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Application research on infrared drying in silk re-reeling process

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Abstract

Drying is an indispensable part of the silk re-reeling process. The existing silk drying method, steam pipe drying, consumes large quantities of energy and adds considerable cost of raw materials. In order to overcome this shortcoming, re-reeled silk slices were dried via infrared radiation and the feasibility of infrared drying in silk re-reeling process was investigated. Compared with conventional steam pipe drying, infrared drying had no adverse effects on the formation of silk slices, the quality and micro-structure of raw silk. Furthermore, the drying temperature inside the infrared re-reeling machine compartments can be lowered more than 10°C and the energy consumption is less than one-sixth of that required by conventional steam pipe drying. The results indicated that infrared drying of re-reeled silk slices seems feasible and it is meaningful to reduce energy consumption and improve workers' working conditions.

Keywords

Infrared drying, raw silk, structure, properties

Introduction

Re-reeling is the process of rewinding a small reel of raw silk onto a big reel or a bobbin. The process provides raw silk with the required properties such as flexibility, strength, elongation, a certain degree of dryness, and so on.

Silk slices are dried during the re-reeling process to achieve a stable quality of raw silk.[1] Therefore, drying is an indispensable part of the silk re-reeling process. At present, the steam pipe drying method is widely adopted by many reeling factories, along with hot air drying. For conventional steam pipe drying, silk slices are dried via hot air heated by the steam pipes, which are set in a re-reeling machine and filled with vapor generated by a coal-fired boiler and transported through the pipelines. However, this method has many disadvantages, such as uneven heating of silk slices, high energy consumption, low thermal efficiency, high quantity of sulfur dioxide emissions, serious environmental pollution, uncontrollable heating temperature, and poor working environment for workers because of the high heat loss. In contrast with steam pipe drying, hot air drying has enhanced the drying rate and uniformity of products. However, this method also has some shortcomings, such as high heat consumption and heat loss, large space requirement, high equipment costs, and so on.[2] Obviously, the method does not meet the requirements of a low-carbon economy, which advocates low consumption, low emissions, and low pollution. Therefore, it is necessary to find a new raw silk drying method with high efficiency, high quality, and low cost.

Infrared (IR) heating transfers heat in the form of electromagnetic waves and generates heat in the material center directly without heating the surrounding air. Thus, IR heating is recognized as a drying method with high thermal efficiency, fast heating rate,[3] simple equipment requirements, easy control of heating

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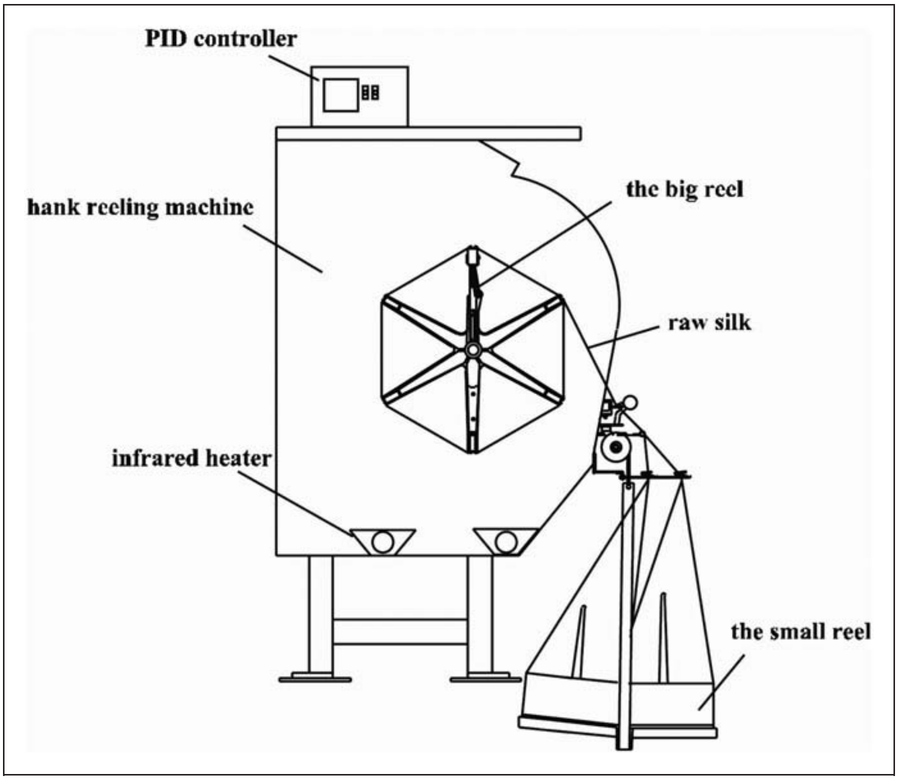

Figure 1. Schematic diagram of the experimental IR re-reeling machine.

temperature, convenient application, significant savings of operation space and energy consumption.[4] In recent years, some studies on infrared drying applied in the plastic and food products industry have shown that this drying method does not affect or even improve the drying quality of products.[5–7]

Early in the 1940s, drying of textiles by infrared radiation was reported,[8,9] and then the research into the application of infrared technology for the pre-drying of polyester, cotton, acetate, etc. was carried out.[10] Langlois and Maisonneuve[11] presented conclusions that high energetic efficiency, low installation costs and space requirement of IR drying gave it a decided advantage through the study on IR drying of viscose, wool, acetate and nylon, etc. However, there is no research about IR technology utilized in silk drying during the re-reeling process. For steam drying, the most widely used method in the silk re-reeling process, silk slices have to be dried by huge quantities of hot drying air, which results in large energy consumption, high temperature of compartments and poor working environment. Therefore, it can not only reduce the costs of drying but also help to improve the working environment.

Silk is a kind of natural protein fiber. Different heating methods in the drying process may affect the structure and performance of silk proteins, which will further affect the quality of raw silk. In order to study the feasibility of IR drying in the silk re-reeling process, IR heating was used to dry the silk slices and was compared with conventional steam heating in terms of the quality, micro-structure of silk slices, as well as energy consumption.

Experimental

Materials

Silk slices on small reels (specification, 20/22 D) taken from an automatic reeling machine were provided by Huzhou Dadongwu Silk Co., Ltd (China).

Drying equipment

The IR re-reeling machine (Figure 1), consisting of the re-reeling machine, IR radiation source, temperature sensor, proportional integral derivative (PID) controller, electric energy meter for energy consumption measurement, and other components, was constructed in our laboratory.

The heating component in the re-reeling machine contained two 2.5 μm medium-wave IR heating tubes.

A parabolic polished aluminum reflector was placed at the bottom of the re-reeling machine compartment.

Compared with far IR, medium-wave IR penetrates an object deeper, and thus, can be used in improving the quality of silk slices. Therefore, medium-wave IR heating tubes were used in the present study.

Drying of re-reeled silk

After humidification and equilibration, the silk slices rewound on small reels were divided into two parts: one part was dried with a factory re-reeling machine by conventional steam drying, and the other was dried using the laboratory-made re-reeling machine via IR drying. The laboratory-made IR re-reeling machine can re-reel and dry five silk slices each time. The five silk slices were numbered, 1 to 5 in sequence. No. 1 and No. 5 were situated at the opposite ends of the machine compartment, whereas No. 3 was placed at the center of the compartment. No. 1 and No. 5 were equidistant from the rest of the silk slices, whereas No. 3 was the farthest from the first two. Hence, No. 1 was compared with No. 3 to determine the effect of different compartment locations on IR drying. The steam-dried silk slices were used as reference samples and labeled 'S'. The randomly selected raw silk from the outer and inner layers of the silk slices were marked 'a' and 'b', respectively (i.e. 1-a for the outer layer of IR-dried silk No.1, 1-b for the inner layer of silk No. 1, S-a for the outer layer of steam-dried silk No.S, and so on).

The experiment was performed as follows: first, the IR re-reeling machine was switched on; second, the initial heating temperature of the IR heating tubes was set using the PID controller; third, the temperature switch was opened and the IR heating tubes began to heat; fourth, the compartment temperature reached the desired level and was kept stable; and finally, the silk slices were re-reeled and dried.

On the basis of previous experiments, the temperature of the compartment inside the IR re-reeling machine was kept at 30 to 35°C to obtain well-formed silk slices.

Determination of raw silk performance

Determination of moisture regain of silk slices after doffing. After re-reeling, the moisture regain of the big reel silk slices after doffing was calculated using the following equation:[12]

$$R = \frac{G - G_0}{G_0} \times 100\% \qquad (1)$$

where G and G_0, are the weights of the sample before and after oven-drying, respectively, and R is the moisture regain.

Quality inspection of raw silk. The quality of raw silk was assessed in terms of clearness, neatness, winding, cohesion, breaking strength, and breaking elongation rate, which may be affected by the drying method. These qualities were inspected by the State Quality Supervision and Inspection Center of cocoon silk according to the requirements of GB/T 1978-2008, which is the testing method for raw silk.

Clearness and neatness tests were performed to determine the types, number, and distribution of big and small defects on the silk fiber against photographic comparison standards. The tests were performed on a seriplane (HBJ 920) in a dark room with light fixture. Each sample was wound at a pre-determined pitch (80 lines per 25.4 mm) onto a quadrate blackboard (1359 × 463 × 37 mm) in 10 equal parts and the width of each part was 127 mm. Soft light shone on the blackboard evenly with average illumination of 400 lx.

The winding test was conducted by examining the winding break times using a silk winder under a specified recoiling tension, coiling speed, and time. According to the requirement of the existing test method for raw silk, the coiling speed was 165 m/min, the readiness time and the inspection time were 5 min and 120 min, respectively.

A piece of raw silk is reeled by several cocoon filament fibers that adhere to one another via their sericin. Raw silk can withstand all kinds of friction during processing because of the adhesive property of sericin. Raw silk cohesion refers to the friction resistance of the silk filament without generating splitting. The cohesion test was carried out on a Y731 cohesion tester. Silk fibers were wound to 10 hooks on both sides of the machine framework and the different parts of silk filaments were rubbed under uniform and constant tension with a rubbing speed of 130 times/min at the same time.

The breaking strength, breaking elongation of *B. mori* silk filaments (steam-dried and IR-dried) were determined using YG065 electronic multifilament tensile strength tester. The active length was 100 mm and drawing speed was 150 mm/min. The original load calculated by 0.5 cN/dtex and the fixed elongation was 5%. The results were obtained by averaging 10 samples.

The winding, cohesion, breaking strength and breaking elongation tests were carried out at laboratory atmosphere, 25°C and 65% relative humidity and the samples were placed under these conditions for more than 12 h before measurement.

Scanning electron microscopy observation. The longitudinal morphologies of raw silk from the outer and inner

Table 1. Clearness and neatness test results on raw silk

Drying method	Clearness (score)	Neatness (score)
Steam drying	99.7	93.30
Infrared drying	99.5	93.20

Table 2. Winding, cohesion, breaking strength, and breaking elongation rates of raw silk

Drying method		Winding (time)	Cohesion (time)	Breaking strength (cN/dtex)	Breaking elongation rate (%)
Steam drying	(No. S)	0	100	3.58	21.90
Infrared drying	(No. 1)	0	99	3.56	21.07
	(No. 3)	0	102	3.56	21.09

layers of both IR- and steam-dried silk slices were observed via scanning electron microscopy (SEM, JSM-5610LV) at an acceleration voltage of 5 kV.

X-ray diffraction analysis. The IR-dried and steam-dried raw silk were ground into powders and analyzed using an ARL X′TRA x-ray diffraction (XRD) system with Ni-filtered CuKα at a 40 kV voltage, 44 mA tube current, 2°/min scan rate, and 5–50° scanning range.

The crystallinity of raw silk was calculated according to the peak separation method proposed by Hermans et al.[13] and using Peakfit v. 4.12 as follows:

$$X_c = \frac{A_c}{A_c + A_a} \times 100\% \tag{2}$$

where X_c is the crystallinity of raw silk, A_c is the area of all crystal peaks, and A_a is the area of the amorphous peak.

FT-IR test. The Fourier transform infrared (FT-IR) spectra of samples were obtained using a Nicolet 5700 FT-IR spectrometer using KBr pellets without nojol. The samples were cut into powders to be mixed with KBr.

Results and discussion

Effect of IR drying on silk properties

Moisture regain of big reel silk slices after doffing. The moisture regain of IR-dried and steam-dried silk slices after doffing was calculated using equation 1. The obtained R values are 8.39% and 8.54%, respectively, which are almost the same. Therefore, both silk slices meet the 7.5%–9% requirement for big reels doffed from the re-reeling machine.[14]

Raw silk quality. The quality of raw silk is closely related to the weaving technology, fabric quality, production cost, trade value, and market competitiveness.[15] Therefore, the quality of raw silk after IR drying is an important criterion in assessing the feasibility of the drying method.

Neatness and clearness of raw silk. Table 1 shows the test results of clearness and neatness of the samples. There is no significant difference in the clearness and neatness of raw silk dried using the two methods, indicating that IR drying does not degrade the aforementioned silk qualities and that its performance is similar to that of steam drying.

Winding, cohesion, and mechanical properties of raw silk. Table 2 shows the winding, cohesion, breaking strength, and breaking elongation rates of the IR-dried and steam-dried raw silk. The cohesion and breaking strength values of the two groups of silk are very close, whereas the breaking elongation rate of the IR-dried silk is slightly decreased. However, all qualities remain at the highest silk level, the 6A grade. In addition, the requirements for weaving and knitting are met, indicating that IR drying has no significant effect on the cohesion and mechanical properties of raw silk. No. 1 and No. 3 also show no obvious difference between their performances, suggesting that the performances of silk situated at the opposite ends and at the center of the IR re-reeling machine are stable. Therefore, IR drying does not affect the quality of raw silk compared with conventional steam drying.

Effect of IR drying on raw silk structure

Surface morphology analysis. Figure 2 shows the longitudinal surface morphology of the outer and inner layers of the IR-dried and steam-dried silk. Raw silk possesses uneven grooves on the longitudinal surface, and the fibrils are regularly arranged, roughly parallel with the fiber axis, and adhered to each other via sericin. In the absence of degumming, the surface of raw silk is rough and has numerous tiny particles, which may be sericin tumors. No obvious difference is observed in the SEM images of each layer of raw silk dried using the two methods. The surface morphologies of the IR-dried No. 1 and No. 3 silk layers show no significant difference. Thus, IR drying has no effect on the surface morphology of raw silk compared with steam drying.

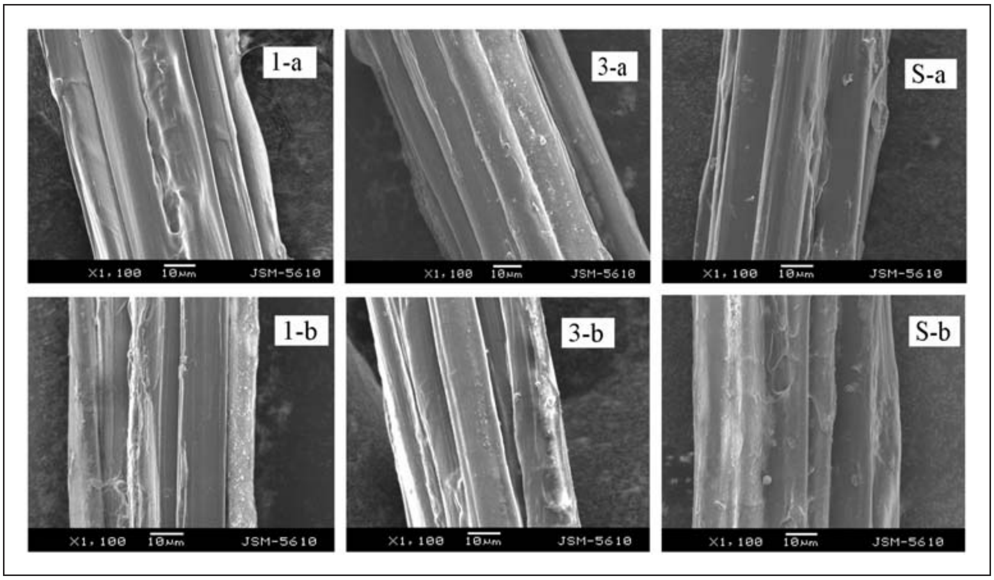

Figure 2. SEM images of raw silk. 1: the infrared-dried silk No.1; 3: the infrared-dried silk No.3; S: the steam-dried silk; a: outer layer of silk; b: inner layer of silk; 1-a: the outer layer of 1; 1-b: the inner layer of 1; 3-a: the outer layer of 3; 3-b: the inner layer of 3; S-a: the outer layer of S; S-b: the inner layer of S.

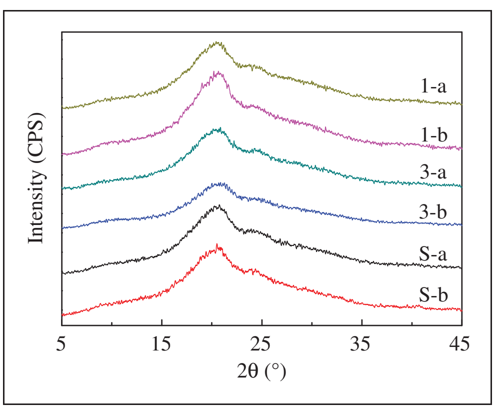

Figure 3. XRD curves of raw silk. 1: the infrared-dried silk No.1; 3: the infrared-dried silk No.3; S: the steam-dried silk; a: outer layer of silk; b: inner layer of silk; 1-a: the outer layer of 1; 1-b: the inner layer of 1; 3-a: the outer layer of 3; 3-b: the inner layer of 3; S-a: the outer layer of S; S-b: the inner layer of S.

XRD analysis. Figure 3 shows that the XRD curves for the medium-wave IR-dried and steam-dried raw silk are roughly the same. All curves exhibit a strong diffraction peak at around $2\theta = 20.6^\circ$, suggesting that the main structure of the silk fiber has not changed. The other major diffraction peaks of the six samples are at around 10.7°, 18.3°, 24.2°, and 27.9°, corresponding to the characteristics of *Bombyx mori* silk fiber with a highly oriented silk II (β) structure,[16] which has few migrations compared with that of pure silk fibroin. This result can be attributed to the effect of sericin in raw silk. However, the crystalline structure of raw silk is still silk II-dominated.[17] The crystallinity of raw silk was calculated via the peak separation method (Figure 4) using Peakfit v. 4.12 (Table 3).

Table 3 shows that medium-wave IR drying has little effect on the crystallinity of raw silk compared with steam drying.

FT-IR spectral analysis. The FT-IR spectra of raw silk after drying are shown in Figure 5. The spectra of the IR-dried silk layers are almost the same as those of the steam-dried silk. However, their absorption strengths are different. The FT-IR spectra of the six samples show strong absorption bands at 3300 cm^{-1} (N–H stretching), 1654 cm^{-1} (C–O and C–N stretching), and 1515 and 1230 cm^{-1} (predominantly N–H bending and C–N stretching).[18] The peak of the silk fiber at 1654 cm^{-1} belongs to the amide I range, corresponding to a typical random coil conformation. The absorption of the silk fiber at 1515 and 1230 cm^{-1} are attributed to amides I and II, respectively,[19,20] corresponding to the β-sheet conformation. The peak relative intensities of the six samples are basically consistent, indicating that medium-wave IR drying has no significant effects on the silk fiber surface groups compared with steam drying.

Drying temperature and energy consumption analysis

As IR heating does not need a heat transfer medium to induce a fast drying rate, the drying temperature inside

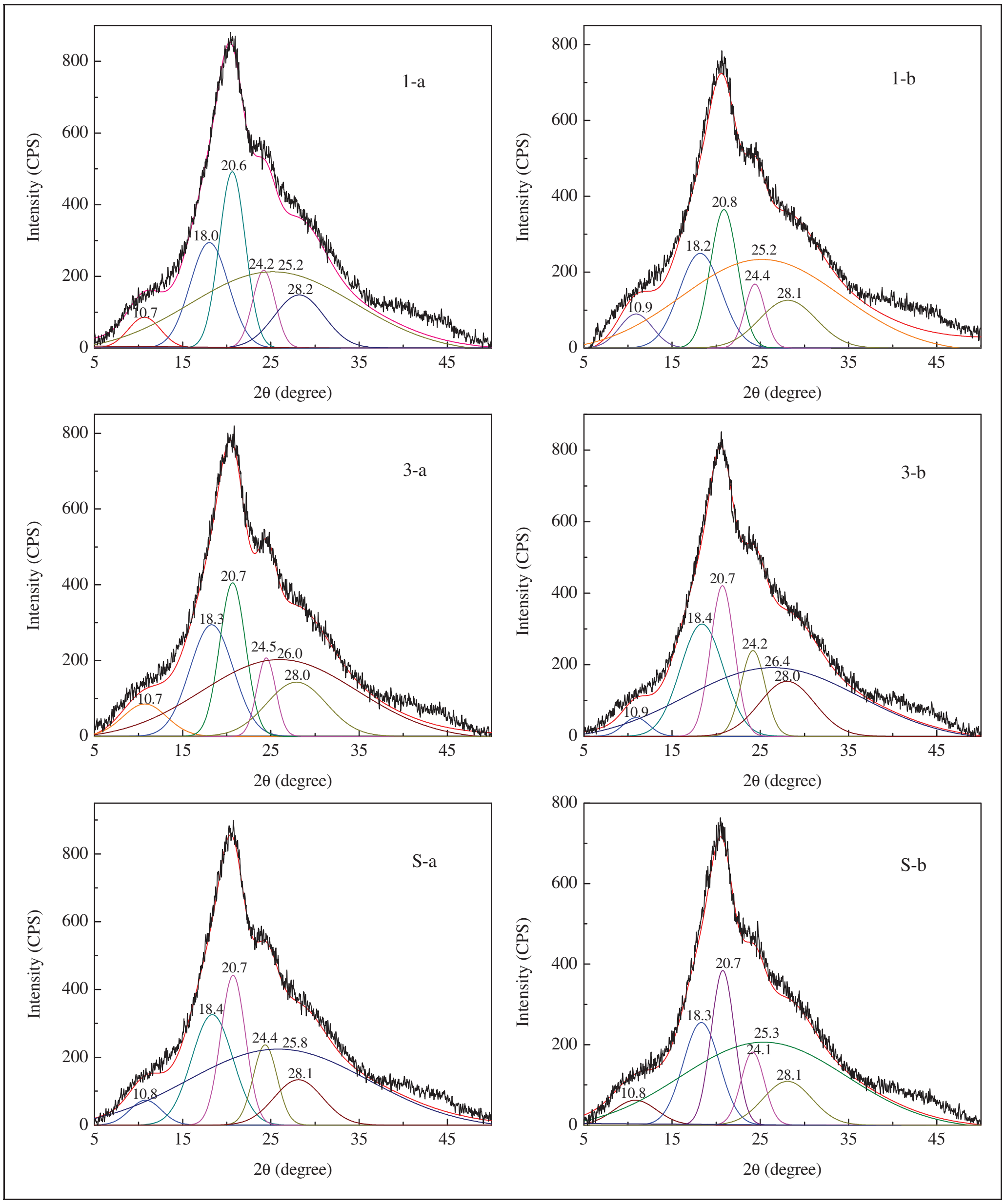

Figure 4. XRD peak separation curves of raw silk. 1: the infrared-dried silk No.1; 3: the infrared-dried silk No.3; S: the steam-dried silk; a: outer layer of silk; b: inner layer of silk; 1-a: the outer layer of 1; 1-b: the inner layer of 1; 3-a: the outer layer of 3; 3-b: the inner layer of 3; S-a: the outer layer of S; S-b: the inner layer of S.

Table 3. Crystallinity of each layer of silk dried via infrared and steam

	Crystallinity (%)		
Sample No.	Outer layer	Inner layer	Average
S[a]	48.2	46.9	47.6
1[b]	51.8	44.7	48.3
3[c]	49.9	49.1	49.5

[a]the steam-dried silk; [b]the infrared-dried silk No.1; [c]the infrared-dried silk No.3.

the IR re-reeling machine is lower than that of steam drying. In this experiment, the temperature of the compartment inside the IR re-reeling machine was kept about 33°C. Meanwhile, the temperature produced by the steam drying method is around 45°C, which is the same temperature used in factories. The compartments in the re-reeling machine are open-ended. Thus, the lower temperature is an advantage in the working environment.

The energy consumption during the re-reeling process was determined by an energy meter. The re-reeling of five pieces of approximately 900 g silk slice require

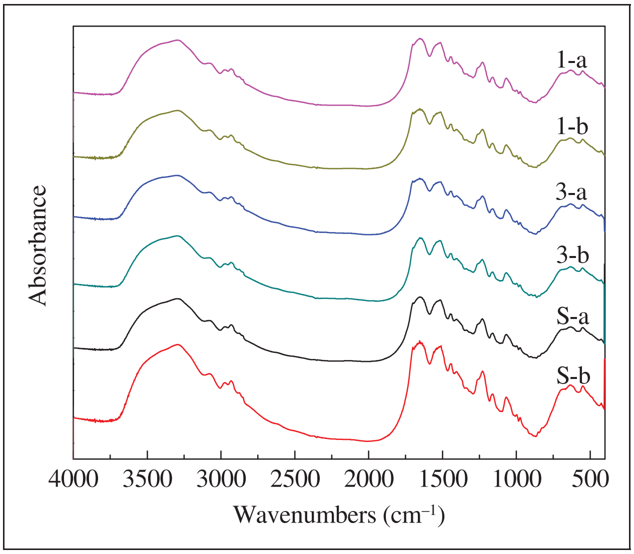

Figure 5. FT-IR spectra of raw silk. 1: the infrared-dried silk No.1; 3: the infrared-dried silk No.3; S: the steam-dried silk; a: outer layer of silk; b: inner layer of silk; 1-a: the outer layer of 1; 1-b: the inner layer of 1; 3-a: the outer layer of 3; 3-b: the inner layer of 3; S-a: the outer layer of S; S-b: the inner layer of S.

0.8 kWh, indicating that an energy consumption of 3420 kJ is needed to dry 1 kg of raw silk. A total of 12 kg of 0.155 MPa water vapor is needed to dry 1 kg of re-reeled silk via steam pipe heating.[21] Pipeline transportation losses are excluded, indicating that more than 25,000 kJ should be consumed to dry 1 kg of raw silk at a condensed water temperature of 30°C. The energy consumption of medium-wave IR drying is significantly lower, amounting to less than one-sixth of that required in conventional drying. Thus, medium-wave IR drying can not only increase the economic efficiency of the factory, but also significantly reduce the sulfur dioxide emissions produced by burning coal.

Conclusions

1. In the silk re-reeling process, medium-wave IR drying was used as an alternative to conventional steam drying to dry silk slices. This drying method shows no adverse effects on the formation of silk slices, the quality, structure and properties of raw silk, indicating that it is feasible to apply infrared drying in silk re-reeling process.
2. Compared with conventional steam drying, the temperature inside the re-reeling machine compartments using medium-wave IR drying can be lowered more than 10°C, which reduces the heat transmission from the compartments to the surrounding environment. Furthermore, it is helpful to improve the working environment and workers' efficiency.
3. The energy consumption required by IR drying is less than one-sixth of that required by conventional steam drying, so the energy-saving effect is significant.

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