ANALYTICAL MODELLING OF DRY-JET WET SPINNING

by

Hong-Yan LIU[a,b,c*], **Zhi-Min LI**[d], **Yan-Ju YAO**[b],
and Frank K. KO[c]

[a] National Engineering Laboratory for Modern Silk, College of Textile and Clothing Engineering,
Soochow University, Suzhou, China
[b] School of Fashion Technology, Zhongyuan University of Technology, Zhengzhou, China
[c] Department of Materials Engineering, University of British Columbia,
Vancouver, B. C., Canada
[d] Rieter Textile Instrument Co., Shanghai, China

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This paper introduces an analytical method for the analysis and design of a dry-jet wet spinning system. The 1-D mass conservation equation is used, and velocity distribution is assumed to derive a simple relationship among various spinning parameters. The effect of spinneret mass flow rate, solution density, spinneret structure including velocity and air-gap length, and drawing velocity on the dry-jet wet spinning was simulated using the proposed analytical model. Theoretical prediction of fiber diameter is obtained, which depends upon spinning conditions, solution properties, and spinneret structure. The theoretical results were verified by comparing experimental data with the numerical solution. It was found obviously that the theoretical prediction has comparable accuracy as that by numerical computation. The analytical model can be useful for preliminary design of a spinning process for fabrication of fibers with controllable diameter by adjusting parameters in spinning conditions.

Key words: *analytical solution, dry-jet wet spinning, fiber diameter*

Introduction

Wet spinning is a widely used technology in polymer science and textile engineering [1-7]. Dry-jet wet spinning technology, a modification of wet spinning, combines both the advantages of melt spinning and wet spinning, which can be used to fabricate high-performance fibers [8-12]. For the dry-jet wet spinning process, the process is usually considered to be composed of two separate parts: the elongational flow in the air-gap region, and the double diffusion in the coagulation bath. The dynamics in the coagulation bath can be regarded as the dynamics of wet spinning, whereas the elongational flow in the air-gap region is usually referred to as a model of the dynamics of melt spinning or dry spinning. Some of the benefits of dry-jet wet spinning are: (a) high speed of spinning, (b) high concentration of dope, (c) high degrees of jet-stretch ratios, and (d) control of coagulation kinetics by monitoring coagulation bath parameters. Among these benefits, (a) to (c) are derived because of the use of dry-jet and the air-gap, while (d) is derived from the use of wet coagulation.

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* Corresponding authors, e-mail: phdliuhongyan@yahoo.com

In this method the polymer is dissolved in an appropriate solvent to make the fiber solution. This solution is then extruded under heat and pressure into an air-gap before it enters a coagulation bath. The produced fiber is then washed and dried before it is heat treated and drawn. This is an alternative method to wet spinning and is required as spinning directing into the bath, for some fibers, creates micro-voids that negatively affect the fiber properties, this is due to the solvent being drawn out of the liquid too quickly. An inert atmosphere may be required to prevent oxidization in some polymers, if so fibers are extruded into a nitrogen atmosphere. This method is often required for high performance fibers with a liquid crystal structure. Due to their structural properties their melt temperature is either the same as, or dangerously close to their decomposition temperature, therefore they must be dissolved in an appropriate solvent and extruded in this manner. Several research works give valuable insight into dry-jet wet spinning. Hauru *et al.* [1] explored spinning stability and discussed the effects of extrusion velocity, draw ratio, spinneret aspect ratio, and bath temperature on mechanical properties and orientation of cellulose filaments from Ionic liquid solution using dry-jet wet spinning method. Qian *et al.* [13] studied the mechanism and characteristics of dry-jet wet spinning of acrylic fibers. Tan *et al.* [14] investigated the spinnability in the dry-jet wet spinning of polyacrylonitrile (PAN) precursor fiber. Yang *et al.* [15] produced ultra-fine fibers using dry-jet wet spinning. The effects of the polymer composition, coagulation bath temperature, and draw ratio on the cross-sectional morphology, structure, and tensile properties were reported by Bajaj *et al.* [16].

From the previous discussion, it is seen that a mathematical model for the spinning process is useful for understanding the relationship between the spinning conditions and fiber properties [17, 18]. Recently Xia *et al.* [2, 4] suggested a full 3-D model to predict numerically the fiber diameter along the spinning line, and important information was revealed. The numerical results can be used for optimal design of the spinning process, however, numerical simulation can not pick out an explicit relationship among spinning conditions, spinneret structure, and fiber properties. Therefore, an analytical model is very much needed for practical applications. We adopt the mass conservation equation in the dry-jet wet spinning process and obtain a simple analytical equation for the model. The analytical prediction is compared with the experimental data and numerical results by Xia *et al.* [2] to show the validity of our method.

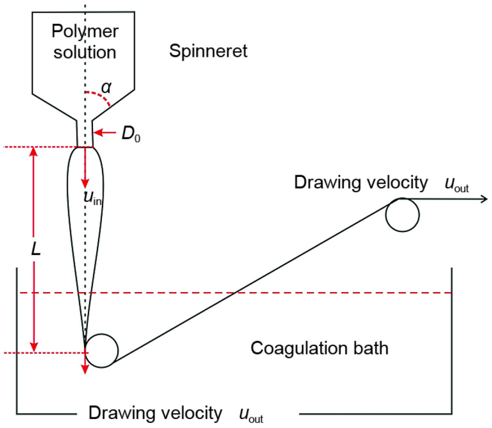

Figure 1. Schematic illustration of the dry-jet wet spinning process

One-dimensional model

A 1-D model is widely used in the morphology control in fiber fabrication process including the bubble electrospinning [19] and the bubbfil spinning [20].

As shown in fig. 1 the dry-jet wet spinning process is described in [4]. The spinning solution enters the spinneret. A polymer filament is extruded from a spinneret into an air-gap region at a mass flow rate, *Q*. The filament is then elongated by a take-up device with a take-up speed, u_{out}. The filament cools as it passes through the air-gap region with a specific length, *L*, and orientation begins to occur at a certain take-up force. The gap between the spinneret and the coagulation bath surface, called air-gap, varies with the type of polymer and technology being used. In acrylic spinning, this gap may be as small as a few millimeters, while in lyocell spinning, it may be up to several centimeters.

The jet, as illustrated in fig. 1 during the spinning process can be approximately considered as a steady 1-D compressible flow. The mass conservation equation is shown [19, 21]:

$$\frac{1}{4}\pi D^2 \rho u = Q \tag{1}$$

where D is the jet diameter, ρ – the fluid density, u – the jet velocity, and Q – the flow rate.

The jet velocity can be solved by the momentum equation and the energy equation. It is a complex solution process, but it can be solved numerically [2]. A simple assumption is made in this paper to have a quick look into the relationship between spinning conditions and fiber diameter. We assume that the jet velocity changes linearly along the spinning line:

$$u(z) = u_{\text{in}} + \frac{u_{\text{out}} - u_{\text{in}}}{L} z \tag{2}$$

where u_{in} is the velocity of the spinning line at the spinneret exit, u_{out} – the drawing velocity as illustrated in fig. 1, and L – the distance between the spinneret exit and the roller. From eq. (1) we can obtain:

$$D^2 = \frac{4Q}{\pi \rho u} \tag{3}$$

Substitute eq. (2) into eq. (3) we acquire:

$$D^2(z) = \frac{4Q}{\pi\rho\left(u_{\text{in}} + \dfrac{u_{\text{out}} - u_{\text{in}}}{L} z\right)} \tag{4}$$

After a simple calculation, we have:

$$D(z) = \sqrt{\frac{4Q}{\pi\rho\left(u_{\text{in}} + \dfrac{u_{\text{out}} - u_{\text{in}}}{L} z\right)}} \tag{5}$$

Equation (5) is an analytical model for predicting the fiber diameter without any complex numerical simulation or computation. This equation gives an explicit relationship among the spinning condition (the flow rate, Q), solution property (density, ρ), spinneret structure, u_{in}, and drawing velocity, u_{out}.

We use the experimental data [2] to verify the prediction of eq. (5) by assuming that the density of the spinning line remains constant during spinning process. The values of parameters involved in eq. (5) are: Q = 0.1236 g/min = $2.06 \cdot 10^{-6}$ kg/s, ρ = 1.056.635 kg/m^3, u_{out} = 0.22 m/s, and $L \approx$ 18 cm. The diameter of the spinneret orifice is D_0 = 0.2 mm, according to eq. (1), we have:

$$u_{\text{in}} = \frac{4Q}{\pi D_0^2 \rho} = \frac{4 \cdot 2.06 \cdot 10^{-6}}{\pi(0.2 \cdot 10^{-3})^2 \cdot 1056.635} = 0.062 \text{ m/s} \tag{6}$$

Submitting all the previous parameters into eq. (5), we can predict the final fiber diameter:

$$D(18\text{ cm}) = \sqrt{\frac{4Q}{\pi\rho\left(u_{\text{in}} + \dfrac{u_{\text{out}} - u_{\text{in}}}{L}z\right)}} =$$

$$= \sqrt{\frac{4\cdot 2.06\cdot 10^{-6}}{\pi 1056.635\cdot 0.22}} = 0.106\cdot 10^{-3}\,\text{m} \quad (7)$$

which is very closed to the experimental observation, 100 μm [2], fig. 2.

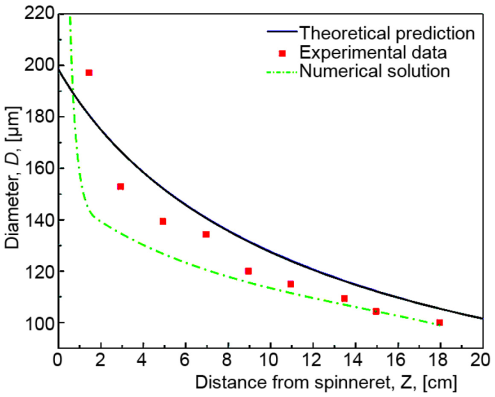

Figure 2. Comparison of the theoretical prediction with experimental data and numerical solution by Xia *et al.* [2]

Results discussion

By substituting eq. (6) into eq. (5), we can re-write eq. (5) in the form:

$$D(z) = \sqrt{\frac{4Q}{\pi\rho\left(u_{\text{in}} + \dfrac{u_{\text{out}} - u_{\text{in}}}{L}z\right)}} = \sqrt{\frac{4Q}{\pi\rho\left(\dfrac{4Q}{\pi D_0^2\rho} + \dfrac{u_{\text{out}} - \dfrac{4Q}{\pi D_0^2\rho}}{L}z\right)}} = D_0\sqrt{\frac{1}{1 + \dfrac{\dfrac{\frac{1}{4}\pi D_0^2\rho u_{\text{out}}}{Q} - 1}{L}z}} \quad (8)$$

where D_0 is the diameter of the spinneret orifice.

Equation (8) reveals that the fiber size depends linearly upon the size of spinneret orifice. When D_0 is in the range of hundreds of micrometers, nanofibers can be prepared as discussed by Liu *et al.* [22], where the spinneret nozzle has a diameter of about 78 μm.

Substitute $z = L$ into eq. (8), the final fiber diameter can be written in the form:

$$D(L) = \sqrt{\frac{Q}{\frac{1}{4}\pi\rho u_{\text{out}}}} \quad (9)$$

This equation shows that a higher drawing velocity or a lower flow rate results in a smaller fiber diameter. Similar phenomena were also observed in the bubble electrospinning [19], the bubbfil spinning [20], and electrospinning [22, 23]

Conclusions

This paper suggests a simple analytical model for predicting the fiber diameter in the dry-jet wet spinning process. Neither complex numerical simulation nor complex derivation is involved, only simple mass conservation, eq. (1), is involved. The prediction equation, eq. (5), reveals the relationship among inlet conditions (flow rate), solution property (density), spinneret structure (input velocity), spinning length, and drawing velocity. Although the analytical model only provides an approximated solution, the calculated results of prediction has almost the same accuracy as numerical one as illustrated in fig. 2, this simple analytical model provides a helpful guide for preliminary design of a broad range of spinning processes for fabrication of fibers with controllable diameter by adjusting parameters involved in eq. (5).

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