EFFECT OF AIRFLOW ON NANOFIBER YARN SPINNING

by

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The paper proposes a new air-jet spinning method for the preparation of continuous twisted nanofiber yarns. The nozzle-twisting device is designed to create the 3-D rotating airflow to twist nanofiber bundles. The airflow characteristics inside the twisting chamber are studied numerically. The airflow field distribution and its effect on nanofiber yarn spinning at different pressures are also discussed.

Key words: *airflow field, nanofiber, yarn structure, mechanical properties*

Introduction

Electrospun nanofibers with ultra-fine scale and high surface area and porosity have the potential for wide applications in many fields [1]. However, the conventional electrospinning method can obtain randomly oriented non-woven nanofiber mats with low mechanical strength [2]. Textile technologies cannot be used for nanofibers unless they are processed into a continuous yarn and integrated into traditional textiles. The fiber used in nanofiber yarn, if oriented along the core axis, can impart unique optical, electrical, and mechanical properties to the material, thus providing it with a broader range of uses.

Currently, there are reports of continuous yarn being prepared using electrospun nanofibers. Yan and Liu [3] collected nanofibers in parallel, twisted them using a pair of metal tubes rotating in opposite directions, and then wound the nanofiber yarn using the rotation of an insulating tube located between the two tubes. Sun and Yao [4] applied voltage with opposite polarities to two oppositely configured metal nozzles, so that nanofibers with opposite charges attracted each other and were neutralized, thus forming a fiber bundle to be drawn and wound. The typical twisting method is mainly in the form of mechanical twisting, in addition, oriented bundling, and twisting are done simultaneously. Hence, the gathered fibers may be twisted into yarn before they can be oriented, which affects the evenness of yarn, resulting in low yield and strength and increased hairiness.

This paper presents a new approach of electrospun nanofiber airflow twisting. The nozzle-twisting device is designed to create the 3-D rotating airflow to twist nanofiber bundles.

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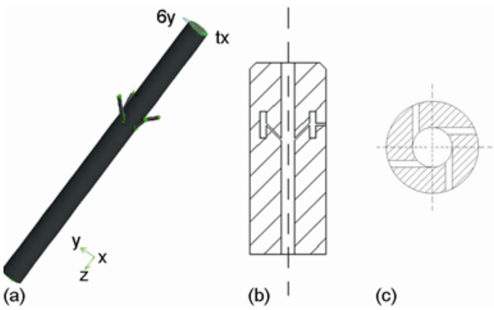

Figure 1. The structure of the nozzle twisting device; (a) 3-D schematic view, (b) longitudinal sectional view, (c) transverse sectional view

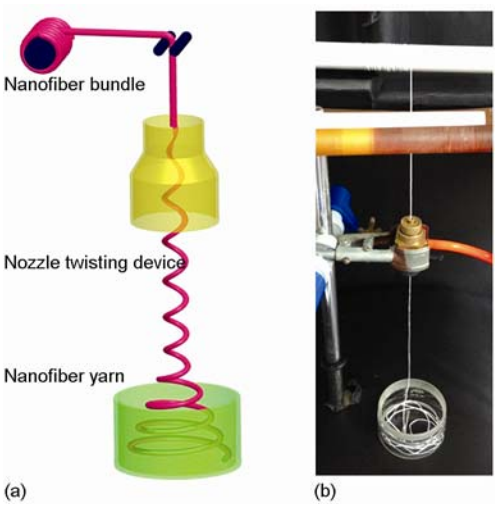

Figure 2. (a) device for airflow twisting, (b) test photo

Experimental

Experimental of airflow twisting

The structure of the nozzle-twisting device that can produce 3-D rotating airflow is shown in fig. 1. It comprises an air inlet, air chambers, jet orifices, a twisting chamber, and other components. The airflow twisting spinning device for preparing the nanofiber yarn is shown in fig. 2(a). It comprises a nozzle-twisting device, yarn guide roller, and a winder device. Nanofiber bundles prepared by our own designed device [5] are transported into the nozzle-twisting device at a constant speed by yarn guide roller. Compressed air is injected into the twisting chamber from the jet orifice to form a 3-D high-velocity rotating airflow in the twisting chamber, and form negative pressure at the nozzle inlet, which can be used to suction and twist the nanofiber bundles, then the nanofiber yarn is wound in a transparent cylinder, fig 2(b). The air pressure was 0.2-0.4 MPa.

Numerical simulation of the airflow field in the nozzle

The flow field simulation uses the standard k-ε turbulence model. The pressure inlet boundary is provided at the inlet of the ejection orifice, and the pressure outlet boundary is provided at the nozzle inlet and outlet. Non-slip boundary condition is applied at all solid walls.

Characterization

A scanning electron microscope (SEM) (Japan JSM-6510) is used to observe the longitudinal morphology and twisting distribution of the fibers in the yarn after the nanofiber yarn has been treated by metal spraying. An electronic strength tester (Instron365, USA) is used to test the mechanical properties. The clamping length is 15 mm. The tensile velocity is 15 mm per minute, and the initial tension is 2 mN. Twenty samples are measured each time.

Results and discussion

Numerical simulation of the airflow field at different pressure

When compressed air is tangentially injected into the twisting chamber through the ejection orifices at a high velocity, the Mach number range is about 0.6-0.9. The model of the airflow in the nozzle is viscous and compressible. The airflow in the nozzle can be considered as a steady flow. The basic governing equations of the nozzle airflow field include a continuity equation, momentum conservation equation and energy conservation equation, expressed as:

$$\mathrm{div}(\rho v) = 0 \tag{1}$$

$$\mathrm{div}(\rho v T) = \mathrm{div}\left(\frac{k}{c_p}\mathrm{grad}T\right) + S_T \tag{2}$$

$$\mathrm{div}(\rho v v - \tau) = -\mathrm{grad}p + f \tag{3}$$

$$p = \rho \mathrm{R} T \tag{4}$$

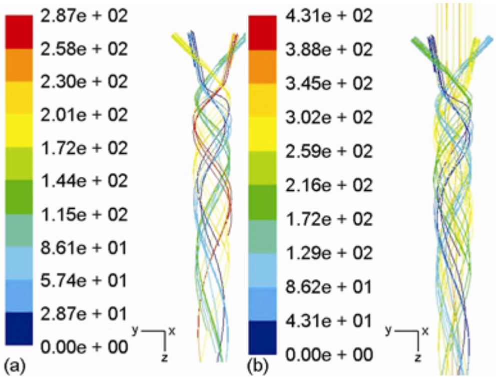

Figure 3. (a) streamlines of the airflow into the nozzle from the ejection orifice, (b) streamlines of the airflow in the nozzle

where ρ is the gas density, v – the gas velocity vector, τ – the viscous stress tensor, p – the gas pressure, f – the force of gravity, T – the gas temperature, k – the specific heat capacity, S_T – the viscous dissipation item, and R – the molar gas constant.

Figure 3 shows streamlines in nozzle-twisting device with the jet orifices pressure at 0.3 MPa. Figure 3(a) shows the airflow entering into the nozzle from the ejection orifices and this airflow is distributed in the outer region within the twisting chamber to form a regular rotation. The streamlines of airflow in the whole airflow field is shown in fig. 3(b). The airflow injected from the nozzle inlet joins the airflow from the jet orifices in the twisting chamber, these two airflows act upon each other to form a complex airflow trajectory, which would result in a slight hairiness on the surface of nanofiber yarn.

Figure 4 shows the velocity vector diagram of the airflow field in different plane. Figure 4(a) shows velocity vector at vertical section of $X = 0$ mm. The air flow that ejected from the ejection orifice tangential to the twisting chamber at a high speed is accelerated in the ejection orifice due to the great pressure difference between the air chamber and the twisting cham-

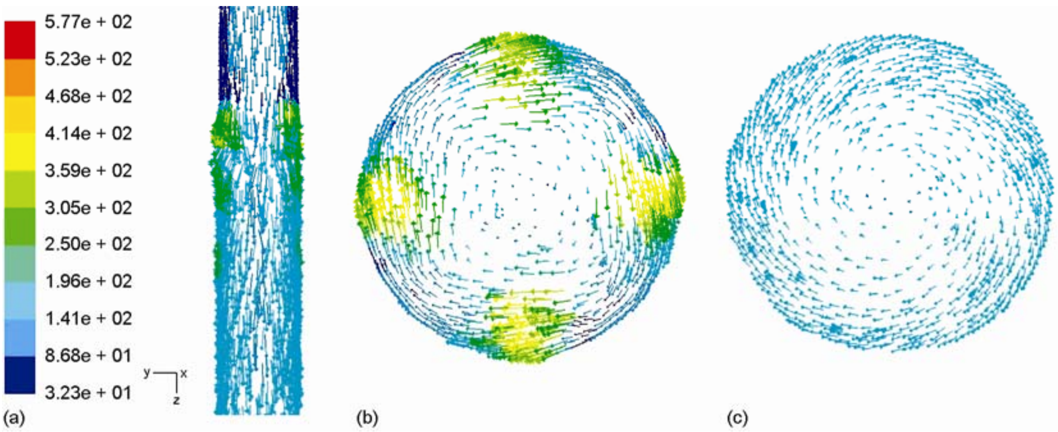

Figure 4. Velocity vector diagrams of airflow in different plane, (a) X = 0 mm, (b) Z = 11 mm, and (c) Z = 17 mm

ber so as to reach a maximum value at the outlet of the ejection orifice. The entrainment of the airflow ejected from the ejection orifice drives the air movement in the twisting chamber of the nozzle-twisting device to form a rotating airflow which can twist nanofiber bundles, figs. 4(b), and (c). An airflow flows into the twisting chamber from nozzle inlet. Under the effect of this airflow, the nanofiber bundles are input through the yarn guide roller and are suctioned into the twisting chamber, which accelerates the front end of the nanofiber bundle while its tail end is still controlled by the yarn guide rollers. Hence, the bundle is drawn prior to twisting. Another weaker airflow enters into the twisting chamber from the outlet of nozzle-twisting device and moves upstream along the wall of the twisting chamber. Then it collides with the airflow ejected from jet orifices. After the collision, the air velocity decreases rapidly, and the airflow direction also changes, which causes the cyclone centre to deviate from the nozzle axis.

Yarn morphology at different air pressure

When the airflow pressure was 0.2 to 0.4 MPa, the nanofiber yarns obtained from the twisting of airflow have a uniform distribution of twists, figs. 5(a), (b), and (c). The twist angle increased from 51.5° to 73.9° with the air pressure from 0.2 MPa to 0.4 MPa.

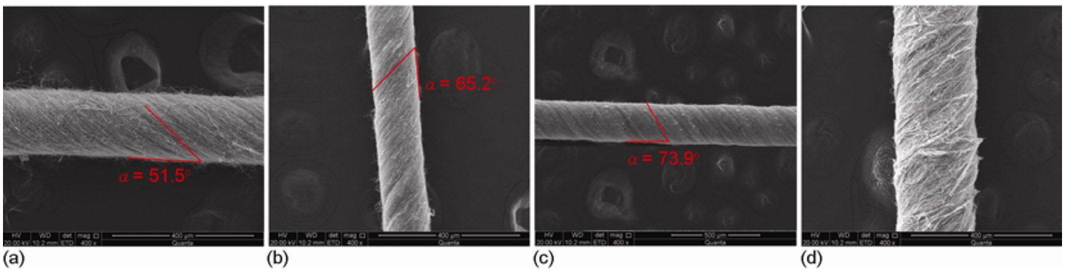

Figure 5. SEM photos of nanofiber yarn at different air pressure; (a) 0.2 Mpa, (b) 0.3 MPa, (c) 0.4 MPa, (d) 0.6 MPa

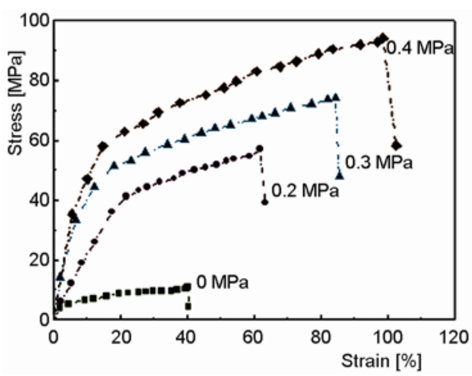

Figure 6. Stretch curves of nanofiber yarn at different pressures

There was a little hairiness on the surface of the nanofiber yarn, which might be associated with the fact that the interaction between the air flow entering from jet orifice and the air flow entering from the nozzle inlet results in complex airflow movement near the ejection orifice. When the airflow pressure was 0.6 MPa, a twist distribution could be observed from the surface of the yarn obviously, but the surface of the nanofiber yarn had many hairiness and the fibers arranged disorderly, fig. 5(d).

Mechanical properties of nanofiber yarn at different air pressure

With an increase in the airflow pressure, the twist angle of nanofiber yarn increased, and the cohesion between the nanofibers in the yarn was closer. Meanwhile the mechanical properties of the nanofiber yarn are significantly improved (fig. 6). The strength and elongation at break of untwisted nanofiber bundles was only 10.7 MPa and 40.4%, respectively. When the air pressure reached 0.4 MPa, the strength and elongation at break could be up to 94.2 MPa and 101.6%, respectively. However, with a further increase in the airflow pressure, both the evenness and the strength would be deteriorated.

Conclusions

A novel method of electrospun nanofiber air-jet spinning was described for fabricating continuous twisted nanofiber yarn. The 3-D rotating airflow characteristics inside the twisting chamber are simulated. Negative pressure formed in the nozzle due to the compressed air flowing from the jet orifices can be used to suction the nanofiber bundles and draft them prior to twisting, then the airflow injected from the nozzle inlet joins with the airflow from the jet orifices in the twisting chamber to form 3-D high-velocity rotating airflow to complete the twisting of nanofiber yarn. By altering the air pressure, nanofiber yarn with different twist angles can be obtained with good parallelism and orientation. When the air pressure was 0.4 MPa, the twist angle of the yarn could be up to 73.9°, and the strength and elongation reached 98.2 MPa and 101.6%, respectively.

Acknowledgments

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