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Design and Fabrication of Thermochromic Jacquard Woven Fabrics

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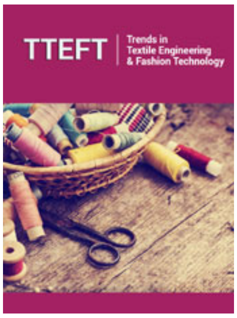

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Abstract

As a major category in textiles, jacquard woven fabrics always draw attention due to their exquisite patterns and brilliant colors. With the rapid development of smart textiles, it is possible to combine jacquard pattern design with functional or smart yarns to yield intelligent textile products with artistic values. To fulfil this goal, thermochromic jacquard woven fabrics have been developed and evaluated. The design process of thermochromic jacquard woven fabrics includes pattern design, weave structure design and process design. Three types of thermochromic jacquard woven fabrics with different weft densities and weave structures were fabricated. The effects of weft densities and weft float lengths on fabric breathability and thermochromic behavior were investigated. The results showed that the breathability of thermochromic jacquard woven fabrics decreased gradually with the increase of weft density and weft float length. Also, the color change time and color recovery time increased gradually with the increase of weft density and weft float length. The design and fabrication of the thermochromic jacquard woven fabric can provide a practical example for the development of smart fabrics with aesthetic values.

Keywords: Jacquard woven fabric; Pattern design; Weaving; Breathability; Thermochromic behavior

Introduction

As a traditional Chinese textile craft, jacquard woven fabric made of silk has been well known worldwide. Jacquard woven fabrics are fabricated by colorful yarns that are interlaced with designated weave structure to form exquisite patterns. Jacquard woven fabrics have high artistic effects; therefore, they are widely used in fields such as garments, home textiles and decorations, etc.

In recent years, the development of functional or smart textiles stimulates a dramatic increase in the customers' demand for diversified, functional or intelligent jacquard woven fabrics, which in turn promotes the research and development of jacquard woven fabrics [1]. For example, Kang et al. [2] fabricated jacquard woven fabrics with 60/25/15 wool/rabbit fleece/cashmere to achieve good moisture absorption, warmth, smoothness, elasticity and softness at the same time. Fan et al. [3] used coffee charcoal fiber to develop jacquard woven fabrics with multi-functionalities such as anti-bacterial and anti-odor, anti-ultraviolet (UV) light, far-infrared emission and negative ion health care. Zhai et al. [4] developed a wrinkle-resistant silk jacquard fabric by interweaving polytrimethylene terephthalate (PTT) shape memory yarns with silk yarns. Yu et al. [5] employed plastic optical fiber as weft yarn in jacquard weaving process to produce luminous jacquard fabric with tunable pattern colors. Among these functional textiles, reversible color-changing fabrics can effectively demonstrate the aesthetical value of jacquard woven fabrics with beautiful patterns when they are potentially used as recreational clothing and anti-counterfeit signs [6,7], etc.

Based on the color-changing mechanisms of the fibers, they can be divided into several types such as stress-induced color-changing fibers, photochromic fibers, thermochromic fibers and electrochromic fibers, etc. [6] Generally, stress-induced discoloration requires external forces to cause the deformation, photo-induced discoloration requires the exposure of the fabric to UV light, whereas electro-induced discoloration requires the application of an electric field [6,8]. These conditions that trigger discoloration often cause fabric deformation or aging, which reduces the service life of the fabrics. In comparison, thermochromic yarns can better meet the ends to increase jacquard woven fabrics' artistic value without severely damaging the fabrics.

Currently, the research and development of thermochromic fibers/yarns in textiles are not quite extensive. Hao et al. [9] obtained cholesterol liquid crystal microcapsules by in situ polymerization, which exhibited dense shell structure, smooth spherical surface morphology and good thermochromic properties. Li et al. [10] microencapsulated the thermochromic compound within fiber structure and prepared the thermochromic fabrics with reversible color change property. The fabricated fabric still possessed a high color change sensitivity even after 6 months. Li et al. [11] produced thermochromic fibers by wet spinning and wove them into fabrics. The fibers exhibited excellent color change stability even after 8000 thermal cycles. Based on these works, it is possible that thermochromic fibers/yarns can be used in jacquard woven fabrics.

To illustrate the thermochromic behavior of fabrics with exquisite patterns and ever-changing color, it is necessary to obtain thermochromic jacquard woven fabrics. In this work, thermochromic jacquard woven fabric is designed and developed with thermochromic yarn as the weft yarn system. The thermochromic jacquard woven fabrics with different specifications have been fabricated to investigate the effect of weft density and weave structure on the breathability and thermochromic behavior of the jacquard woven fabrics. The interaction of the fabrics with the ambient temperature will draw more attention on the development of intelligent fabrics with artistic values that can be potentially used as home textiles such as curtains, sheets, etc. to directly indicate the temperature fluctuation with the visual color change of the fabrics.

Experimental Section

Materials

The weft yarn is a 15 tex × 2 polyester thermochromic yarn (purchased from Lumia Co., China), which changes between the orange and yellow colors. The microencapsulated thermochromic powders in the yarn cause the color change of the yarn reversibly when the temperature changes. The critical temperature [6] to initiate the color change of the yarn is 31 °C. The warp yarn is a 16.7 tex polyester yarn.

Pattern Design

The design of jacquard woven fabrics includes two sections, which are pattern design and weaving design. The pattern design is achieved by CorelDRAW software. Later, plan of weave was obtained by Computer Aided Design (CAD) (ZDJW Ltd. Co., China) software. This process includes different steps such as the design of the weave repeat, the designation of warp and weft densities, color separation, the arrangement of picking order, the design of weave structure and the generation of electronic jacquard card for weaving [1].

As shown in Figure 1a, the pattern of jacquard woven fabrics in the work has the characteristics of simplicity. This pattern employs fallen leaves as the theme. The poet Zizhen Gong from Qing Dynasty once wrote: The fallen petals, in return, will transform into soil to nourish the flower in spring. Thus, fallen leaves are used here to express the spirit of selflessness and dedication in Chinese culture. There are totally five colors in the designed pattern. Each color block corresponds to one specific weave structure, which will be discussed later. It should be noted that the fallen leaf patterns have four different color blocks. The red and blue blocks are twill weave structures with two different floating lengths. Orange and green blocks represent two different satin weave structures. With each color block representing weave structures with different float lengths, it is easier to observe the effect of the weave structure on the thermochromic behavior of the fabric.

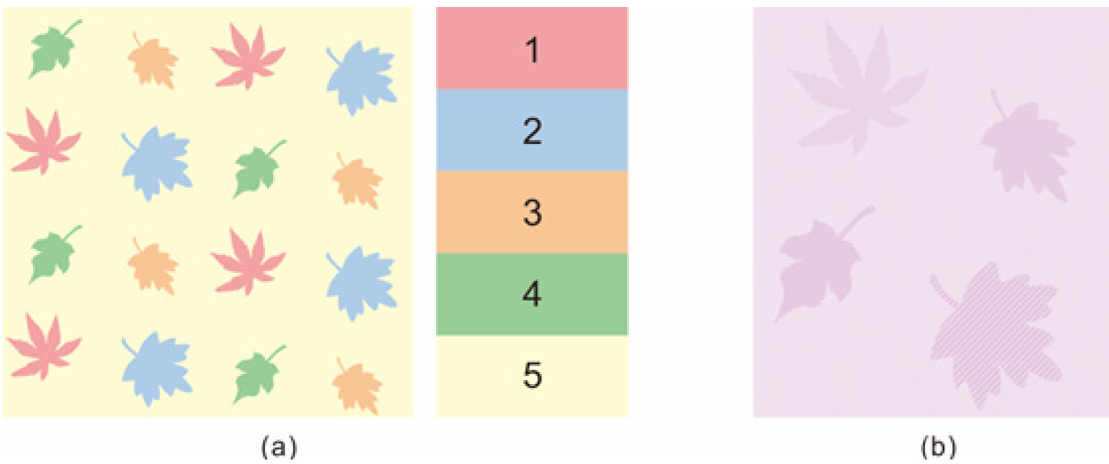
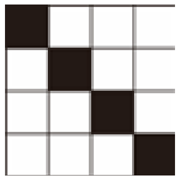
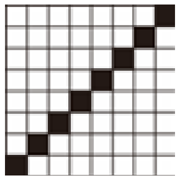
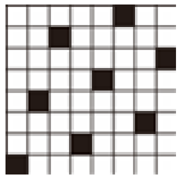
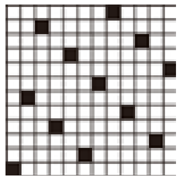
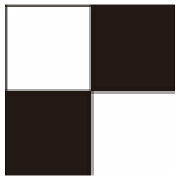


Figure 1: (a) The designed pattern of thermochromic jacquard woven fabric with five color blocks and the corresponding (b) plan of weave.

Figure 1b demonstrates the plan of weave, which indicates different elements of the designed patterns. Each element has different weave structures, which will be discussed later.

Design of weave structure

Table 1: Different pattern elements and their corresponding color blocks and weave structures.

Pattern Element	Color Block	Weave Structure
Red leaf	1	 1/3 LHT
Blue leaf	2	 1/7 RHT
Orange leaf	3	 8/3 Weft-faced satin
Green leaf	4	 12/5 Weft-faced satin
Background	5	 Plain weave

In this work, one type of warp yarn and one type of weft yarn were used for the development of thermochromic jacquard woven fabrics. Four basic weave structures were employed to indicate the thermochromic effect of the leaf patterns. The relationships of pattern elements and color blocks (Figure 1) with correspondingly designed weave structures are summarized in Table 1. No. 1-4 color blocks represent different shapes of leaves in the pattern and they are formed of 1/3 left hand twill (LHT), 1/7 right hand twill (RHT), 8/3 weft-faced satin and 12/5 weft-faced satin respectively. The weft float in the twill weave structure of No. 2 color block is more than twice that of twill weave structure in No. 1 color block. Similarly, satin weave structure in No. 4 color block has much longer weft floats than the satin weave structure in No. 3 color block. The purpose of designing weave structures is to better differentiate the thermochromic behavior of weave structures with different weft floats. And No. 5 color block consists of a tight plain weave structure serving as a background.

Fabrication

Three types of thermochromic jacquard woven fabric samples with weft densities of 240, 360 and 480 pick/10cm, respectively, were successfully fabricated and labeled as sample A, B and C, respectively. The specifications for the fabrication of the thermochromic jacquard woven fabrics are shown in Table 2. The digital photographs of sample fabric before and after temperature-induced coloration are demonstrated in Figure 2. It was observed that the leaf pattern in the sample fabric showed an orange color when temperature is at room temperature (<31℃). When the fabric sample was heated with hot air to reach a temperature higher than 31 ℃, the orange leaf pattern with thermochromic weft yarn floats on the fabric surface clearly turned into yellow color. The background of the fabric also experienced color change as the temperature changes. However, the color change is less significant in the background than the leaf pattern. This is because the plain weave structure that serves as the background of the fabric has much shorter weft floats than the leaf pattern, corresponding to No. 2 color block.

Table 2: The specifications for different thermochromic jacquard woven fabrics.

Sample	A	B	C
Warp yarn (16.7 tex)	100% Polyester yarn		
Weft yarn (15 tex × 2)	Polyester thermochromic yarn		
Warp density (pick/10cm)	540		
Weft density (pick/10cm)	240	360	480
Thickness/mm	0.469±0.039	0.454±0.041	0.494±0.070
Weaving machinery	SGA598 Jacquard Weaving Machine (Tongyuan Textile Machinery Ltd. Co., China)		
Reed	Reed count: 136 # (metric)		End per dent: 4
Number of needles	2688		
Fabric width	Usable width: 46cm		Overall width: 50cm

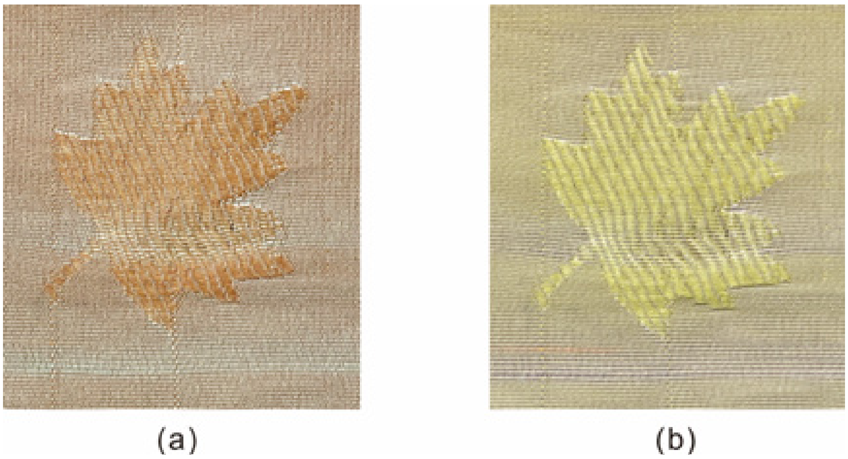


Figure 2: The fabricated thermochromic jacquard woven fabric sample with the weft density of 240 pick/10cm (a) before (<31 °C) and (b) after (>31 °C) color change.

Performance measurement

As shown in Table 2, three types of thermochromic jacquard woven fabrics were named as sample A, B and C in the order of the smallest to the largest weft density. Fabric breathability and thermochromic behavior of each fabric sample were measured.

Fabric breathability testing: Fabric breathability testing was conducted by YG461G automatic air permeability meter, in accordance with the standard GB/T5453-1997. In each fabric sample, weave structures of 1/3 LHT, 1/7 RHT, 8/3 weft-faced satin and 12/5 weft-faced stain were tested. The test pressure was 100Pa and the test area was 20cm^2. The nozzle aperture of sample A and B was Φ 6.0 mm, and that of sample C was Φ 4.0mm.

Evaluation of thermochromic behavior: To evaluate the thermochromic behavior, the jacquard woven fabric specimen was placed at room temperature (25 °C) with a UV lamp (power 6-8W) serving as a heat source, which was stationed 5cm away. The test procedure is as follows: the fabric sample was placed under the UV lamp, and the timing started immediately as the UV lamp was turned on to heat up the fabric. The color-changing process of the fabric pattern from orange to yellow was observed. Timing was stopped when the fabric sample no longer changed color. This duration is the fabric color change time. Later the UV lamp was turned off and time was recorded again until the fabric color returned from yellow to orange completely. This duration is defined as the fabric color recovery time. Each type of fabric sample was measured three times for color change time and color recovery time, respectively.

Result and Discussion

Fabric breathability

The effects of weft density and weave structure on the breathability of jacquard woven fabrics have been investigated in this section. Figure 3 demonstrates the fabric breathability of thermochromic jacquard woven fabrics with different weft densities. In Figure 3a, breathability of twill weave part (1/3 LHT) in sample A, B and C gradually decreased from 536.05 to 358.74L•m^{-2}•s^{-1} as the weft density increased from 240 to 480 pick/10cm. Similarly, with twill structure of 1/7 RHT, decreasing trend of fabric breathability was observed: it decreased from 885.35 to 529.50L•m^{-2}•s^{-1} when the fabric weft density went up from 240 to 480 pick/10cm. It was observed that at the same weft density or within the same fabric sample, the breathability of 1/7 RHT was always higher than 1/3 LHT. For instance, in sample B (weft density of 360 pick/10cm), the breathability of 1/7 RHT was 837.26L•m^{-2}•s^{-1}, which was greater than that of 1/3 LHT (429.43L•m^{-2}•s^{-1}). This indicates that fabric with longer weft floats (1/7 RHT) has a smaller number of interweaves and looser structure, thus more air penetration of the fabric.

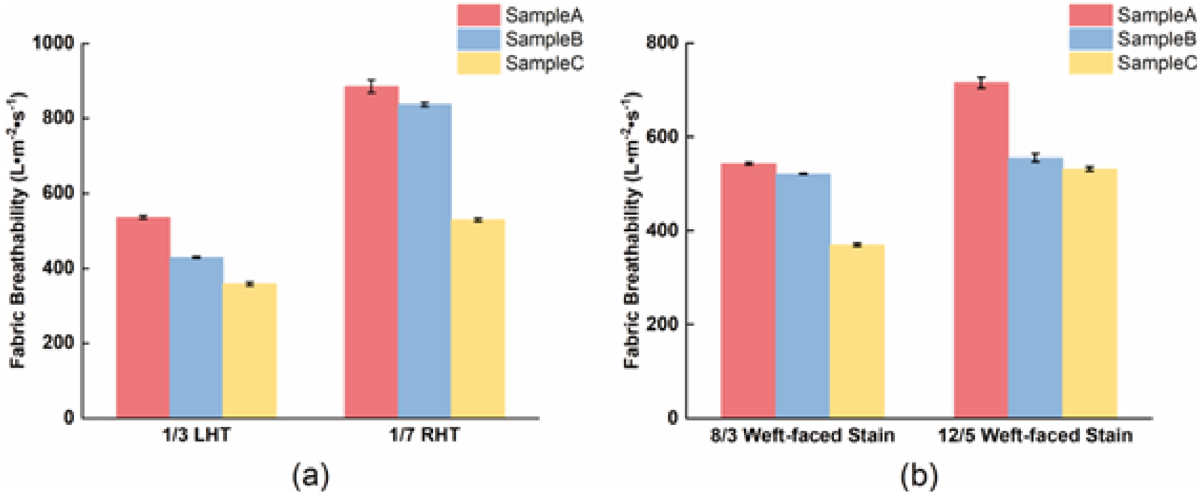


Figure 3: Fabric breathability of (a) twill weave and (b) satin weave structures in three samples with different weft densities.

In Figure 3b, with the increase of fabric weft density (from sample A to C), the breathability of each satin weave structure (both 8/3 weft-faced satin and 12/5 weft-faced satin) also became smaller. In the same fabric or when the weft density was same, breathability of 12/5 weft-faced satin was always higher than that of 8/3 weft-faced satin. Thus, it can be concluded that the larger the weft density of the fabric, the worse breathability; the longer fabric weft floating length, the better breathability.

Thermochromic behavior of jacquard woven fabrics

The influence of the weave structure and weft density on the thermochromic behavior of jacquard woven fabrics has been investigated in this section. The color change time and color recovery time of all measured samples with different specifications is shown in Table 3.

Table 3: Color change time and color recovery time of fabric samples with different specifications

Sample	Weft Density (pick/10cm)	Observed Weave Structure	Color Change Time (s)	Color Recovery Time (s)
A	240	1/3 LHT	13±1.0	53±17.1
		1/7 RHT	14±0.9	65±6.3
		8/3 Weft-faced satin	16±1.9	74±3.3
		12/5 Weft-faced stain	20±1.6	78±9.7
B	360	1/3 LHT	13±0.7	60±1.7
		1/7 RHT	15±1.0	74±4.6
		8/3 Weft-faced satin	18±1.4	102±11.1
		12/5 Weft-faced stain	23±1.2	85±3.0
C	480	1/3 LHT	14±1.8	88±6.3
		1/7 RHT	20±1.5	88±3.0
		8/3 Weft-faced satin	20±1.7	122±10.0
		12/5 Weft-faced stain	24±0.8	141±10.6

To better visualize the results, a comparison of the coloration time and color recovery time of four weave structures (1/3 LHT, 1/7 RHT, 8/3 weft-faced satin and 12/5 weft-faced satin) within three types of fabric samples is shown in Figure 4. In Figure 4a, the average coloration time of 1/3 LHT weave structure in sample A, B and C was 13, 13 and 14 s, respectively. The average color recovery time of fabric pattern with 1/3 LHT in sample A, B and C was 53, 60 and 88 s, respectively. With increased weft density of the fabric, the coloration time of 1/3 LHT was close while the color recovery time of fabric pattern with this weave structure was significantly prolonged. In Figure 4b, the increasing trend in color change time was more obvious in 1/7 RHT weave structure as the weft density increased from 240 to 480 pick/10cm: 14, 15 and 20 s, respectively. The color recovery time also had the same increasing trend, which was 65, 74 and 88 s, respectively, for sample A, B and C.

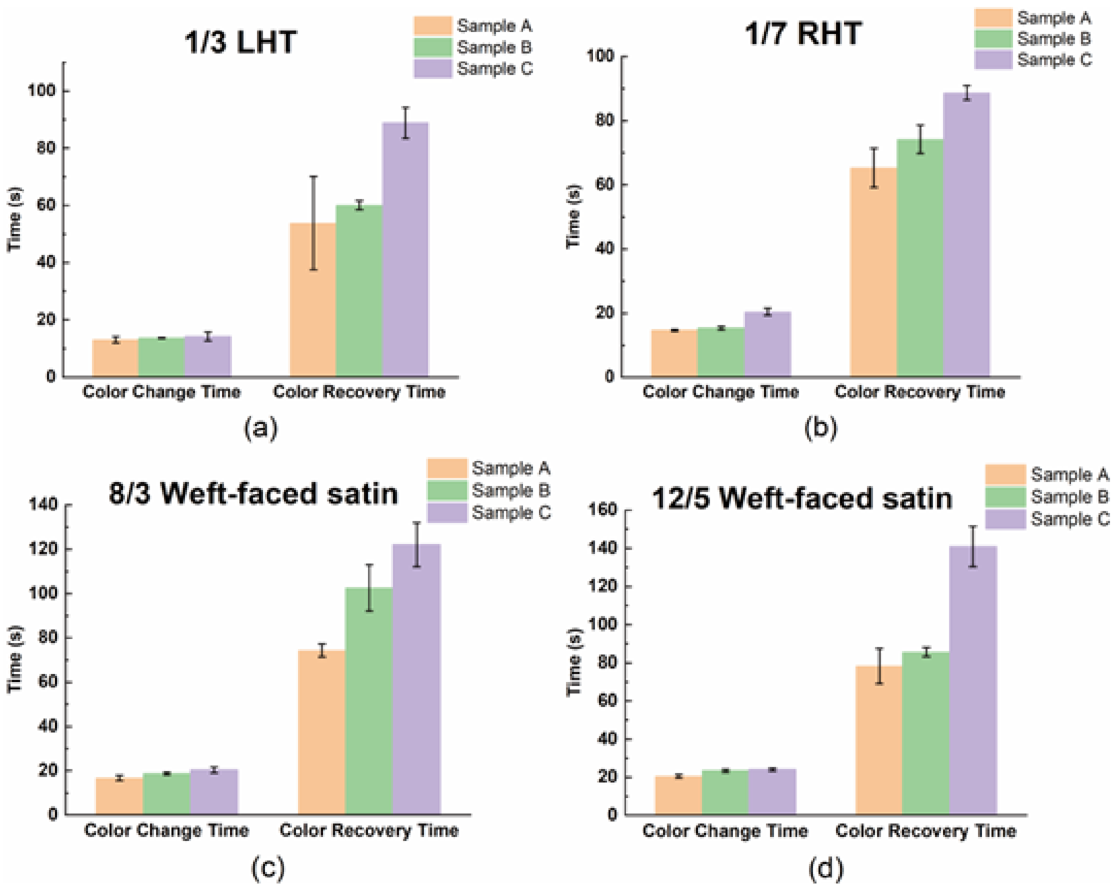


Figure 4: Color change time and color recovery time of (a) 1/3 LHT, (b) 1/7 RHT, (c) 8/3 weft-faced satin and (d) 12/5 weft-faced satin weave structures within three samples.

In Figure 4c, the coloration time of 8/3 weft-faced satin weave structure in three samples was 16, 18 and 20 s, respectively. The color recovery time of fabric pattern with this weave structure was prolonged:74, 102 and 122 s for sample A, B and C, respectively. In Figure 4d, a similar trend was observed for 12/5 weft-faced satin weave structure in sample A, B and C: the color change time was 20, 23 and 24 s, respectively, and the color recovery time was 78, 85 and 141 s, respectively.

Based on Figure 4, it can be concluded that when the weave structure is the same, the increased weft density results in longer color change time and color recovery time. The jacquard woven fabrics with larger weft density are with more thermochromic weft yarns in unit area, implying that the weft yarns are more closely packed and the fabric surface area exposed to UV lamp for heat absorption is less. Thus, it takes longer time for fabrics with larger weft density to reach the critical temperature of 31 °C to initiate color change process, corresponding to longer coloration time.

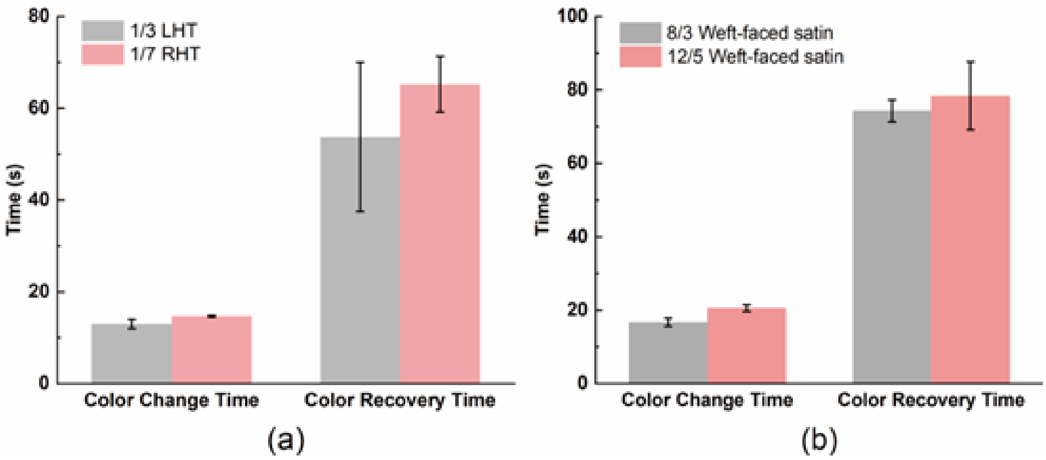


Figure 5: Thermochromic behavior of (a) twill and (b) satin weave structures with different float lengths in fabric sample A with a weft density of 240 pick/10cm.

To better demonstrated the influence of float length on the thermochromic behavior of fabrics, the color change time and color recovery time fabric patterns with different structures of twill and satin weave in sample A (weft density of 240 pick/10cm) were depicted in Figure 5. In Figure 5a, with twill weave structure, the color change time and color recovery time of 1/7 RHT are always more than those of 1/3 LHT in the same fabric. In Figure 5b, with satin weave structure, both the color change time and color recovery time of 12/5 weft-faced satin are longer than those of 8/3 weft-faced satin. With longer weft floats, color change time and color recovery time are also extended. This is because longer weft float in the fabric pattern of the same fabric often absorbs more heat energy by the thermochromic weft yarns, and it also takes more time to release heat during the cooling process to reach the critical temperature and return to its original color.

Conclusion

Jacquard woven fabrics play an important role in textile products, and the development of thermochromic jacquard woven fabrics will motivate more creation of fabrics with high technological and artistic values. This work incorporated thermochromic property into jacquard woven fabrics to enable the color change of fabric pattern at different temperatures and added more technological value to the artistic fabric. Thermochromic jacquard woven fabrics can be potentially used in homes textiles such as curtains, bed sheets, etc., and fashion apparel to indicate ambient temperature change. Moreover, the effects of weft density and weave structure on the breathability and thermochromic properties of the fabrics were investigated. The research results have practical implications for the innovation of high-quality thermochromic smart textiles with artistic value.

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Conflict of Interest

The authors declare no conflict of interest.

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