NOZZLE DESIGN IN A FIBER SPINNING PROCESS FOR A MAXIMAL PRESSURE GRADIENT

by

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Short paper
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The thickness of a spinneret is always a geometrical constraint in nozzle design. The geometrical form of a nozzle has a significant effect on the subsequent spinning characteristics. This paper gives an optimal condition for maximal pressure gradient through the nozzle.

Key words: *nozzle, spinneret, analytic solution, optimal design*

Introduction

The nozzle is one of the most important parts of a spinneret in various fiber spinning processes, its form will greatly affect the morphology of its productions and output. Figure 1 shows a widely used spinneret and its nozzle structure.

The top size of the nozzle section is determined by the number of nozzle in a spinneret, while its low size and its geometrical form are determined by fiber requirements. The thickness of a spinneret is a main geometrical constraint in many practical applications. This paper is to optimally design a nozzle with maximal pressure drop in the nozzle.

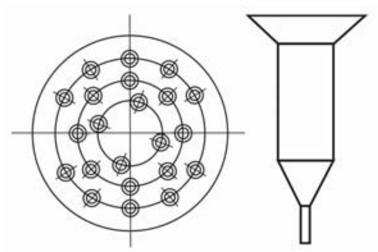

Figure 1. A spinneret and nozzle geometry

Theory

Assuming that the flow through a nozzle follows the Darcy law, that is:

$$u = \kappa \nabla p \tag{1}$$

where κ is the constant, u – the flow speed, and ∇p – the pressure gradient through a nozzle.

In order to improve its output, a high spinning velocity is predicted, that means a higher pressure gradient in a nozzle is an appropriate choice in the design of a nozzle.

For a cone nozzle, the velocity distribution on its section can be expressed as:

$$u = k(R^2 - r^2) \tag{2}$$

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where k is the constant, and R – the inner radius of the nozzle.

The constant k in eq. (2) can be determined by the mass conservation law, which requires:

$$Q = \int_0^R 2\pi k \rho r(R^2 - r^2)\mathrm{d}r = \frac{1}{2}\pi R^4 \rho k \tag{3}$$

where Q is the flow rate, and ρ – the density of the flow. From eq. (3), we have:

$$k = \frac{2Q}{\pi R^4 \rho} \tag{4}$$

The velocity in a nozzle can be obtained, which reads:

$$u = \frac{2Q}{\pi R^4 \rho}(R^2 - r^2) \tag{5}$$

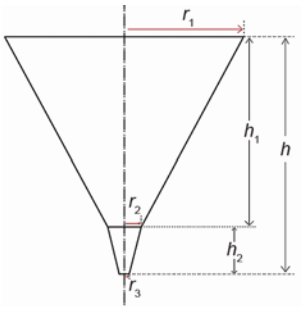

Figure 2. A nozzle with complex geometrical form

Due to geometrical constraint of the thickness of a spinneret, complex nozzles appear in many applications. Assume that the radii of the top and low sections of the nozzle are r_1 and r_3, respectively, and its thickness is h as illustrated in fig. 2.

The velocity distribution in each section of the nozzle can be determined by eq. (5). Assume that the flow in the nozzle is viscous and incompressible; the flow is laminar and there is no acceleration of fluid in the nozzle, the momentum equation becomes:

$$\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}z} = \mu \frac{\mathrm{d}^2 u}{\mathrm{d}z^2} \tag{6}$$

where μ is the viscosity coefficient.

In practical applications, the nozzle height is thin (*e. g.* 1 mm), so the second derivative of the velocity can be approximately expressed:

$$\frac{\mathrm{d}^2 u}{\mathrm{d}z^2} \approx \frac{h_1(u_3 - u_2) - h_2(u_2 - u_1)}{h_1 h_2^2} \tag{7}$$

Equation (6) becomes:

$$\Delta p = \rho h \mu \frac{h_1(u_3 - u_2) - h_2(u_2 - u_1)}{h_1 h_2^2} = \rho h \mu \frac{(h - h_2)(u_3 - u_2) - h_2(u_2 - u_1)}{(h - h_2)h_2^2} \tag{8}$$

The pressure drop at $r = 0$ is:

$$\Delta p(r = 0) = \rho h \mu \frac{(h - h_2)(\bar{u}_3 - \bar{u}_2) - h_2(\bar{u}_2 - \bar{u}_1)}{(h - h_2)h_2^2} = \rho h \mu \frac{h(\bar{u}_3 - \bar{u}_2) - h_2(\bar{u}_3 - \bar{u}_1)}{(h - h_2)h_2^2} \tag{9}$$

where $\bar{u}_1$, $\bar{u}_2$, and $\bar{u}_3$ are maximal flow speed at the top, middle, and low sections of the nozzle, respectively:

$$\bar{u}_1 = \frac{2Q}{\pi r_1^2 \rho} \tag{10}$$

$$\bar{u}_2 = \frac{2Q}{\pi r_2^2 \rho} \tag{11}$$

$$\bar{u}_3 = \frac{2Q}{\pi r_3^2 \rho} \tag{12}$$

In practical applications, r_1, r_3, and h are constants, and r_2 and h_2 should be such determined that its pressure drop at $r = 0$ through the nozzle is maximal, that requires:

$$\frac{\mathrm{d}\Delta p}{\mathrm{d}h_2}(r=0) = \rho h \mu \frac{-(h-h_2)h_2^2(\bar{u}_3-\bar{u}_1)-(2hh_2-3h_2^2)\left[h(\bar{u}_3-\bar{u}_2)-h_2(\bar{u}_3-\bar{u}_1)\right]}{\left[(h-h_2)h_2^2\right]^2} = 0 \tag{13}$$

From eq. (13), $\bar{u}_2$ can be determined, which reads:

$$\bar{u}_2 = \frac{(h-h_2)h_2^2(\bar{u}_3-\bar{u}_1)+(2hh_2-3h_2^2)\left[h\bar{u}_3-h_2(\bar{u}_3-\bar{u}_1)\right]}{hh_2(2h-3h_2)} \tag{14}$$

According to eq. (12), for a fixed h_2, its nozzle section can be determined:

$$r_2 = \sqrt{\frac{2Q}{\pi\rho\bar{u}_2}} = \sqrt{\frac{2Q\left[hh_2(2h-3h_2)\right]}{\pi\rho\left\{(h-h_2)h_2^2(\bar{u}_3-\bar{u}_1)+(2hh_2-3h_2^2)\left[h\bar{u}_3-h_2(\bar{u}_3-\bar{u}_1)\right]\right\}}} \tag{15}$$

Equation (15) can be used for practical design of a nozzle.

Conclusions

In this paper, we adopt approximately a difference definition for the second derivative of the velocity in the derivation, and obtain a formula, eq. (15), for determining the radius of the middle section of a nozzle for a maximal pressure drop in the nozzle.

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