A Review on Raw Materials, Commercial Production and Properties of Lyocell Fiber

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ARTICLE INFO

Article history:
Received 30 August 2019
Received in revised form 29 October 2019
Accepted 12 November 2019
Available online 5 January 2020

Keywords:
lyocell fibers
N-methylmorpholine-N-oxide (NMMO)/H2O solution
spinning dope
dissolving pulp

ABSTRACT

As one of the regenerated cellulose fibers, viscose fiber has the largest output. However, the wastes produced in the manufacturing process are difficult to eliminate, which restricts the development of viscose fiber. Lyocell fiber is claimed as "green and eco-friendly fiber" with a good application prospect in the 21st century. The preparation of lyocell fiber is based on the cellulose non-derivative solution system, i.e., N-methylmorpholine-N-oxide system which is nontoxic and recyclable. Firstly, the demands of dissolving pulp properties for regenerated-cellulosic fiber (RCF), especially for lyocell fiber, were introduced in detail. Next, the whole manufacturing processes including pretreatment, preparation of spinning dope, spinning, posttreatment and efficient solvent recovery technologies were reviewed emphatically. Then, the properties and structural characteristics of lyocell fiber were illustrated. At last, some suggestions were proposed for lyocell fiber development in China.

1. Introduction

Regenerated-cellulosic fiber (RCF) is made from chemically dissolved natural cellulose (cotton linter, wood, bamboo, bagasse, etc.) following spinning treatment. It is a kind of artificial/man-made fibers without changing the chemical structure. Compared with the other man-made fiber i.e., synthetic fiber which are produced from synthetic high molecular-weight polymers, the raw material of the RCF are natural polymers. Figure 1 (Woodings, 2001) shows the classification of fibers and the difference of them.

Natural cellulose fiber can be dissolved by derivative and non-derivative dissolution systems. Cellulose is usually dissolved by grafting new groups onto the molecules to form a new intermediate in the derivative dissolution (Sixta, 2008). The typical derivative dissolution system is NaOH/carbon disulfide (CS2) for making viscose fibers and esterification dissolution in the production of cellulose acetate fiber. Natural cellulose suffers from mercerization, aging, and xanthation treated with CS2, the resultant cellulose xanthate can be easily dissolved in dilute aqueous caustic soda (Treiber et al., 1962; Sayyed et al., 2019). Cellulosic derivatization will take place in the preparation of viscose spinning dope. However, a large amount of industrial discharge generated in this process will restrict the development of viscose fiber industry. About 25%–30% of CS2 would not be recovered. Approximately 20 kg of exhaust, 300–600 t of wastewater and some toxic waste residue were emitted with one-ton production of viscose fiber (Vanhoorne et al., 1991; Deo, 2001; Camper and Bott, 2006; Chen and Burns, 2006; Zhang, 2010). In the production of cellulose acetate fiber (LaNieve, 2006; Ertas and Uyar, 2017; Wang, 2018), purified cellulose fiber is treated with a mixture of acetic acid, acetic anhydride, and concentrated sulfuric acid for acetylation. After ripening, the flakes of cellulose acetate are precipitated, and then dissolved in acetone. Due to the use of acetone, the production process is environmentally unfriendly and even noxious. The merits and limitations of the viscose and cellulose acetate fibers processes are shown in Table 1 (Wang, 2010; Shaikh et al., 2012).

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Table 1 Comparison of several typical regenerated cellulosic fiber production processes

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Merit</th>
<th>Limitation</th>
<th>Output (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscose fiber</td>
<td>1) Low breaking strength, high elongation; 2) Moderate reaction; 3) Cheap</td>
<td>1) Heavy pollution loads; 2) Poor resiliency</td>
<td>4.5 million</td>
</tr>
<tr>
<td>Cellulose acetate fiber</td>
<td>1) Excellent drapability, handle and comfort properties; 2) Good permeability and adsorbability</td>
<td>1) Poor physical strength; 2) Acetone pollution</td>
<td>800–900 thousand</td>
</tr>
<tr>
<td>Cuprammonium fiber</td>
<td>1) Mechanical strength, abrasion resistance and softness are better than viscose; 2) slender</td>
<td>1) High consumption in cuprammonium; 2) Poor acid resistant ability; 3) Expensive</td>
<td>20 thousand</td>
</tr>
</tbody>
</table>

As some hazardous by-products generated in the derivative dissolution, the non-derivative one becomes the research hot-spot gradually. In the non-derivative dissolution system, cellulose can be dissolves directly in a solvent only accompanied by destroying the crystalline structure (Sayyed et al., 2019). These dissolution systems, including NaOH/H2O/dissolving promoter (for example, NaOH/H2O/urea, NaOH/H2O/ZnO, NaOH/H2O/zinc nitrate) (Luo et al., 2009; Fu et al., 2014; Wang et al., 2019), ionic liquid (Andre et al., 2010; Yuan et al., 2019), LiCl/N,N-dimethylacetamide (Ramos et al., 2011; Medronho and Lindman, 2014) and high concentration inorganic salt (for example, zinc chloride/H2O) (Thomas et al., 2000), have their own flaws, such as high cost, difficult recovery, heavy pollution, harsh dissolution condition, unstable and limited dissolution. Among them, the production of cuprammonium fiber has been industrialized. In this process, the raw materials are firstly purified by mechanical washing and chemical bleaching. After dissolved in cuprammonia, aging, deaerating, wet spinning, the cuprammonium filament are obtained (Woodings, 2001; Kotek, 2008). In addition, the characteristics of the cuprammonium manufacturing process can be found in Table 1 (Kang et al., 2011).

By comparing the characteristics of these typical and full-scale commercial processes, a new cellulose dissolution technology is desired. The dissolution mechanism of cellulose in N-methyl morpholine-N-oxide (NMMO) aqueous solution supports that the lyocell process is the most promising technology to replace the above processes, and it has been used industrially (Karimi and Taherzadeh, 2016; Sayyed et al., 2018).

The lyocell route to the RCFs is based on non-derivative dissolution of cellulose in an organic and aprotic solvent. Compared with the preparation of viscose fiber, lyocell has some advantages: 1) The NMMO/H2O solvent could directly dissolve the cellulose, without mercerization, aging, xanthation and other treatments. The whole process last for 3–4 h, and the production efficiency has been greatly improved (Liu, 1997; Mo, 2002); 2) No derivatization is involved, thus the original degree of polymerization (DP) of the cellulose could have the maximum conservation; 3) Very few chemicals are applied, so the NMMO solvent recovery is higher than 98.5%–99.0%. In addition, the NMMO has the advantages of non-toxic, environmentally harmless, and biodegradable (Meiste and Wechsle, 1998).
The objective of this paper is aimed at reviewing the RCF with lyocell process, mainly including the raw materials, the keys and emphases of industrial preparation, the structure and properties of the lyocell.

2. Raw Materials

2.1. Raw materials for regenerated cellulosic fiber

The raw material of the RCF is defined as dissolving pulp. It is a kind of fiber pulp, with high content of cellulose and low content of other chemical components, obtained by chemical refinement/purification treatment. The raw material of dissolving pulp is mainly wood and cotton linter. The wood-based dissolving pulp mainly comes from the countries and regions rich in forest resources, e.g., Europe, U.S., Brazil and South Africa. Most dissolving pulps in China are produced from cotton linter. An undeniable fact is that the proportion of the wood-based dissolving pulp in China is increasing year by year.

The production process of regenerated cellulose fiber required certain properties and conditions of dissolving pulp, including high $\alpha$-cellulose and DP, low metal ion and ash, and remarkable reactivity (or solubility) properties. According to these requirements, acid sulfite (AS) or pre-hydrolysis kraft (PHK) pulping are selected for producing wood-based dissolving pulp (Li et al., 2015). They account for 42% and 56% of the global production capacity of dissolving pulp, respectively. The PHK method, which has gradually become the mainstream technology, accounts for 78% of the process of dissolving pulp in China (Chen et al., 2015). It is a combination process of acid pre-hydrolysis with alkaline cooking. Compared with the AS, the PHK is widely adaptable to raw materials and controls the DP and viscosity easily. Besides softwood, the raw materials with high hemicellulose and resin content also can be used to produce dissolving pulp by the PHK. Figure 2 shows a traditional industrial process of wood-based dissolving pulp produced by the PHK.

![Fig. 2 Traditional industrial process of wood-based dissolving pulp produced by prehydrolysis kraft pulping](image)

The functions of each process of the PHK are as follows: 1) Pre-hydrolysis (Schild and Sixta, 2011). Removing part of hemicelluloses can destroy the primary wall of fiber, and lead to some voids opening on the cell wall. Thus, the accessibility of fiber cell wall can be improved. The subsequent reactions can be accelerated. Pre-hydrolysis involves acid pre-hydrolysis, hot water pre-hydrolysis and steam pre-hydrolysis. Steam pre-hydrolysis is generally used in the industrial production because of short heating time and rapid reaction. 2) Alkaline extraction (Ingruber et al., 1985; Liu et al., 2016). It is a refining section of the dissolving pulp production, which can dissolve the remaining hemicellulose. Cold caustic extraction and hot caustic extraction are available. The first one with the best protection for cellulose belongs to a physical purification process. It requires a high alkali concentration. As a comparison, the latter with a relatively low alkali concentration is the main method to purify dissolving pulp in the industrial production. 3) Bleaching (Vila et al., 2004; Viviana, 2010). The aim of this step is to decrease the content of the remaining lignin. The bleaching method involves oxygen delignification, hypochlorite and chlorine dioxide bleaching. The chlorine dioxide bleaching is generally used due to the selectively degradation of lignin and lightly damage of cellulose. 4) Acid treatment (Maréchal, 1993). It can remove alkali-resistant hemicellulose, ash and metal ion in the dissolving pulp, purify the cellulose to minimize the degradation of NMMO and improve the solubility of fiber.

2.2. Dissolving pulp for lyocell fiber

The production processes and product features of varied RCFs have different demands on the performance of raw material. According to the researches and production experience, the requirements of the dissolving pulp for lyocell fibers are as follows:

1) The DP and reactivity (or solubility). The DP of dissolving pulp directly affects the mechanical strength of lyocell fiber. In theory, the higher DP the better mechanical strength can be occurred. However, an excessively high DP may result in a poor solubility and an increase in the viscosity of spinning dope. How to balance the relationship between DP and the solubility of dissolving pulp has a great impact on the spinning process and the performance of corresponding fiber. The specific methods involve improving the pre-hydrolysis strength and moderating the cooking conditions. In the new process of lyocell production, a pretreatment process is used to improve solubility of lyocell fiber in the NMMO aqueous solution. It is found that the DP between 650 and 750 is better (Li and Zhuang, 2001).

2) $\alpha$-cellulose. Results of some studies have shown that the dissolving pulp which is suitable for lyocell fiber does not de-
mand a high $\alpha$-cellulose (Tong et al., 2005; Zhang, 2007). It is because that in the production of spinning dope, hemicelluloses in the dissolving pulp also can be dissolved in the NMMO aqueous solution. However, an exorbitantly high hemicellulose may reduce mechanical strength of lyocell fiber.

(3) Others. Lyocell fiber demands that dissolving pulp should be relatively pure, i.e., with low metal ions and ash. The metal ions, especially iron ions, are easy to degrade the NMMO, thus affecting the dissolution of fiber and the recovery of the NMMO. The viscosity, the filtration of spinning dope, and the stability of spinning section also will be influenced by other impurities, such as blocking the nozzle.

Taking wood-based dissolving pulp as an example, the quality indexes of dissolving pulp applied for lyocell fiber are shown in Table 2 (Gao et al., 2019a).

<table>
<thead>
<tr>
<th>Project</th>
<th>Index demand of dissolving pulp for lyocell fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$-cellulose (%)</td>
<td>$\geq 92$</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>Degree of polymerization</td>
<td>650–750</td>
</tr>
<tr>
<td>Pentosan (%)</td>
<td>$&lt; 2.5$</td>
</tr>
<tr>
<td>Intrinsic viscosity (mL/g)</td>
<td>280–350</td>
</tr>
<tr>
<td>Whiteness (%)</td>
<td>$\geq 90$</td>
</tr>
<tr>
<td>Resin (%)</td>
<td>$&lt; 0.3$</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>$\leq 10$</td>
</tr>
<tr>
<td>Carboxyl group (%)</td>
<td>$&lt; 0.2$</td>
</tr>
<tr>
<td>Dust (mm$^2$/m$^3$)</td>
<td>$\leq 0.2$</td>
</tr>
<tr>
<td>Iron (mg/L)</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td>Copper content (mg/L)</td>
<td>$&lt; 1$</td>
</tr>
</tbody>
</table>

### 3. Industrialization Process of Lyocell

The research on the NMMO/H$_2$O dissolution system began in the 1940s. However, the industrial and commercial scale had been established after the year of 1980 (Cheng, 1999; Lin and Ke, 2000; Gavillon and Budtova, 2007; Sayyed et al., 2018). Nowadays, the RCF based on the NMMO/H$_2$O dissolution system mainly involves Tencel (Lenzing of Austria) and Newcell (Akzo Nobel of Netherlands). The annual production of lyocell fiber in Lenzing is about 220 thousand t (Li, 2018), accounting for the largest proportion in the world. The relevant research in China lag behind 20 years, and the development was also slow. The production capacities of lyocell fiber in China are mainly focused on Shanghai Leo, Baoding swan, Xinxiang Bailu and Shandong yingli limited companies Figure 3 shows the industrial production process of lyocell fiber in Baoding swen chemical fiber Co. Ltd. (Gao et al., 2019a), mainly consisting of five steps of pre-treatment, dissolution, filtration, spinning and post-treatment.

**Fig. 3** Industrial production process of lyocell fiber in Baoding Swen Chemical Fiber Co. Ltd.

#### 3.1. Pretreatment

In order to improve the efficiency of cellulose dissolution, decrease dissolution temperature and retention time, the pretreatment
technologies of dissolving pulp are necessary. Mixing technologies of high and low viscosity pulps, cellulose activation, pressing and smashing of pulp are employed in Baoding swan fiber Co. Ltd. After that, the treated pulp is mixed with the NMMO aqueous solution, antioxidants and stabilizers to make a premix.

3.2. Preparation of spinning dope

The nature of the N—O group is best described by a coordinate covalent bond. The highest electron density is located at the oxygen atom. Due to the high polarity of the N—O bond, the NMMO has an extremely high dissolving capacity in water, and a pronounced tendency to form hydrogen bonds (Chaudemanche and Navard, 2011). When the temperature reaches a certain degree, the NMMO can disrupt the hydrogen bond network of cellulose and form solvent complexes by establishing new hydrogen bonds between NMMO and the cellulose, in both crystalline and amorphous regions (Dogan and Hilmioglu, 2009; Periyasamy and Khanum, 2012). Finally, a new and re-structural hydrogen bond network is established, which leads to the cellulose dissolution. The mechanism of dissolving cellulose in the NMMO is exhibited in Fig. 4 (Pinkert et al., 2010; Peng et al., 2017).

Fig. 4 Mechanism of dissolving cellulose in N-methyl morpholine-N-oxide (NMMO)/H₂O dissolution system

The preparation of spinning dope of lyocell, i.e., the NMMO aqueous solution of cellulose, is one of the key points and difficulties in the industrialization of lyocell fiber. Although cellulose can be directly dissolved in the NMMO solution, the dissolution method is indirect rather than a simple mixture. In other words, cellulose should be mixed with the low-concentration NMMO aqueous solution at first. After the cellulose is fully swollen, a vacuum distillation is conducted to evaporate the extra water (Wang et al., 2017). The use of this indirect dissolution method can be attributed to a narrow region of solubility of cellulose and the difficulty to accurately control moisture in the NMMO aqueous solution (Wang and Pan, 2000). Moreover, cellulose may be dissolved in the high-concentration NMMO aqueous solution at an incredible rate. The resultant solution is heterogeneous. In the low-concentration NMMO aqueous solution, water molecules are easier to establish hydrogen bond with cellulose than NMMO molecules, and the excessive water are favorable to the sufficient swelling of cellulose molecules before dissolution, thus resulting in a homogeneous spinning dope.

A reasonable cellulose dissolution procedure in NMMO/H₂O is presented. The first step is pre-mixture for swelling. The typical mixed conditions are of 50%-60% NMMO, 20%-30% water and 10%-15% cellulosic fiber (Rosenau et al., 2001). The next is distillation. A desired ratio of NMMO/water/cellulose is of 76:10:14 (Rosenau et al., 2001). At last, the cellulose is dissolved in the NMMO aqueous solution for about 15–30 min at 90–120 °C with stirring to form a high viscosity dope. During the dissolution, some stabilizers, e.g., isopropyl gallate, can be added to prevent from the NMMO degradation at high temperature (Wendler et al., 2008; Ingildeev et al., 2013).

The preparation technologies of lyocell fiber spinning dope involve kettle-type dissolution, twin-screw extruder dissolution, vacuum mixed propulsive dissolution and vacuum membrane propulsive dissolution technology. The first one is intermittent, while the others are continuous (Wang et al., 2017). The kettle-type dissolution, with a slow dissolution and fiber quality variation, is easy to operate. The fiber originated from the continuous twin-screw extruder dissolution is stable and the production capacity is inferior. The production capacity and the fiber quality of the continuous vacuum mixed propulsive dissolution technology are wonderful. In comparison, the equipment structure is complex and the processing cost is high. At present, the most widely used technology in industrial production is continuous vacuum film propulsive dissolution technology. The NMMO aqueous solution, additives and cellulose pulp are mixed, and scraped to form the film in the evaporator. The bubble-free solution is quickly obtained under a certain temperature and vacuum (Qian, 2018). Its superiorities involve low manufacturing cost, high efficiency, stable product quality and simply corresponding equipment, but the control is relatively difficult (Gao et al., 2019a).
Prior to spinning, the dope needs to filter various impurities out. The impurities mainly are the undissolved fibers or inorganic compounds coming from raw materials.

### 3.3. Spinning

Lyocell fibers are produced in an “organic solvent dry jet wet spinning” process, as shown in Fig. 5 (Fink et al., 2001; White, 2001). The spinning dope is extruded out from a block spinneret. The pore diameter of spinneret is about 4–100 μm, and the capillary tube is 200–800 μm long (Mo, 2002). It was designed for high concentration and viscosity of the spinning dope which determines the strength properties of lyocell fiber and the stability of spinning process. The ejected filaments out from spinneret passes an air gap and then pulled into the spinning or coagulation bath (Perepelkin, 2007).

The parameters influencing spinning process include air gap length, coagulation temperature, concentration, spinning speed and draw ratio (Mortimer and Peguy, 1996b; Mo, 2002; Reddy and Yang, 2014). Air gap length, a critical factor, determines the orientation of lyocell fiber. A long air gap allows enough time for orientation of cellulose macromolecules (Periyasamy and Khanum, 2012). This highly oriented structure is fixated by the entry in the normally aqueous precipitation bath (Mortimer and Peguy, 1996a; Mortimer et al., 1996), and therefore an anticipated strength will be obtained. If the spinning rays directly enter the aqueous coagulation bath, the properties of fiber will be generally inferior to viscose (White, 2001). However, an overlong air gap will lead to a reduction in orientation (Zhang et al., 2018) and some unexpected fibrillation (Chavan and Patra, 2004; Uddin et al., 2010).

The coagulation degree and rate depend on the concentration of the NMMO in coagulation bath. The 10% is a satisfactory concentration (Duan et al., 1999). When the concentration is high, the spinning ray with insufficient coagulation will be broken under the stretching state. In the opposite case, the strength properties of lyocell fiber will be decreased. The temperature of coagulation is also a key factor. Under a fixed spinning speed, crystallinity, birefringence, and orientation of lyocell fiber declined as the temperature increased. The temperature of coagulation is between 0 and 25 degree in general (Duan et al., 2001). In addition, spinning speed and draw ratio will also affect crystallinity, birefringence, and orientation of lyocell fiber (Maron et al., 1994). Typical parameters in spinning stage are as follow: spinning speed of 24–40 m/min; temperature of spinning dope of 80–120 °C; Air gap length of 10–50 mm; coagulation temperature of 15–25 °C; coagulation concentration of 10%–25% (NMMO); and draw ratio of 2–6 times.

### 3.4. Regeneration of NMMO aqueous solution

The NMMO is nontoxic but expensive. The recovery system is another key point for the industrialization. Recycling is difficult in consideration of the properties of the NMMO and the system. In the production of lyocell, several side reactions and byproducts will form in the system, e.g., hemicelluloses, silicate generated from the dissolution of cellulose, N-methylmorpholine (NMM), morpholine and methanal during the deoxygenation and degradation of the NMMO, taste fibers and colloidal particles produced during spinning, and metal ions, inorganic and organic anions introduced by raw materials and production equipment (Rosenau et al., 2001; Zhang et al., 2001). These impurities can cause detrimental influence, such as the disappointing dissolution of cellulose, pronounced degradation of the NMMO, lower performance of the fiber, increased consumption of chemicals (Rosenau et al., 2001; Yue et al., 2002; Konkin et al., 2007; Xu et al., 2012). As a result, the impurities should be removed. In order to reduce the occurrence of side reactions, antioxidant, for example, isopropyl gallate, can be added.

Recycling of the NMMO consists of two stages: purification and evaporation. Purification involves filtration, adsorption, oxidation, and ion exchange method. Using these multiple methods together can get better purification efficiency. Figure 6 illustrates a new process of the NMMO recovery system. For the non-dissolved, colloidal or waste fiber impurities are removed by flocculation precipitation and filtration. The metal ions, organic anions, the NMMO by-products and other impurities can be removed by cation and anion exchange resins. The concentration of the NMMO aqueous solution after removing impurities is low, which needs to be evaporated to the required concentration. The whole process constructs the recycling system of the NMMO. After purification and evaporation, the recovery can be up to 99%. The specific consumption of the NMMO varies from 0.01 kg/kg to 0.03 kg/kg of fiber (Perepelkin, 2007).
3.5. Posttreatment

After spinning, the fibers will undergo posttreatment. The fiber tows from different spinnerets are washed together with hot de-ionized water in the form of multiple countercurrents. The spent liquor leaving the wash system goes into the coagulation bath and the NMMO recovery system. Then the washed fiber is treated in different ways to meet properties or special requirements, for instance, soft, antistat and bleaching finishing.

4. Structure and Properties of Lyocell Fiber

Lyocell fiber is quite different from viscose fiber and native cotton fiber in structure. The cross-sections are lace shape, roughly circular and flat for viscose, lyocell and cotton, respectively, as shown in Fig. 7 (Woodings, 2001; Yang and Yang, 2002; Gao et al., 2019b).

The lyocell fiber is easy to form a skin-core structure (Zhang, 1999; Kongdee et al., 2004; Abu-Rous et al., 2007; Biganska and Navard, 2009). It seems that a thin skin wraps the fibrils together. The skin is very thin with low degree of crystallinity, and the percentage of crystallinity is about 3% in area. The core is mainly composed of numerous fibrils arranged along the fiber axis with high orientation, regular structure, low contact area and lateral cohesion between fibril bundles. Table 3 shows structural parameters for different cellulosic fibers (Schuster et al., 2004). It can be seen that the DP of lyocell is higher than that of viscose fiber.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lyocell</th>
<th>Ordinary viscose</th>
<th>High-modulus viscose</th>
<th>Cotton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystallinity</td>
<td>0.62</td>
<td>0.39</td>
<td>0.39</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Note: DP is degree of polymerization.

Fibrillation is defined as a phenomenon that some filaments split along the fiber axis under the action of swelling, mechanics and friction, always in the wet state (Wan and Wang, 1999). Fibrillation is commonly seen in fiber, especially in lyocell owing to the weakened intermolecular binding force by swelling (Rohrer et al., 2001). Furthermore, the high ordering of the structure causes less entanglement between fibrils, which is beneficial to the separation of fibrils (Zhang, 1999). The fibrillation effect provides the imagination for the application of lyocell. Although the fibrillation has been regarded as a disadvantage for some applications, the filaments create excellent touch which is so-called “peach skin” (Periyasamy and Khanum, 2012). Some approaches are employed to improve the fibrillation, such as enzyme, easy care resins and crosslinking chemicals treatments (Reddy and Yang, 2014).
The property comparison of the lyocell and other cellulosic fibers are listed in Table 4 (Perepelkin, 2007; Hohberg and Thumm, 1998). The mechanical strength of lyocell is higher than those of viscose and cotton. These can be attributed to the difference in the structure (Schuster et al., 2004; Eva, 2008): 1) Almost no degradation of cellulose in the spinning of the lyocell type. The cellulose chain is long and the intermolecular hydrogen bonds are strong; 2) high crystallinity and a tightly contact of cellulose molecule; 3) high orientation in both crystalline and amorphous regions of lyocell, the highly ordered cellulosic chains arrangement and the strong valence bonds.

<table>
<thead>
<tr>
<th></th>
<th>Elongation, dry (%)</th>
<th>Elongation, wet (%)</th>
<th>Strength (cN/tex)</th>
<th>Deformation modulus, wet (GPa)</th>
<th>Deformation modulus, wet (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyocell</td>
<td>11–16</td>
<td>17–19</td>
<td>35–47</td>
<td>8–10</td>
<td>3–4.5</td>
</tr>
<tr>
<td>Viscose</td>
<td>18–25</td>
<td>21–23</td>
<td>20–26</td>
<td>3–5</td>
<td>0.6–1</td>
</tr>
<tr>
<td>High-modulus viscose</td>
<td>12–15</td>
<td>13–15</td>
<td>32–36</td>
<td>5–6.5</td>
<td>1.5–2</td>
</tr>
<tr>
<td>Cotton</td>
<td>8–10</td>
<td>12</td>
<td>25–40</td>
<td>5–9</td>
<td>–</td>
</tr>
</tbody>
</table>

5. Application of Lyocell

Compared with other RCFs, lyocell fiber has excellent properties. Thus, it is widely used in clothing, non-woven, conveyor belts, industrial filter material, and even medicine fields. Lyocell fiber can also be blended with cotton, hemp, silk, synthetic fiber, viscose fiber for textile.

In terms of laboratory research, some explorations on producing carbon fiber, tire cord, specialty paper, etc. using lyocell fiber as raw materials have been conducted. However, there is still a long way for relevant research to achieve industrialization (Peng, 2003; Zhang et al., 2010).

6. Prospects

Research on lyocell fiber in China has a history of 50 years, but its industrialization is still behind the developed countries. In order to meet the demands of environmental and increasing performance, lyocell fiber, instead of viscose fiber, will become the most dominant production capacity of the RCF in China. It is of great significance to the transformation and upgrading of the RCF industry. The high cost is the crucial factor in hindering the large-scale industrialization. Some suggestions are proposed:

1) Raw material. Compared with other RCFs, lyocell fiber has higher requirements on the DP and solubility of dissolving pulp. However, most of dissolving pulp is produced for viscose fiber in China. Therefore, the production of special dissolving pulp which is suitable for lyocell fiber is the premise to achieve the industrialization.

2) Recovery technology of the NMNO. The lyocell process allows reduced consumption of chemicals by several times in comparison to the viscose fiber. In the further development of lyocell production technology, significant improvement of recycling of the NMNO is required, as this would minimize consumption. In recent years, the relevant technology has been gradually mastered by enterprises in China.

3) Special equipment. There is still a big gap between enterprises in China and other countries in the key equipment such as cellulose dissolution, spinning and solvent recovery. How to achieve the localization and intelligence of this key equipment is the support to the industrialization of lyocell.

4) Application and development. Accelerating the application and development of lyocell fiber products, enriching the downstream market, providing technical support for downstream, and establishing a complete industrial chain are helpful to the industrialization of lyocell.

Acknowledgements

This work was financially supported by National Key Research and Development Program of China (No. 2017YFB0308200 and No. 2017YFE0101500).

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