

Dimensional change of wool fabrics in the process of a tumble-drying cycle

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Abstract

Currently domestic tumble dryers are popularly used for drying garments; however, excessive drying and inappropriate way of tumble agitation could waste energy and cause damage to or the dimensional change of garments. Shrinkage of wool fabrics during tumble drying causes a serious problem for wool garments. The current study investigated the shrinkage of untreated and Chlorine-Hercosett-finished wool fabrics at different drying times. Temperature of air in the tumble dryer, temperature of fabric, moisture content of fabric, and dimensional change at different drying times were measured. For the duration of tumble drying, the rise of fabric temperature and the reduction of moisture content on the wool fabric were investigated to explore their relationship to the shrinkage of wool fabrics in the tumble-drying cycle. It was found that tumble drying process can be divided into different stages according to the temperature change trend of wool fabrics. The shrinkage mechanisms of the untreated and the treated fabrics were different. The dimensional change of untreated wool fabric was caused mainly by felting shrinkage during tumble drying. Chlorine-Hercosett-finished wool fabric can withstand tumble-drying process without noticeable felting shrinkage due to the surface modification and resin coating of surface scales of wool fibers. The finding from the current research provides further understanding of the shrinkage behavior of wool fabrics during tumble-dry process, leading to optimizing operational parameters at specific stages of a tumble-drying cycle.

Key words: tumble drying, wool, Chlorine-Hercosett finishing, dimensional change, felting shrinkage, moisture content

1. Introduction

Wool fabric is highly popular with consumers due to its excellent properties such as resilience and comfort. However, shrinkage in wool assemblies during laundering and tumble drying is a serious defect.¹ Shrinkage during tumble drying can be broken down into three different types: (a) dimensional change due to relaxation; (b) dimensional change which takes place when the moisture content of a relaxed fabric is

altered; and (c) felting shrinkage.^{2,3} Relaxation shrinkage occurs as a change in the length or width of the fabric due to the relief of the strain resulting from any stages of the previous processing.⁴ Felting is the process of progressive entanglement of the fibers in an assembly, occurring as a result of persistent rootward migration of fibers due to the differential frictional effect of wool fibres,⁵ which is not reversible.

Wool felting is known to be influenced not only by the configuration of fiber surface scales, but also by mechanical properties of fibers (e.g. extensibility, recovery power, resistance to extension, etc.).^{6,7} A review of the literature revealed that many previous researches focused on the influence of properties of wool fabric materials and washing conditions on the felting shrinkage of wool.^{1,8} There are only several scientific papers involved in tumble drying, for example on different “machine-washing and tumble-drying” cycles and comparison of line-dried and tumble-dried processes,^{9,10} but few references could be found on shrinkage behavior of wool fabrics in the process of a tumble-drying cycle and their different shrinkage mechanisms. Considering that domestic tumble dryers are popularly used for drying garments, especially during winter or bad weather conditions,¹¹ wool fabric shrinkage behavior in a tumble dryer needs to be studied in order to maintain the quality of wool garments.

In tumble-drying process, temperature, mechanical force applied on the fabrics and moisture change may play an important role in the process of felting shrinkage. Previous research believed that temperature is a minor factor causing wool felting shrinkage while the major influence on felting is the amount of agitation in laundering.¹² In general, the more severe the mechanical action of a washing machine, the more rapid the felting shrinkage when other factors are being held constant.¹³ For moisture content, Wemyss *et al.* found that shrinkage was shown to be appreciable in milling when water addition exceeded 10% on the mass of conditioned wool.¹⁴ It can be seen that previous studies focused on the laundering or milling environment, and few studies were involved in the process of tumble drying, in which temperature and moisture content of fabric change in a complicated manner.

There are many processes available for imparting shrink resistance to wool based on partial removal of the cuticle scales or smoothing the edges of the overlapping

scales.^{15,16} Chlorine-Hercosett finishing is the conventional shrink-resist treatment of wool through oxidative chlorination and Hercosett resin coating of wool top to achieve machine washable wool. Domestically, untreated wool garment and some shrink-resist-finished wool garments are normally washed by hand wash and machine wash, respectively. The current study focused on the shrinkage of the untreated wool fabric and shrink-resist-finished wool fabric in the process of tumble drying after washing. As a common treatment of wool for easy care in the industry, Chlorine-Hercosett-treated wool fabric was used in the current study. In order to study the shrinkage in the drying process of wool fabrics without any change of drying environment caused by operating and measuring specimens, fabrics shrinkage in different drying time programs was studied. For the duration of the tumble drying, temperature of air in the tumble dryer, temperature of fabric, moisture content of fabric, and dimensional change at different drying times were investigated. The rise of fabric temperature and the reduction of moisture content on the wool fabric were discussed to explore their relationship to the shrinkage of wool fabrics in the tumble-drying cycle.

2. Experimental part

2.1 Preparation of materials

Wool fabrics used in the current research were supplied by ZheJiang XINAO Textiles Inc.. They were untreated wool and Chlorine-Hercosett-finished wool fabrics, both made from the same 19.5 μm merino wool. Scanning electron microscope images of untreated and treated wool fibers are shown in Figure 1. The surface topography of untreated wool fiber shows well-defined edges of scales while Chlorine-Hercosett-treated wool shows a smooth surface with a coating of polymer on the fiber surface. The untreated merino wool and Chlorine-Hercosett-finished merino wool were spun into the same diameter of yarns (yarn counts of 2/30 Nm and 2/26.5 Nm, respectively) and weft-knitted using a 12-gauge flat knitting machine into plain fabrics with the same knitting structure.

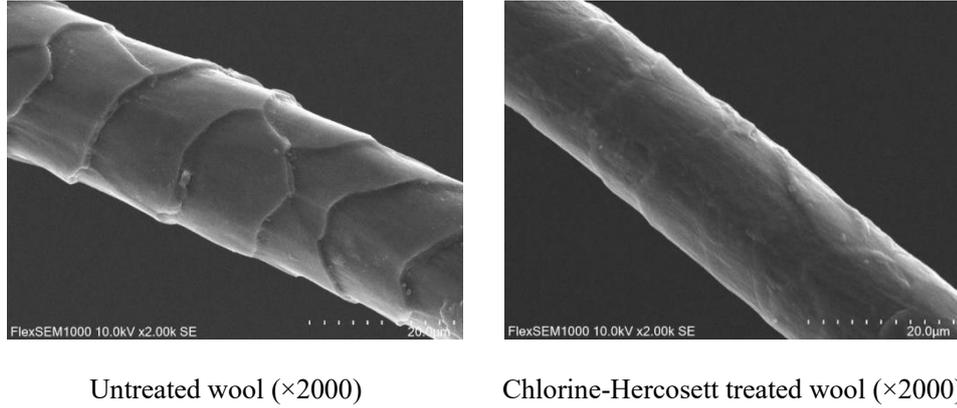


Figure 1 Scanning electron microscope images of untreated and treated wool fibers

The test specimens of the wool fabrics were prepared and made into double layers with a size of 300 mm x 400 mm and the marked size for measurement was 220 mm x 300 mm. With reference to *Test Method TWC-TM309 Performance of Domestic Tumble Dryers for “Hand Wash” Wool Products*, all fabric samples were relaxed by the relaxation procedure, i.e. wetted in water at 40 °C for 30 min and then twice at 20°C for 2 min followed by flat drying. After being dried flat, the prepared test specimens were conditioned in the standard atmosphere of 65±3% relative humidity (RH) and 20±2°C for at least 24 h. The fabric parameters of fabric samples in terms of fabric weight, thickness and bulk density were determined. The detailed fabric parameters are shown in Table 1. Seven samples of each fabric were used to determine these fabric parameters. It shows that there was no significant difference between the thickness of the two fabrics, while both the area weight and the bulk density of Chlorine-Hercosett-finished fabric are slightly higher than those of untreated fabric. This was due to the different linear densities of the two yarns.

Table 1 Fabric parameters

Fabric samples	Fabric structure	Shrink-resist finishing	Fabric area weight (g m ⁻²)	Thickness (mm)	Bulk density (g cm ⁻³)
1	plain knitted wool fabric	untreated	255.79 ± 5.07	0.99 ± 0.02	0.257 ± 0.005
2		Chlorine-Hercosett finished	268.43 ± 2.76	0.97 ± 0.03	0.278 ± 0.003

Three untreated wool specimens and three Chlorine-Hercosett-finished wool specimens with sufficient wool fabric ballast to make up the total fabric weight at 2.00 (± 0.01) kg were soaked in water in the same way as the relaxation process. This simulated the hand-washing procedure. After soaking, the water content of the full fabric load was controlled to $60 \pm 2\%$ by spinning in a Haier top-load washer.

The iButton (Maxim Integrated, USA), a small wireless device, was used to measure temperature of the fabrics in the drying process.

2.2 Drying procedures tested

In order to investigate the change in temperature, moisture and dimension of fabric specimens during the process of tumble drying, previous studies measured the fabric samples by interrupting the drying process at regular intervals during tumble drying.¹⁷ However, this could cause a change in temperature and relative humidity of drying environment due to the interruption of the drying cycle every 10 min. Therefore, the current study carried out the drying process without the interruption but used different drying time cycles of 10, 20, 30 and 40 min. All the other drying parameters (heat power, rotating speed of drum and airflow velocity) were kept same except the drying time as shown in Table 2. The tumble dryer used in the study was a modified domestic thermoelectric air-vented dryer (GDZ10-977, Haier Co., Ltd, China) with adjustable parameters.¹⁸ As shown in Figure 2 of a flow diagram of a drying program operation, “Drying time” in this study referred to the time from turning on the heater to turning off the heater. All the results were the average of two repeats.

Table 2 Tumble drying programs

Drying program	Total time of drying (min)	Heater power (W)	Rotating speed of drum (rpm)	Air flow velocity (m/s)	Initial water content (%)
1	10				
2	20				
3	30	$3000 (\pm 10)$	$50 (\pm 2)$	$5.5 (\pm 0.5)$	$60 (\pm 2)$
4	40				

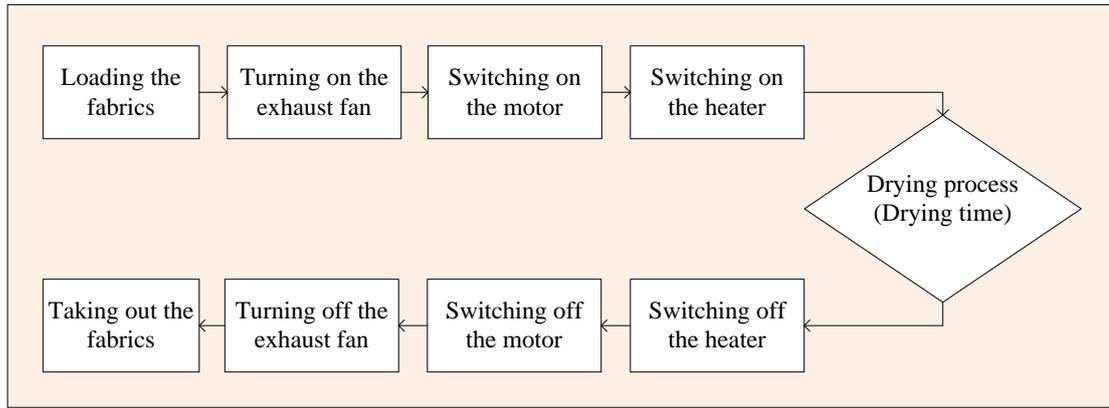


Figure 2 The flow diagram of a drying program operation.

2.3 Fabric monitoring and their measurements

In this study, temperature of fabrics and air in the tumble dryer, moisture content of fabrics, and their dimensional change during the drying process were measured.

(1) Temperature of fabric samples and air in the tumble dryer

iButtons (DS 1922T), able to measure the range of temperature from 0 to 125 °C with the resolution of 0.5 °C, were fixed in between two layers of fabric specimens to measure temperature of the fabric during the tumble-drying process. Three iButtons were used in three fabric specimens in each drying cycle. In addition, temperature of air in the tumble dryer was monitored by a thermocouple.

(2) Moisture of wool fabric samples

Moisture content of fabric was calculated using equation (1) with reference to IEC 61121: 2005 (Ed 3.1) “Tumble dryers for household use—Methods for measuring the performance”.

$$\mu_t = \frac{W_i - W_o}{W_o} * 100\% \quad (1)$$

Where μ_t is moisture content of fabric, w_o is initial weight of specimen being in the standard atmosphere of 65 % RH and 20 °C for 24 hours before washing and drying, w_i is the weight of specimens after washing and drying.

(3) Dimensional change of wool fabrics

Length change of fabric samples was calculated using equation (2) with reference to AATCC Test Method 135—2014 “Dimensional Changes in Automatic Home

Laundering of Woven or Knitted Fabrics”.

$$LC = \frac{B - A}{A} * 100\% \quad (2)$$

Where LC is length change of fabric sample in percentage, A is original length of fabric sample before washing and drying, and B is length after washing and drying. All of the specimens were measured after being conditioned in the standard atmosphere of 65% RH and 20°C for at least 16 h.

Area change was calculated using Equation (3) with reference to Woolmark Test Method TM254—2008 “Tumble drying performance after washing”.

$$AC = LC + WC - \frac{LC * WC}{100} \quad (3)$$

Where AC is area change percentage, LC is length change percentage, WC is width change percentage.

3. Results and discussion

3.1 Temperature and moisture of fabric

In order to investigate the change in temperature and moisture content of the fabrics during the tumble drying-process of wool fabrics without interruption of the drying environment, the drying processes of wool fabrics under different drying times of 10, 20, 30 and 40 min were carried out. The fabric temperature was monitored using iButton. It was found that the temperature of the fabrics increased with increasing drying time (Figure 3). After switching off the heat power, the fabric temperature might increase slightly further until switching off the exhaust fan and taking the fabric samples out of tumble dryer. The temperature of fabrics then dropped naturally in the room environment. Due to the same drying parameters (heat power, rotating speed of drum and airflow velocity) used in the drying process, the trend of the increase in the fabric temperature at the same drying time over different drying programs was very consistent. At the first 8 min of drying, the temperature of the fabrics increased rapidly, followed by a slow increase for a further 27 min, and then a rapid increase after 35 min drying.

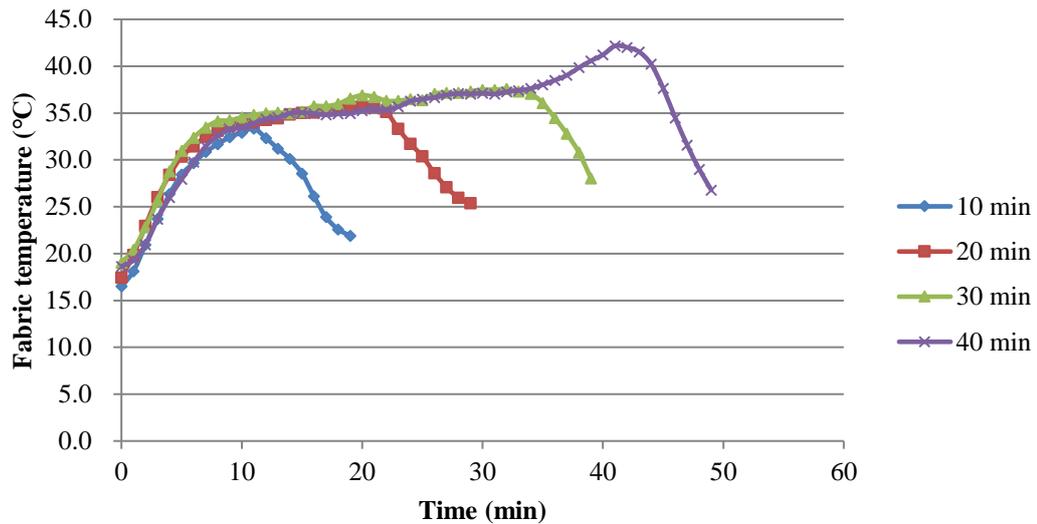


Figure 3 Fabric temperature in different drying-time programs.

During the 40 min of the tumble-drying process under the heater power of 3 KW and drum rotating speed of 50 rpm, not only the temperature of air in the tumble dryer but also the temperature and moisture content of wool fabrics were monitored. Figure 4 shows the change in the moisture of fabric and the temperature of fabric and air in the tumble dryer at different drying times under a 40-min drying program. It was found that the temperatures of air and fabric increased at similar trend for the duration of tumble drying while the moisture content on the wool fabrics reduced steadily. By observing the change of temperature of fabric, the fabric drying process can be divided into three stages. The temperature went up rapidly in the first 8 min (first stage) followed by a slow rise (second stage), and at the final 5 min the temperature of fabric rose faster again (third stage). In the first stage, energy input from heater was mainly used to increase the temperature of the fabrics and the body of the dryer. Although the temperature in this stage was lower, the moisture content of both untreated and shrink-resist-finished wool fabrics decreased steadily. An explanation for this is that “free water” on the surface of fabric has a weak binding force between water and fabric, resulting in easier migration and evaporation in the first stage even at a lower temperature.¹⁸ At the second stage, evaporation of the moisture from the fabrics primarily took place. The surface of the wool fabric could be considered to be saturated

with water.¹⁹ The moisture could migrate from the inside of the wool fabric to the fabric surface and compensate for the evaporation of free water on the fabric surface.¹⁸ In the third stage, the moisture on the surface of the material decreased and some of the energy input was used to further increase the temperature of the drum and the fabric.¹⁹ In this stage, the main removed water was moisture from inside the fibers, and the bonding force of water to the fiber was stronger so that the higher temperature is required to remove the moisture from inside the fibers.^{18, 20}

Figure 4 also shows that the untreated wool fabric dried slightly quicker than the Chlorine-Hercosett-finished wool fabric when the moisture content was more than 25%. Because undamaged wool has a hydrophobic layer on the cuticle surface of fibers, water on the surface of the untreated wool fibers could easily be evaporated due to the hydrophobic property of the wool surface. The partial removal of surface scales of wool fibers by chlorine treatment could make the wool surface become hydrophilic, therefore more energy is required to evaporate the surface water from the hydrophilic surface of the wool due to the increased bonding between fiber and water molecules. For moisture inside the fibers, the cuticle scales of untreated wool and the Hercosett surface coated polymer of treated wool may affect the escape of the moisture. The detailed mechanisms to explain these observations need to be studied further.

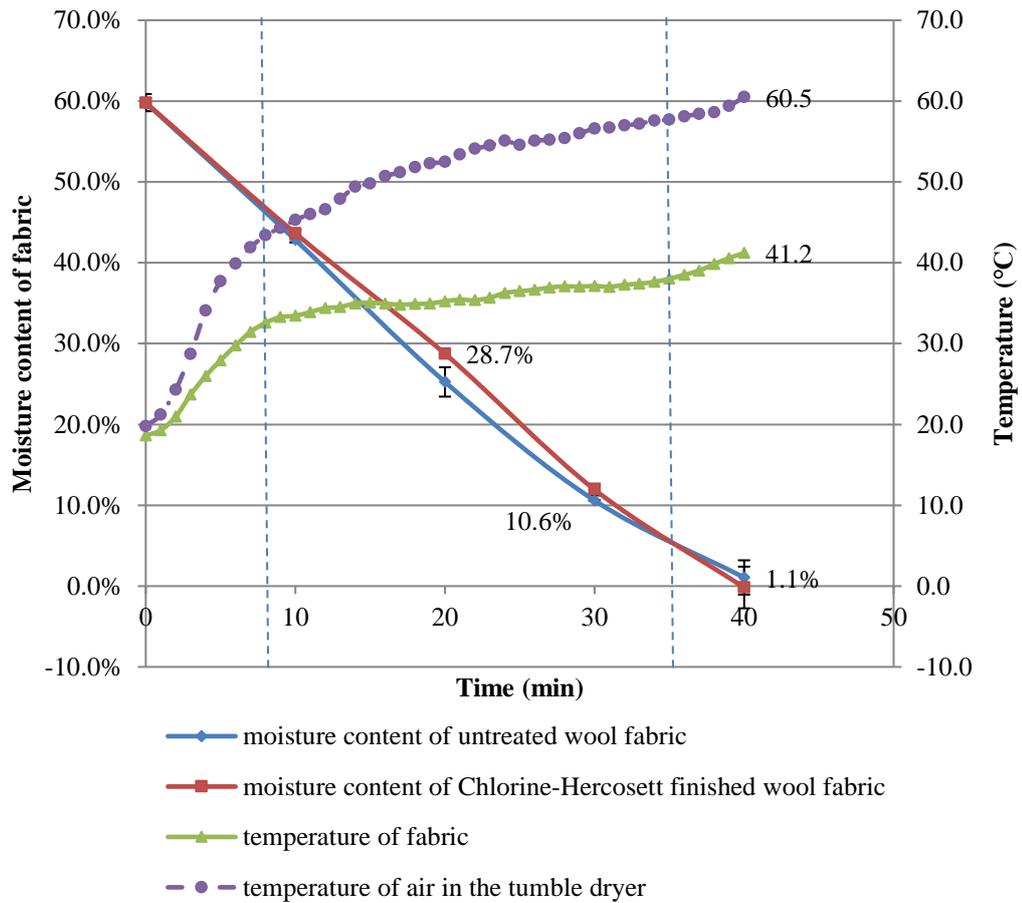


Figure 4 The moisture content of fabrics and the temperature of fabrics and air in the tumble dryer at different drying times in the process of a 40-min drying program.

3.2 Dimensional shrinkage

Tumble drying of wool fabrics, as compared to flat drying, could result in higher shrinkage in the wale direction but a lower degree of growth in the course direction.²¹ Length change and area change of untreated and shrink-resist-finished wool fabrics at different drying times are given in Figure 5. The trends of area changes for both fabrics were similar to their length changes. As expected, the shrinkage of the untreated wool fabric was much higher than that of the Chlorine-Hercosett-finished wool fabric.

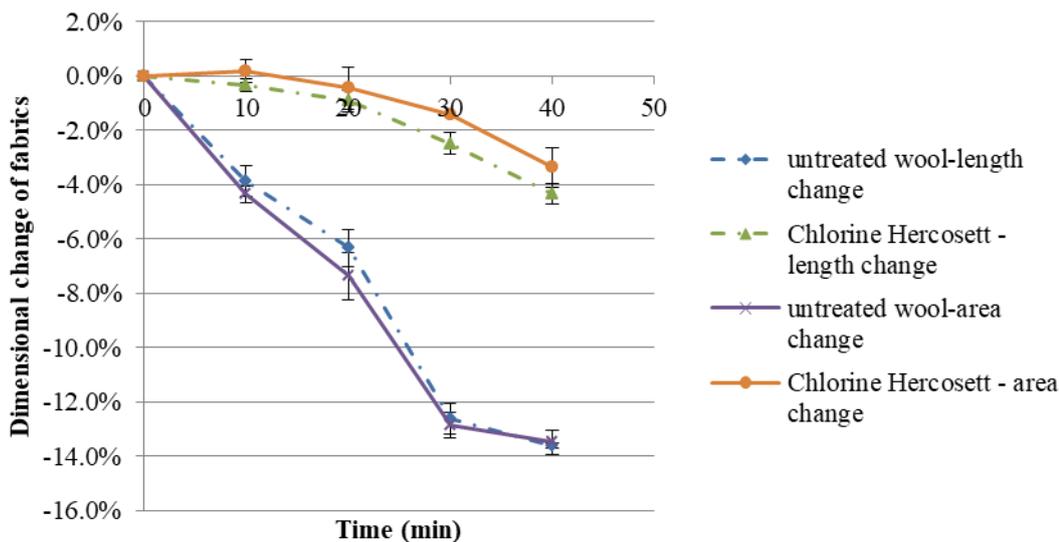


Figure 5 Dimensional change of fabrics in different drying-time programs.

Tumble drying of untreated wool fabric under a normal drying cycle caused significant area shrinkage. The rate of decrease in the area dimension of the untreated wool fabric was constantly higher in the first 30 minutes, in which moisture content on wool fabric was more than 10%. This is mainly due to felting shrinkage of the untreated wool fabric. In the process of tumble drying, temperature, moisture content and mechanical force could affect the felting shrinkage. With a further 10-min drying at a higher temperature, the shrinkage of untreated wool fabric was smaller. In the current study, the rate of agitation was kept constant, so it is not mechanical force that caused the smaller rate of dimensional change in area shrinkage from 30 to 40 min. In this 10-min period, the fabric temperature went up from 37.1 to 41.2 °C and the moisture content of untreated wool fabric went down from 10.6 to 1.1%. The previous researches found the rate of felting of an untreated wool fabric in buffer solutions increased with increasing temperature until a maximum rate of felting was reached at above 40 °C.^{6,7} It was believed that temperature is a minor factor for felting in laundering.¹² For moisture content, it was found from the previous study that area shrinkage was shown to be appreciable in milling when water addition exceeded 10% on the mass of conditioned wool.¹⁴ However, unlike these environmental conditions, in tumble-drying process, the temperature and moisture of fabric changed with time and there was little chemical

reagent in the water or on fabrics; previous findings could not be used directly to explain the shrinkage behavior during tumble drying. From the current research, it was found that the rate of felting shrinkage could be directly related to the moisture content in the wool fabric.

Temperature and moisture could influence the fiber properties including Hookean modulus and relative rigidity,²² which have significant effect on the shrinkage rate of untreated wool fabric.²³⁻²⁵ Pierlot pointed out that felting shrinkage is related to glass transition temperature (T_g). At the glass transition temperature, large changes in the mechanical properties of the wool fiber are known to occur, which influences felting.²⁶ The temperature at which this transition occurs depends on the water content of the fiber, since water acts as a plasticizer.²⁷ Dependence of the glass transition temperature of wool on regain of moisture has been shown in the reference.²⁷ T_g decreases with the increasing regain, from 167°C for dry fiber to -15°C when wet.²⁷

The moisture regain of the untreated wool was calculated assuming all the water resided in the wool, and the regain of untreated wool fabric after preconditioning at the temperature of 20°C and relative humidity of 65% was around 14%. From 30 to 40 min of drying process, the moisture regain of untreated wool fabric was reduced from 25 to 15% approximately. In the last few minutes of drying, due to the decrease of regain, the temperature of fabric did not reach T_g . So the rate of change of felting shrinkage decreased.

Different from the untreated wool, the trend of the dimensional change of the Chlorine-Hercosett-finished wool fabric was similar to that of cotton plain knitted fabric.²⁸ For the Chlorine-Hercosett-finished wool fabric, the rate of dimensional change in area increased when the fabric became drier. Especially, from 20 to 40 min of the drying process, there was a noticeable reduction in dimensional size, as moisture content fell below 30%.¹⁷ When water was removed from fibers during tumble drying, the presence of agitation could overcome inter-fiber and inter-yarn adhesions, thereby allowing yarn diameters to contract. As yarn diameters reduced and inter-yarn adhesions were overcome, further shrinkage was possible.²⁸

Felting is not reversible. Figure 6 shows the shrinkage of the untreated and the

shrink-resist-finished wool fabrics after three drying cycles. It was found that the shrinkage of the untreated wool fabric increased steadily after repeat washing and tumble drying. By considering the standard deviations shown in Figure 6, the dimension of Chlorine-Hercosett-finished wool fabric can be recovered slightly or remained after first cycle of washing and drying. The Chlorine-Hercosett finishing broke down surface scales of the wool fibers and covered the remaining scales with resin, therefore the dimensional change was not mainly caused by felting.

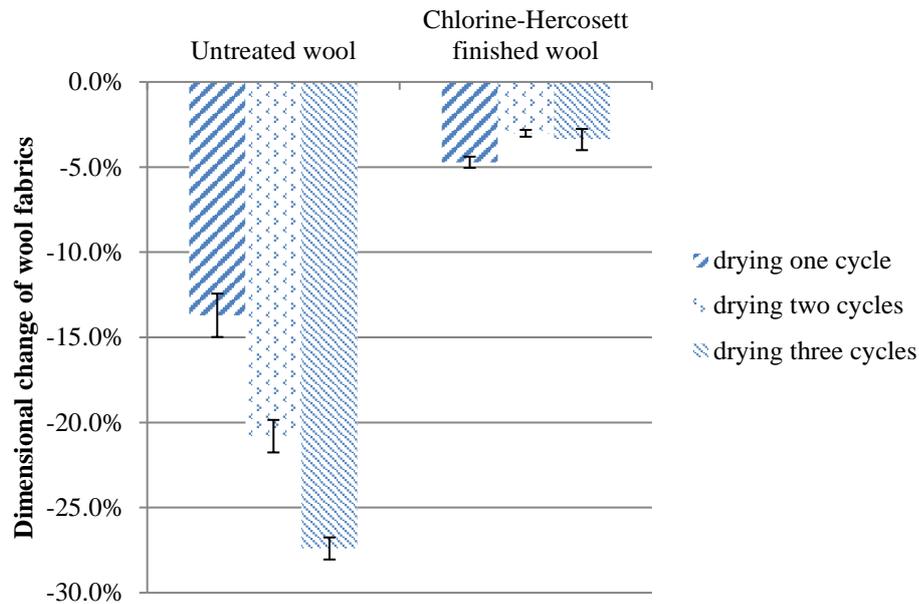


Figure 6 Length change of fabrics in different drying cycles (the drying time of each cycle is 40 mins). Vertical lines indicate standard deviation.

4. Conclusions

Shrinkage of wool fabrics during tumble drying causes a serious problem for garments. The dimensional changes of the untreated and shrink-resist-finished wool fabrics at different drying times were investigated to explore the shrinkage behavior and mechanisms in a drying process.

During the tumble drying for 40 min at the heater power of 3 KW and drum rotating speed of 50 rpm, the drying process of the wool fabric can be divided into three stages: rapid rise of fabric temperature (first stage), followed by a slow increase of temperature (second stage), with a sharp increase in fabric temperature (third stage).

The area shrinkage of the untreated wool fabric was slower in the last few minutes prior to complete drying of the wool fabric (third stage).

The shrinkage of the untreated wool fabric increased steadily after repeat washing and tumble drying, while the dimension of the Chlorine-Hercosett-finished wool fabric can be recovered or remained after the first cycle of washing and dry. For the untreated wool fabric, the felting was the main shrinkage during tumble drying. Due to modification of the surface scales of the fibers and further resin coating the shrinkage of the Chlorine-Hercosett-finished wool fabric was not mainly caused by felting but reversible shrinkage.

The finding from the current research provides further understanding of wool fabric shrinkage during tumble-drying process, leading to optimizing the wool fabric drying program in a tumble dryer for improved quality of wool garments.

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