Pei Feng[1,3],
Jun Pan[1],
Qihua Ma[1],
Chongchang Yang[1,2,*]

Studies on the Melt Spinning Process of Square 8-hole Hollow Polyester Fibre

DOI: 10.5604/01.3001.0011.7297

[1] **Donghua University, College of Mechanical Engineering,**
Shanghai, 201620, China
* E-mail: ycc@dhu.edu.cn

[2] **Ministry of Education, Engineering Research Center of Advanced Textile Machinery,**
Shanghai, 201620, China

[3] **Georgia Institute of Technology, School of Materials Science and Engineering,**
Atlanta, 30332, USA

Abstract
In this paper, the shape of the spinneret capillary was discussed, and optimized spinneret capillaries were successfully processed by a computer numerical control processing method which takes a C-shape silver electrode as the basic unit. Based on the optimised spinning process, a new type of square 8-hole hollow PET fibre was prepared by the experimental method.

Key words: *square 8-hole hollow fibre, melt spinning spinneret capillaries.*

RESEARCH & DEVELOPMENT

Introduction

Hollow microporous material has good thermal insulation performance, and multi-channeled fibre differs from regular hollow fibre in that it has irregularly shaped cross-sections. The hollow structure contributes to the loftiness, elasticity, heat retention and lightweight of the fibre [1-4]. As a result, hollow fibre has been widely used in the garment, decoration and technical textile industries [5-6].

In the early 1960s, hollow fibre was introduced to the United States, and soon afterwards profiled hollow fibre was developed [7-10]. More complex profiled hollow fibres were produced in previous researches [11-14]. Of the several production methods, the profiled spinneret technique is the most widely used and effective [15], whose design principle is the Barus Effect [16]. Because profiled spinneret capillaries are complicated and require accuracy and fine finish, the processing technique plays an important role in determining the number of holes, degree of hollowness and quality of the fibres [17].

Square hollow fibre has both the advantages of hollow fibre and square fibre. It has the characteristics of being waterproof, warm and light, and can be used for the production of tents, waterproof coats etc. However, the use of square hollow fibre has not been reported yet. In this paper, a multi-channel spinneret was designed and produced in small quantity. Formulation of the dynamics of the square hollow fibre spinning process was carried out using a C-shape silver electrode as the basic unit, and square 8-hole hollow PET fibre was prepared by an experimental method.

Material and methods

Design and manufacture of spinneret

In most cases, profiled capillaries are manufactured by electrical spark charging of an electrode, which is made of copper, molybdenum, etc. The shape of the fibre cross-section resembles that of capillaries. Meanwhile the shape of the capillaries is determined by the electrode. As a result, the shape of the electrode and capillary is a very important factor in spinneret design for multi-channeled hollow fibres.

The design of the profiled capillaries, which can be manufactured by a set of electrodes assembled in a guider, is based on a previous research [18]. Capillaries of square 8-hole hollow fibre are difficult to manufacture using a set of I-shaped electrodes assembled in a guider [19-20]. The processing design of a C-shaped slit die is shown in ***Figure 1***. According to the processing design of the C-shaped slit die, the C-shaped moulds are processed by specialised numerically controlled electrical discharge machining [18]. Taking the C-shaped electrode as a basic unit and via a CNC (Computer Numerical Control) processing method using a C-shape silver electrode as the basic unit, our experiment finally obtained the spinneret capillaries expected. The spinneret capillary of the square 8-hole hollow fibre is shown in ***Figure 1***.

Materials and spinning process parameters

Fibre grade polyester chips made by Shanghai Petrochemical Co. Ltd (China) were used, the specifications of which are shown in ***Table 1***.

Test-spinning final parameters of the experiment are shown in ***Table 2***.

Calculation

Spinneret design and processing

The spinning process requires small melts to flow smoothly down all the "C" slits. According to Ziabicki [20], melt extruding from a spinneret capillary would bulge in all directions. This phenomenon can be explained by following equations. Assuming the polymer flow is a Newtonian Fluid, and the flowing capacity for "C" is Q_1 and Q_2, the following equations are derived [21]:

For the flow of a "C" slit,

$$Q_1 = \frac{\pi\phi_2^{\,4}}{128\eta}\frac{\Delta P}{L}[(1-K^4)-\frac{(1-K^2)^2}{2\ln(1/K)}] \quad (1)$$

For the flow of a "C" slit of height h,

$$Q_2 = \left[1-\frac{1}{\pi}\arccos\left(\frac{2h}{\phi_1}-1\right)\right]\cdot \cdot\frac{\pi\phi_2^{\,4}\Delta P}{128\,\eta L}\left[\left(1-K^4\right)-\frac{\left(1-K^2\right)^2}{2\ln\left(1/K\right)}\right] \quad (2)$$

where ϕ_1 – external diameter ; ϕ_2 – core diameters, L – depth of the spinneret, η – apparent viscosity of the melt, ΔP – pressure drop of the spinneret $K = \phi_2/\phi_1$.

It can be seen from ***Equations (1)*** and ***(2)*** that the flow capacity Q1 and Q2 are proportional to the slit dimensions.

Derivation of C-shaped silver electrode mould

For the C-shaped spinneret capillary, the spinneret design can be made in accordance with the flat capillary shear rate.

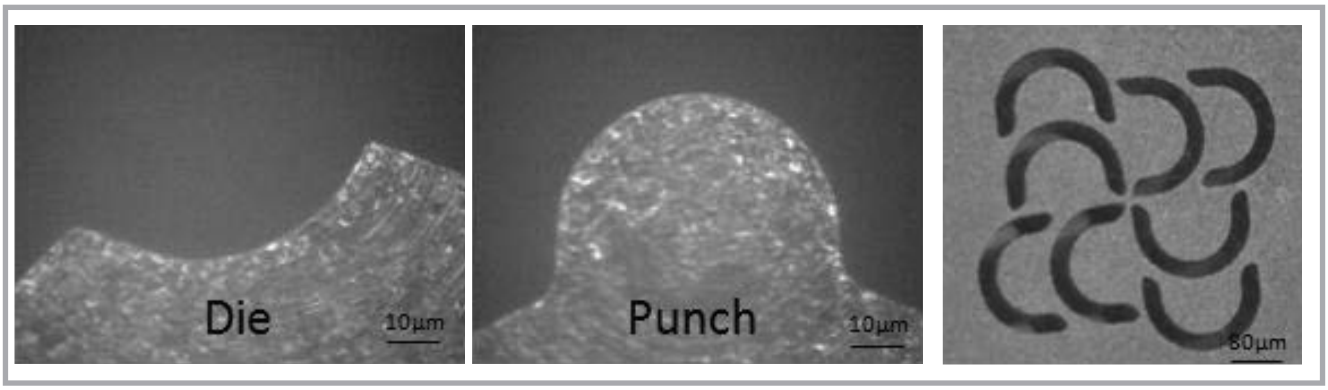

Figure 1. Capillary of square 8-hole hollow fibre.

The relationship between the shear rate of the melt flow through the flat capillary, single hole output volume, and capillary structure parameters is as follows [20]:

$$\dot{\gamma}=\frac{2\left(1/n+2\right)Q}{HW^2} \quad (3)$$

Where $\dot{\gamma}$ – shear rate, n – Non-Newtonian Index, for a Newtonian fluid n = 1; Q – single flow, H – capillary length, W – capillary width, $H = \pi (d_1 + d_2)/2$, $W = (d_1 - d_2)/2$, d_1, d_2 – outer and inner diameter of the capillary, respectively.

Computation of the single hole throughput can be described with the formula below:

$$q = \frac{D_0 KVN}{\rho \times 1000 \times 60} \quad (4)$$

To develop multi-channeled hollow fibres of 8 dtex, the following procedure was employed. According to ***Equations (1)*** and ***(2)***, when the single C-shaped capillary diameter is $\phi 0.8 \times \phi 0.64$, the arc height 0.6 mm and shear rate $\dot{\gamma}$ is 3.5×10^3 (s^{-1}), according to a Newtonian fluid, n = 1, the single flow is calculated as 0.00586 cm^3/s.

According to ***Equation (2)***, when the actual take-up speed is 1000 m/min and its length is stretched to 3.26 times the original, the denier of 8-hole hollow fibre is 11.84 dtex. This indicates that by using a copper electrode, the smallest denier of the fibre that can be produced is 11.84 dtex, which is unsatisfactory for the development of multi-channeled hollow fibre that requires 8 dtex, thus further improvements would be needed on the copper electrode.

According to literature [17], the machining and discharge characteristics of silver are superior to those of copper. Firstly the design of a C-shaped silver electrode mould is considered. When producing 8dtex multi-channeled hollow fibre with ***Equation (2)***, the flow of each C-shaped slits is 0.0039 6 cm^3/s. According to ***Equation (1)***, take C-shaped slits with a width of 0.08 mm and stretching length of 1.05 mm, thus the single size of the C-shaped silt is $\phi 0.56 \times \phi 0.48$. According to the previous theoretical calculations, to achieve 8 dtex in square 8-hole hollow fibre, the structural size of the C-shaped needed would be $\phi 0.5 \times \phi 0.34$.

Table 1. Specifications of fibre grade polyester chip.

Intrinsic viscosity, dl/g	Melting point, °C	Colour, b value	Carboxyl content, mol/t	Diethylene glycol content ,%
0.645±0.013	≥260	7.2±2	≤29	≤1.1

Result and discussion

According to Liu's pulsation model [22], when the polymer concentration approaches infinity, pulsation of the jet will not happen. Moreover the spinning temperature plays an important role in the spinning process. Therefore in experiments performed for this research, the spinning temperature was lower than normal to increase the polymer viscosity. As the spinning temperature becomes low, the solidification point approaches the spinneret, and the deformation region becomes short. Meanwhile our research found that a fixed clearance between the two slits is critical in producing desirably shaped profiled fibres in experiments. If the clearance is too large, the porous fibres desired cannot be obtained, and if it is too small, the melt will cluster together soon after getting out of the unit. Besides a small clearance would shorten the service life of the spinneret. In this work, experiment results suggest an ideal clearance of 0.08 ± 0.01mm for profiled fibre.

Table 2. Main spinning parameters.

Parameters	Value
Linear density, dtex	8
Spinning temperature, °C	286
Take-up speed, m/min	1000
Quenching air velocity, m/min	0.75
Quenching air temperature, °C	25

The size of the hollow portion is determined by the inner and outer diameters at the solidification point, which decreases down the spinline. The melt extruding from the die forms annulus, which maintains the cross-sectional shape of the die, continuing over the whole spinline, with variation only in the hollow portion. Melt extruding from a spinneret capillary would bulge in all directions, the cross-sectional shape change continuously, and become a circular shape in every C-shape unit (***Figure 1***). Due to surface tension between adjoining C-shape units and the high degree curvature of the C-shape, the curved surfaces between two adjoining C-shape units would be stretched to the horizontal, producing and retaining square cross-sections for each original C-shape unit.

The quality of the product is satisfactory based on values of physical properties (shown in ***Table 3***). Square 8-hole hollow PET fibre was successfully prepared, shown in ***Figure 2***.

Main quality indicators of the square 8-hole hollow fibre are shown in ***Table 3***. They reached our expected objectives, and these indicators also demonstrated

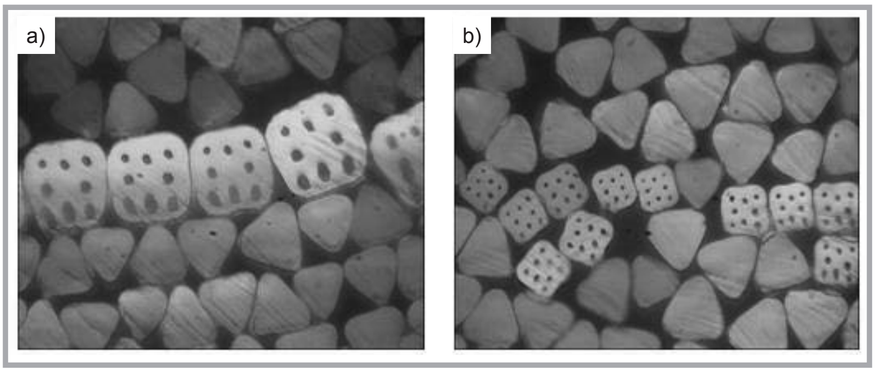

Figure 2. *Cross-section of square 8-hole hollow fibre: a) before drawing, b) after drawing.*

Table 3. *Physical properties of square 8-hole fibre.*

Item	Unit	Values	Testing standard
Linear density	Deviation, %	-1.9	
	CV value, %	0.92	
	Linear density per filament, dtex	8.12	
Breaking tenacity	cN/dtex	3	GB/T 14337-93
	CV value, %	3.4	
Breaking elongation	%	28.6	
	CV value, %	1.4	
Shrinkage in boiled water	%	9.6	FZ 50004-91
Oil content	%	0.43	GB/T 14340-93
Hollowness degree*	%	≥15	

$$^{*}\text{Hollowness degree }(\%) = \frac{\text{hollow area of the fiber cross-section}}{\text{the whole area of the fiber cross-section}}$$

the feasibility of the technology used in developing a silver-electrode mould for square 8-hole hollow fibre and processing a C-shaped die subtle silver electrode.

In the experimental part, quenching conditions have a strong effect on profile development and final dimensions. The diameters of the square and hollow portions of as-spun fibre are thought to be dependent on the variables of the position of the solidification point. In the square 8-hole hollow polyester fibre spinning process, the solidification point varies with quenching conditions, and the diameters of the square and hollow portions of as-spun fibre change accordingly. Lowering the quench air temperature is expected to have a similar effect to increasing the quench air velocity.

Conclusions

In this study, optimised spinneret capillaries were successfully processed by a computer numerical control processing method which takes a C-shape-unit. The experiments and mass production signal a useful, efficient way to produce a high quality spinneret capillary and profiled multi-channeled fibres with a noncircular cross-section full of circular holes. Square 8-hole hollow PET fibre was successfully prepared. From the results, the following conclusion can be made:

1) Even smaller sizes of the spinneret capillary can be achieved by using a silver electrode, in which the method of mould extrusion has to be used;
2) A hole pattern of 8 hollow spinneret capillaries can be achieved by means of a C-shaped basic unit, which is assembled by a CNC machine;
3) The CNC machining processing method based on the silver electrode basic unit can be applied to industrial production.

Acknowledgements

This work was funded by the National Key R&D Program of China (item number: 2016YFB0302900-2016YFB0302901-1). The authors of this paper appreciate each participant in the discussion.

References

1. Washino Y. *Functional Fibers*, Toray Research Center, Osaka, Japan, 1993.
2. Bueno M A, Aneja A P, Renner M. *J Mater Sci*. 2004; 557: 39.
3. Oh T H, Lee M S, Kim S Y, Shim H J. *J Appl Polym Sci*. 1998; 1209: 66.
4. Esra Karaca, Nalan Kahraman, Sunay Omeroglu, Behcet Becerir. *FIBRES & TEXTILES in Eastern Europe* 2012; 20, 3(92): 67-72.
5. Rwei S P. *J Appl Polym Sci*. 2001; 2896, 82.
6. Rovere A D, Shambaugh R L. Polym Eng Sci. 2001; 1206: 41.
7. Shantilal Shah C. U.S. Patent 4001369, 1977.
8. Takarada W, Hiroshi I, Kikutani T, Okui N. Studies on high-speed melt spinning of noncircular cross-section fibers. II. On-line measurement of the spin line, including change in cross-sectional shape. *J of Applied Polym Sci* 2001; 80: 1575.
9. Sakihara Akio. J.P. Patent 57106708, 1982.
10. Puri S. Pushpinder. Spinneret for making hollow fibers having different wall thicknesses. EP0277619A2, 1988.
11. Wang H P, Yu X W, Hu X C. The Computer Simulation of Unsymmetry of the Melt-spinning Hollow Fiber [J]. *Journal of China Texile University* (Eng. Ed.), 1999; 16(2): 7-10
12. Inoue K, Kagawa T, Isoda H. Refrigeating device JP6119811B2,1986-1-28.
13. Yingbo Chen, Xinping Hu, Xiaoyu Hu, et al. Polymeric hollow fiber membranes prepared by dual pore formation mechanism. *Materials Letters* 2015; 143, 15 March: 315-318.
14. Meisheng Lia, Shouyong Zhoua, Ailian Xuea, et al. Fabrication of porous attapulgite hollow fiber membranes for liquid filtration. *Materials Letters* 2015; 161, 15 December: 132-135.
15. Karaca E, Ozcelik F. Influence of the cross-sectional shape on the structure and properties of polyester fibers. *J of Applied Polym Sci* 2010, 103(4): 2615-2621.
16. Okubo S, Hori Y. Notes: Model Analysis of Oscillating Flow of High-Density Polyethylene Melt. *J of Rheol* 1980; 39, 24.
17. Chongchang Y, Cheng Q. The design and manufacture of profiled multi-channeled hollow polyester fibers. *Fiber & Polymers* 2009; 10, 5: 657-661.
18. Yang CC. *Studies on Design, Manufacture and Applications of Spinneret for Melt-spinning Shaped Fibers*. Ph.D. Dissertation Donghua University, China, 2009.
19. Wang Y. M.S. Thesis, Donghua University, China, 2002.
20. Ziabicki A, Jarecki L, Wasiak A. *Computational and Theoretical Polym Sci.* 1998; 8: 143.
21. Jin RG. *Polymer Rheology and its Processing Application*, Chemical Industry Publisher, Beijing, 1986; 23-30.
22. Liu Z, He CH, Zhang SZ, et al. A Mathematical Model for the Formation of Beaded Fibers in Electrospinning. *Thermal Science* 2015;19(4): 1151-1154.

Received 20.02.2017 Reviewed 23.02.2018