 j \tag{11}$$

By solving eq. (11), we could obtain:

$$a \quad \frac{\rho u_0 \quad \sqrt{\rho^2 u_0^2 \quad 4\mu\beta u_0^{1/2}(v \quad u_0)^2 j}}{2\mu} \tag{12}$$

When u_0 is extremely high, namely u_0 is bigger than v, airflow applied on jets plays a opposite role in drawing jets, so:

$$a \quad \frac{\rho u_0 \quad \sqrt{\rho^2 u_0^2 \quad 4\mu\beta u_0^{1/2}(v \quad u_0)^2}}{2\mu} \tag{13}$$

and the corresponding jet velocity equation should be expressed:

$$u(x) \quad u_0 \exp \frac{\rho u_0 \quad \sqrt{\rho^2 u_0^2 \quad 4\mu\beta u_0^{1/2}(v \quad u_0)^2}}{2\mu} x \tag{14}$$

When u_0 is pretty low, namely u_0 is smaller than v, airflow applied on jets has a positive effect on making jets fine, so:

$$a \quad \frac{\rho u_0 \quad \sqrt{\rho^2 u_0^2 \quad 4\mu\beta u_0^{1/2}(v \quad u_0)^2}}{2\mu} \tag{15}$$

and the corresponding jet velocity equation should be expressed:

$$u(x) \quad u_0 \exp \frac{\rho u_0 \quad \sqrt{\rho^2 u_0^2 \quad 4\mu\beta u_0^{1/2}(v \quad u_0)^2}}{2\mu} x \tag{16}$$

Discussion and conclusions

The jet velocity is an important factor in spinning process, and it affects greatly fiber size, higher velocity results in smaller nanofibers. According to eq. (14), low viscosity of solution leads to a high velocity of the jet. The blowing air is also used to twist nanofibers to produce nanofibrous yarns, which have wide applications in various fields due to high friction among nanofibers. To elucidate this property, we consider a yarn with radius of 3 mm consisting of nanofibers with radius of 50 nm.

The number of nanofibers in a yarn with radius of 3 mm is:

$$N = \left(\frac{3 \times 10^{-3}}{50 \times 10^{-9}}\right)^2 = 3.6 \times 10^9$$

The surface area of a single nanofiber is $2\pi rL$, where r = 50 nm and L is the length of the yarn. Total surface area is:

$$A = 2\pi rLN = 2\pi L(50 \times 10^{-9})3.6 \times 10^9 = 2\pi L \, 180 \text{ m}^2$$

While a surface area of classic yarn with radius of 3 mm is:

$$A_0 = 2\pi RL = 2\pi L(3 \times 10^{-3}) = 2\pi L3 \times 10^{-3} \text{ m}^2$$

The surface area increases greatly:

$$\frac{A}{A_0} = 6000$$

According to [11], the friction force between fibers:

$$f \propto A^a$$

where A is the area between contact surface, a = 1 ~ 3 for fabric. We choose: a = 2

$$\frac{f}{f_0} = \left(\frac{A}{A_0}\right)^2 = 3.6 \times 10^7$$

The friction of a nanofibrous yarn is seven orders of magnitude higher than that of classic yarn with same size. The extremely high friction can absorb all energy from stab, making the yarn stab-proof.

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