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Effect of surface modification on the dynamic heat and mass transfer of wool fabrics

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ABSTRACT

Surface functionalization of fibers is widely used to grant performance or functions to textiles. Modified textile surface, with different morphology and wettability together with different thermal conductivity, has a profound effect on the wellbeing of wearer, because the thermal and moisture transfer of the surface-modified textiles in dynamic moving conditions is totally different to unmodified ones. To benefit the design of performance/functional textiles with enhanced wellbeing of wearer, it is important to understand the dynamic thermal and mass transfer of textiles before and after surface modification. Using wool as a sample fiber, this work reveals the effect of typical surface modification on the dynamic thermal and moisture transfer of wool fabrics. It has been found that the surface characters of wool fiber change after surface modification with etched and peeled off scales, enhanced water absorbing capacity and wettability. The surface temperature of modified wool fabrics was lower than pristine wool fabrics when attaching to a rotating hotplate with a temperature of 35 °C, resulting in a lower energy consumption of the hotplate and enhanced warmth retention rate. Modified wool fabrics took longer time to accomplish the dynamic moisture transfer process with a longer stage three in the transfer cycle. This work will provide insights on how the surface of fiber affects the dynamic thermal and moisture transfer of textiles, which will further benefit the development of functional/performance clothing with its comfort well maintained.

1. Introduction

Surface of fiber plays an important role in determining the function of fibrous materials and the wellbeing of the wearers. Most of the fabrication and application of fibrous materials are surface and interfacial phenomena. For instance, the fabrication from fiber to fabric involves the interaction between fibers and yarns, yarns and sizing materials, fibers and dyes or other finishing materials. The surface characters of fiber or yarn, such as the morphology, affinity, hydrophobicity, chemical activity, coated components and/or other added materials, greatly affect the properties and functions of their final products. The properties and function of clothing, including handle, esthetic traits and comfort, and protection against different threats and media, are thus determined by the surface of fibrous materials and their interfacial properties with air, water and human skin. Engineering the surface of fibers with desired functions or performance has been well-developed. Many products, especially protective clothing and

performance apparels are successfully developed. Even though these products serve well for the purpose of protection or functions, the comfort of these products together with the wellbeing of wearers have always been neglected or considered as unimportant. In fact, the wellbeing of wearer determines the work efficiency and in some extreme cases the safety of workforce, the comfort of the protective/performance textiles should be investigated after surface modification of fibers during their fabrication stage. Understanding the surface and interfacial characters of fiber is thus important in benefiting the development of next-generation textiles with performance and functions, but also in maintaining the wellbeing of human in the interaction of clothing-skin-environment.

Wool fiber has a special surface, and by which most of its properties are determined. Especially the existence of scales on the surface of wool fibers has brought wool fabrics itchy handle, surface hydrophobicity, felting and shrinking (Simpson and Crawshaw, 2002). Because of these properties, there are challenges in manufacturing wool products with

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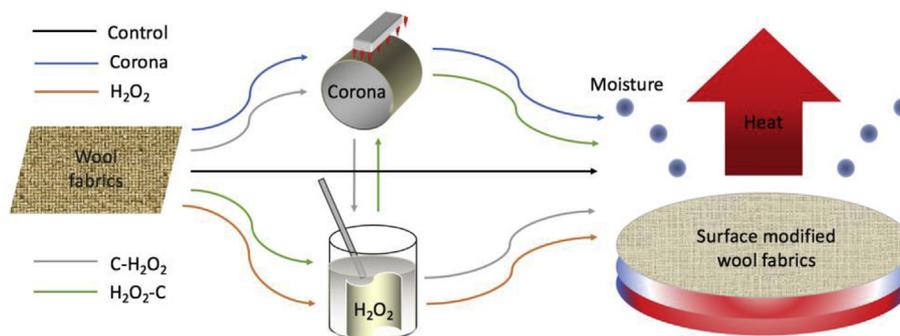


Fig. 1. Schematics of surface modifications and dynamic thermal and mass transfer.

excellent dimensional stability, good handle and excellent next-to-skin comfort. Surface modification of wool is widely applied in clothing for various reasons including shrinkproofing, moisture management, protection and performance. To be specific, surface treatment with chlorine to peel off or damage scales of wool fibers results in shrinkproofing fabrics; surface coating with resin will greatly hamper the directional movements of wool fibers (Simpson and Crawshaw, 2002); surface oxidation of wool fibers will enhance its hydrophilicity and wettability (Wang et al., 2009a); corona discharge modified wool surface shows a range of changed surface properties (Ke et al., 2008). It is evident that surface modification is necessary to bring functions or performance to wool products. However, with a modified surface on wool fibers, the comfort of them is altered inevitably as the thermal and moisture behavior of the modified fibers is totally different than untreated fibers.

The comfort of textiles is largely determined by the thermal and moisture behavior of the surface of fiber (Pan and Gibson, 2006; Song, 2011). The thermal conductivity, water absorbing capacity, wicking and moisture transfer properties of fabrics change a lot after surface modification, thus the comfort of the surface modified wool is expected to be totally different. Traditionally, comfort of textiles was objectively characterized by the thermal and moisture resistance/transfer in a static condition (Song, 2011; Huang, 2006). The wellbeing of human in contact with textiles was also subjectively analyzed by handle, stiffness. Manikin was also developed to mimic human with clothing, even though the mechanism together with measuring process was quite complex (Fan and Chen, 2002). With a focus on the very surface of textiles and their interfacial phenomena with microclimate near them, the surface thermal and moisture behavior (Li et al., 2013; Wang et al., 2014) together with electric conduction (Wang et al., 2009b) were characterized in static conditions. Besides, the thermal and moisture behavior of textiles in movement were also studied so as to understand their role in the clothing-skin-environment system (Li et al., 2018, 2019), and related characterization method was established (Li et al., 2016).

Previous work has revealed that surface modified wool fabrics exhibited quite a different surface thermal and moisture behavior of their surface, especially the thermal and moisture resistance together with the surface temperature and humidity changed a lot (Wang et al., 2015). In real application of wool as clothing, the fabric is subject to a complicated surface and interfacial thermal and moisture behavior, and the overall thermal and moisture behavior on the surface of fibers and within the fibrous system together with interfacial behavior within the liquid-fiber-air system will result in a dynamic thermal and moisture transfer. This dynamic thermal and moisture transfer determines the wellbeing of wearer directly, and it is highly affected by the intrinsic properties of fibers, the fibrous structure and the complex surface factor. The dynamic thermal and moisture transfer of wool fabric will be totally different since the modification of the surface of wool fibers has changed the intrinsic properties of wool, the fibrous structure and

the surface of fiber and the interfacial characters in between fibers. This work answers how the surface modification affects the dynamic thermal and moisture transfer of wool fabrics. Typical surface modification methods for wool fabrics were selected and the dynamic thermal and moisture transfer of the modified wool fabrics were tested. This work will reveal the complex surface and interfacial thermal and moisture transfer within wool fibrous system.

2. Experimental

2.1. Materials

Wool twill fabrics (serge, 200 g/m²) were provided by the No.3 Wool Factory, Lanzhou, China. All the samples were washed in deionized water, then dried and conditioned at a conventional condition (temperature 20 °C and relative humidity 60%). Hydrogen peroxide (30%), sodium carbonate and sodium silicate (chemical grade) were purchased from Shanghai Chemical Reagents Co. Ltd. Shanghai, China.

2.2. Preparation and treatment

The experimental design is schematically illustrated in Fig. 1, in which different surface modifications are conducted on wool fabrics and the dynamic thermal and mass transfer of these treated fabrics are analyzed.

Corona discharge was performed on a 6-kW glow discharge generator (SDCD16-2-10, Dalian No. 9 Electronic, Inc., Dalian, China). The treatment was conducted in conventional condition with applied voltage of 12 kV. The fabrics were passing through the discharging zone between the PVC roller and the electric wires with a moving speed of 1 m/min. Samples were treated four times to ensure uniformity of the treatment.

Hydrogen peroxide treatment was conducted in an aqueous bath at 65 °C with a liquid-to-fabric ratio of 25:1. The bath contains 12% hydrogen peroxide, 0.2% (w/w) Na₂CO₃ and 0.7% (w/w) Na₂SiO₃. Fabrics were introduced into the aqueous bath under stirring for 1 h to ensure sufficient surface modification of wool fibers.

In the combined modification of corona discharge and hydrogen peroxide, wool fabrics were first treated with corona discharge as per the previous recipe followed by the hydrogen peroxide treatment, coded as C-H₂O₂. Alternatively, the wool fabrics were first treated with hydrogen peroxide followed by corona discharge treatment, coded as H₂O₂-C.

2.3. Characterization and measurements

SEM photos were obtained from a scanning electron microscope (VAGE-3-SBH, TESCAN, Czech Republic). Samples were sputter coated with gold before observation, and the applied voltage was 15 kV.

Water contact angle was obtained on an OCA-20 DataPhysics

Instrument (GmbH, Germany). In the test, a drop of 1–1.5 μL water was dropped on the surface of fabric at an ambient temperature of 20 °C while photos of the droplet on the fabric were captured immediately.

Liquid moisture management properties were tested on an SDL Atlas Moisture Management Tester (MMT) according to AATCC Test Method 195–2012. The tested sample with the size of 80 cm \times 80 cm was put on the testing platform and a saline solution was placed on the top of the fabric. The droplet was then penetrating from the top to the bottom of the sample or staying on the sample, and MMT profile of the sample was reported on the associated computer.

In the dynamic thermal transfer test, a purpose-built apparatus (Li et al., 2016) was used to monitor the surface temperature on both sides of the fabrics and the energy consumption of the hotplate. The method was developed to mimic the situation of a moving body with clothing attached on the body. A hotplate with a heating device was developed to ensure a constant surface temperature of the hotplate during testing, and the surface temperature together with energy consumption were monitored all the time. In the test, a hotplate was mounted on the purpose-built apparatus to provide active heating, and the fabric was attached to the hotplate with a constant temperature of 35 °C while the data of temperature and energy consumption were recorded wirelessly (Li et al., 2016). The rotating speed of the hotplate was increased gradually after every 100 s.

In the dynamic mass transfer test, the fabrics were first immersed in deionized water followed by centrifugal drying to remove water on the surface of fabrics. The initial moisture regain of all the samples was 85% and the fabrics were attached onto the rotating hotplate with a constant speed of 2.51 m/s while temperature and energy consumption were recorded wirelessly (Li et al., 2016, 2019).

3. Results and discussion

Owing to the complex chemical structure and morphology of the surface layer of wool fibers, surface modification has direct effects on the thermal and mass transfer of wool fabrics. Surface modification directly alters the surface morphology and destroys and structure of the surface layer of wool fibers. The way water penetrates into fibers and transports through the fibrous structure is totally different after surface modification. Because the interfacial behaviors between wool fiber and environment (air, vapor and liquids) and even between neighboring fibers within the fibrous structure change greatly with a modified surface of fibers. Thus, different thermal and mass transfer of wool fabrics in a dynamic moving process is expected after surface modification.

3.1. Morphology

Surface morphology of wool fibers after typical physical modification, chemical modification and their combination was revealed by SEM photos, as shown in Fig. 2. Wool fiber shows the typical morphology with scales covering its stem (Fig. 2a). The profile of scales can be clearly seen with the tips of scales protruding from the stem of fibers. The special morphology of wool fibers determines most of the properties of wool fabrics, such as felting and shrinking when being subject to a force in wet conditions, movements of neighboring fibers due to the contacts between tips of scales, water repellency and itchy handle.

As a typical physical surface modification method, corona discharge has an evident etching effect on the surface of wool fibers. As a result, the tips of scales as seen in Fig. 2b are rounded as compared to pristine wool fibers, and this is in agreement with previous findings (Wang et al., 2009a). Furthermore, occasionally breakage of scales can be observed as per the SEM photos, which is probably due to the attacking of the high energy electrons ionized in the treatment process. As a whole, the surface of wool fiber becomes rough with rounded scale tips and occasional breakage of scales.

Chemical modification has more even effect on the surface of wool fibers as the treatment is usually happening in a bath with chemicals in

it. Hydrogen peroxide, as a typical bleaching agent for wool, has strong oxidation effect to wool surface with most scales heavily damaged and some scales removed (Wang et al., 2012). Fig. 2c shows some typical SEM photos of hydrogen peroxide treated wool fabrics. The profile of scale is not that clear as compared with corona discharge treated ones. The surface is smooth due to the severe damaging/removing of scales, and sometimes the debris of scales or partly peeled off scales can be seen. In the treatment of hydrogen peroxide, the perhydroxy form from hydrogen peroxide attacks the epicuticle of wool fiber (Wang et al., 2009a). The disulfide bonding of wool fiber is also attacked and ruptures by hydrogen peroxide, resulting in disulfide oxidation products including cysteic acid and intermediate sulfoxides (Wang et al., 2012).

The combination of physical and chemical surface modification has ended up with the similar morphology (Fig. 2d and e) to that of chemically modified surface (Fig. 2c), but the damaging/peeling off/etching effect is more evident than physically treated only or chemically treated only.

It is noticed that all the modifications are on the scale layer of wool fibers and the stem of fibers are preserved properly. From the SEM photos as shown in Fig. 2, the profile of fibers after modifications are clear with the lines of the scale beds visible. It is thus expected that the intrinsic properties of wool are preserved after surface modification, but just surface and interfacial behaviors will be changed. Wool fiber with a different morphology will result in different handle and serviceability of wool products. Since the scales are damaged and partly peeled off, the handle of the end products will be less itchy with shrinkproofing performance. As the intrinsic properties of wool are preserved, the elasticity of wool products is expected to be preserved as well.

3.2. Water contact angle

The breakage of scales creates tunnels for mass transfer. Surface hydrophobicity has been tuned into hydrophilicity and interfacial performance between fiber and water/moisture will be altered accordingly. A straightforward way to indicate the change is by measuring the water contact angle (WCA), as shown in Fig. 3a. Due to the hydrophobic nature of the surface layer of wool fiber, a WCA of roughly 120° was observed. The water repellency of wool fiber is due to the sulfur-rich resistant membrane in the epicuticle layer of scale with a high degree of crosslinking via disulfide and isodipeptide bonding (Wang et al., 2012).

Physical modification of wool fabrics has enhanced the water absorbency capacity of wool fabrics. It was reported previously that the water absorbing time for wool fabrics changed from more than 1800 s to around 1 s, and the wicking height enhanced from 0.5 cm to 5 cm (Wang et al., 2009a). Apparently, the wettability of wool fiber has been greatly enhanced after corona discharge treatment. Fig. 3a shows the WCA profile of corona discharge treated wool fabrics, and the WCA is around 60°. From the WCA, the interact of wool fiber with water has been greatly improved, and the fabrics can be defined as hydrophilic due to the enhanced wettability. The enhanced wettability of wool fiber after corona discharge is due to the change of morphology and structure of wool fiber. First, the etched scale with occasional holes create tunnel for water to penetrate inside the stem of wool fiber, which is highly hydrophilic due to the rich hydrophilic groups in the chemical structure of wool. Once the hydrophobic layer of scale is cracked, water will be absorbed into the stem of wool through those holes and cracks. Second, XPS analysis of corona discharge treated wool fabrics showed increased oxygen content and decreased sulfur content (Ke et al., 2008). Evidently, corona discharge has grafted oxygen rich hydrophilic groups onto wool fibers with the cracking of disulfide bonding, resulting in enhanced hydrophilicity of the treated wool fabrics.

Fig. 3a shows the WCA profile of hydrogen peroxide treated wool fabrics. The water droplet was absorbed and spread so fast that a WCA angle of around 20–30° could be obtained. The excellent wettability of hydrogen peroxide treated wool fabrics was noticed before and was

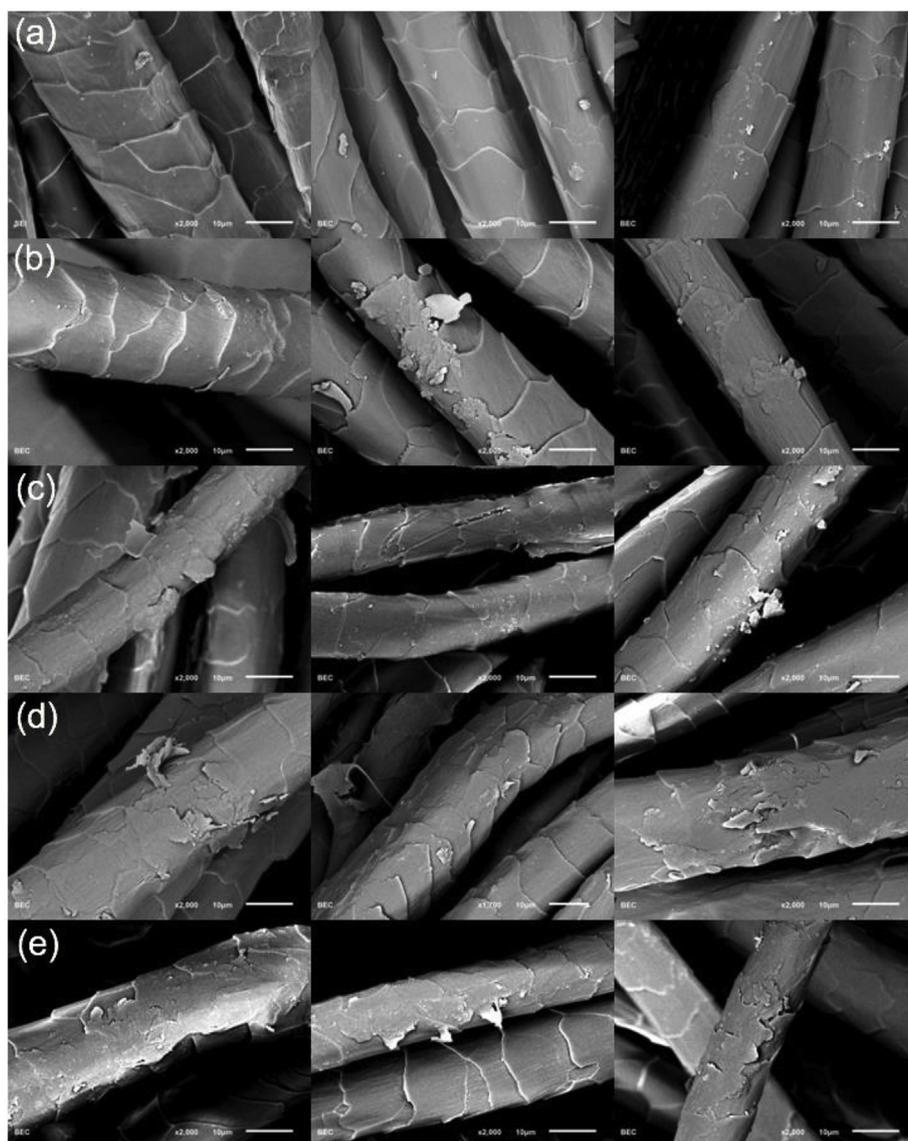


Fig. 2. SEM photos of untreated wool (a), corona discharge treated wool (b), hydrogen peroxide treated wool (c), corona discharge pretreated plus hydrogen peroxide treated wool (d) and hydrogen peroxide pretreated plus corona discharge treated wool (e). (Bar = 10 μm).

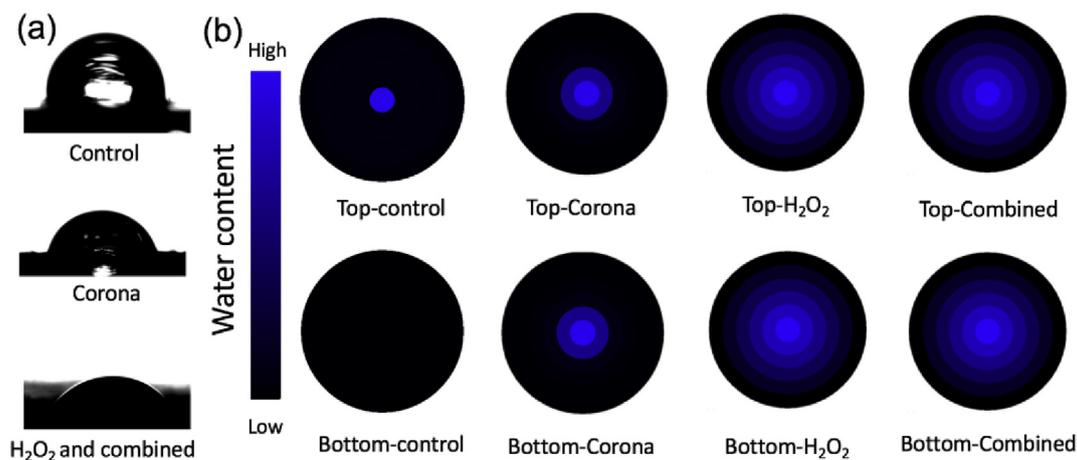


Fig. 3. Water contact angle (a) and MMT profiles (b) of wool fabrics before and after surface modification.

expressed as water absorbing time of less than 1 s and an enhanced wicking height of 12 cm (Wang et al., 2012). The wettability of wool fabrics after hydrogen peroxide treatment is the same as that of cotton fabrics, suggesting the water-like nature of the surface of the treated wool fabrics. It is apparent that hydrogen peroxide has greatly oxidized the disulfide linkage of cystine and peptide linkage of wool fibers with the scales heavily damaged and partly removed. Water has direct access to the stem of wool fibers due to the modified surface of wool fiber. Thus, quite a different interfacial contact as shown the WCA angle.

The wool fabrics treated by combined method of corona discharge and hydrogen peroxide show similar WCA profiles as that of hydrogen peroxide treated only. Apparently, once the fabrics are treated by hydrogen peroxide, excellent wettability with a fast water absorbing capacity will be granted to wool fabrics.

3.3. MMT profiles

Owing to the enhanced wettability and wicking properties, surface modified wool fabrics show enhanced moisture management properties. As shown the MMT profiles in Fig. 3b, the water droplet on the top surface of pristine wool fabrics shows as a sphere, whereas there is no droplet on the bottom side. As per the WCA of pristine wool fabrics, water cannot penetrate into the fibrous structure of wool fabrics, resulting in a droplet on the surface. It is evident that pristine wool fabrics are waterproof fabrics without water penetrating inside the fibrous structure. The MMT profiles for corona discharge treated wool fabrics show a large wet area on both sides of the fabrics, suggesting the water droplet spreads to some extent and the water penetrates into the fabrics. It is apparent that the moisture transfer properties of wool fabrics have been enhanced after corona discharge. The corona discharge treated wool fabrics have showed enhanced water absorbency with an enhanced wicking height (Wang et al., 2009a; Ke et al., 2008), suggesting that water can transport within the fabric structure.

Hydrogen peroxide has changed wool fabrics with different moisture management properties as per the MMT profiles in Fig. 3b. The water droplet spread quickly with the biggest wet area on the surface as compared with that of pristine and corona discharge treated wool fabrics. Meanwhile, the water penetrated swiftly to the other side of the fabrics, resulting in almost an identical wet area on the bottom side of fabrics. The different moisture management properties of hydrogen peroxide treated wool fabrics are due to their cotton-like water absorbing capacity and enhanced wicking properties. Water transports quickly and homogeneously within the fibrous structure of fabrics due to the enhanced water absorbing capacity of wool fibers after surface modification and the excellent capillary absorbing properties of the fibrous structure.

It is noticed that combined surface treatment has no evident impact on the MMT profiles of wool fabrics, and the treated wool fabrics show almost the same MMT profile as that of hydrogen peroxide treated wool fabrics. Hydrogen peroxide treatment has altered the wettability and wicking properties together with the interfacial contacts with water of wool fabrics to a satisfied level, further treatment of corona discharge has limited effect on the moisture management properties of wool fabrics. With the enhancement in wettability, the clothing from surface modified wool fibers are expected to absorb liquids/moisture such as sweat swiftly, granting the products with potential in next-to-skin clothing and sportswear.

3.4. Dynamic heat transfer

With the differences in the surface wettability and interfacial interactions with water, wool fabrics after surface modification show different heat transfer in moving conditions. Fig. 4a shows the surface temperature of wool fabrics during the dynamic heat transfer process with different rotating speeds. Owing to the enhanced wettability and wicking properties of fabrics, the equilibrium moisture regain of surface

modified wool fabrics are much higher than that of pristine wool fabrics. The moisture regain was tested as 14.5%, 15.3%, 16.8%, 18.4% and 17.9% for control, corona, H₂O₂, C-H₂O₂ and H₂O₂-C, respectively. Apparently, surface modification has resulted in more water absorbed into wool fabrics with larger moisture regains. In the beginning of the heat transfer test, wool fabrics were attached to the hotplate with a constant temperature of 35 °C. The heat of the hotplate was transferred immediately due to the thermal gradient between the hotplate and the environment. As a result, the surface of pristine wool fabrics showed a temperature of 32.1 °C. However, the surface temperature of surface modified wool fabrics was around 31 °C, as shown in Fig. 4a. As the water content in surface modified wool fabrics is higher than that of pristine wool fabrics and most of water is bonded with the hydrophilic groups of fibers, the moisture resistance of wool fabrics is increased after surface modification (Wang et al., 2015). Thus, the surface temperature of surface modified wool fabrics was always lower than that of pristine wool fabrics.

In the dynamic heat transfer, rotating speed has an evident effect on the surface temperature. The increase of rotating speed consolidated the thermal convection as the hotplate together with the fabrics were subject to strong passive wind. The dynamic heat transfer was then consolidated with the surface temperature of wool fabrics dropped immediately. Meanwhile, the energy consumption of the hotplate increased simultaneously with the increase of rotating speed (Fig. 4b). Because more heat was transferred to environment as a result of enhanced heat transfer, more energy was consumed to maintain the hotplate at the constant temperature of 35 °C. As shown in Fig. 4c, the power of the hotplate increases almost linearly with the increase of rotating speed.

Surface modification has played an important role in the dynamic heat transfer of wool fabrics. The energy consumption together with the power of hotplate are lower when the hotplate was covered with surface modified wool fabrics than with pristine wool fabrics, and this is especially the case when the rotating speed is high. First, as the thermal resistance of surface modified wool fabrics is higher than that of pristine wool fabrics, heat is easier to conduct through pristine wool fabrics and rotating further enhances the conduction. Second, the moisture inside of surface modified wool fabrics evaporates slower than pristine wool fabrics due to its stronger bonding with hydrophilic groups of fibers. The moisture resistance of surface modified wool fabrics has found to be higher than pristine wool fabrics (Wang et al., 2015). The evaporation of moisture will be consolidated under rotating, and thus more heat will be consumed for pristine wool to release more moisture. For this reason, the energy consumption and power for hydrogen peroxide treated are lower than that of corona discharge treated. In the end, the energy consumption and power of hotplate are much higher with increased gap under high speed as shown in Fig. 4b and c.

The warmth retention rate of different wool fabrics has been calculated accordingly as shown in Fig. 4d, and the sequence of the rate is pristine wool < corona discharge treated < hydrogen peroxide treated < combined. The sequence of warmth retention rate has found to the same as the sequence of equilibrium moisture regain and thermal resistance of surface modified wool fabrics. It is evident that the enhanced wettability and wicking properties of surface modified wool fabrics have resulted in their higher warmth retention rates. The enhanced warmth retention rate of surface modified wool fabrics is beneficial in designing sportswear. The energy consumption will be lower and the wear will feel warmer when wearing surface modified wool products. However, the surface temperature of the products will be slightly lower than untreated wool products.

3.5. Dynamic mass transfer

Fig. 5 shows the evolution of surface temperature of wool fabrics and the energy consumption of the hotplate in the process of dynamic mass transfer. The pattern of curves shows typical concave and convex

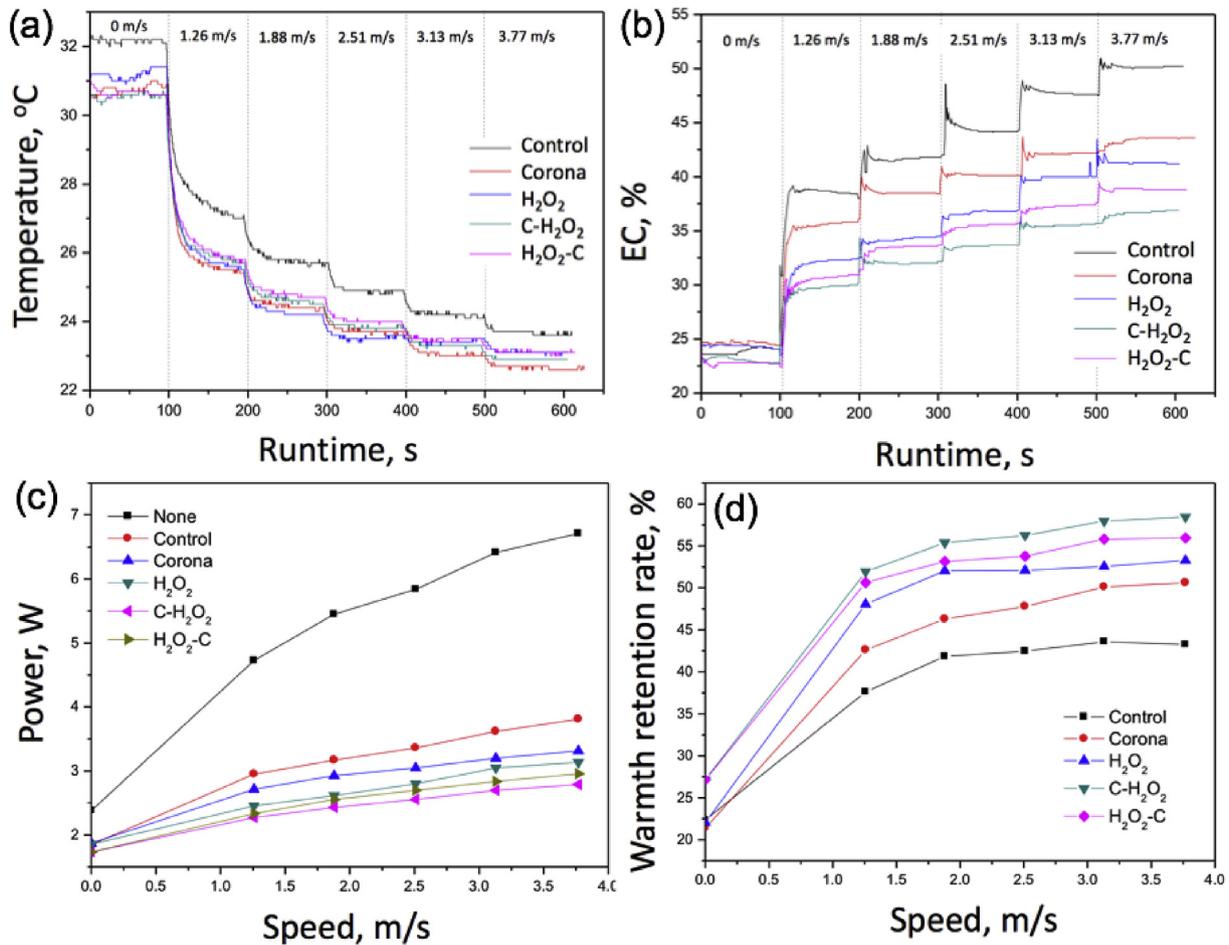


Fig. 4. The surface temperature of wool fabrics (a), energy consumption (b) and power (c) of the hotplate, and warmth retention rate (d) of wool fabrics with different surface modifications.

shape for surface temperature and energy consumption, respectively. Four evident stages of the dynamic mass transfer process can be seen from the curves, corresponding to the loading of sample, adding of water, water evaporation and drying (Li et al., 2019). Surface modification has complex impact on the mass transfer of wool fabrics. The surface temperature of surface modified wool fabrics at the evaporation stage is higher than that of pristine wool fabrics. This is probably due to the higher thermal resistance and moisture resistance of the surface modified wool fabrics. Considering the heat provided by the hotplate at

stage three is saturated at 100%, surface modified wool fabrics conduct the heat slowly than that of pristine wool fabrics, resulting in a higher surface temperature. The time to accomplish the whole dynamic moisture transfer process is longer for surface modified wool fabrics than that of pristine wool fabrics. As a result, the slope of the curves in stage four the drying process for surface modified wool fabrics is smaller than that of pristine wool fabrics. The evaporation of water/moisture from fiber structure is harder when the surface of wool fibers is modified, longer time and higher energy consumption are needed for

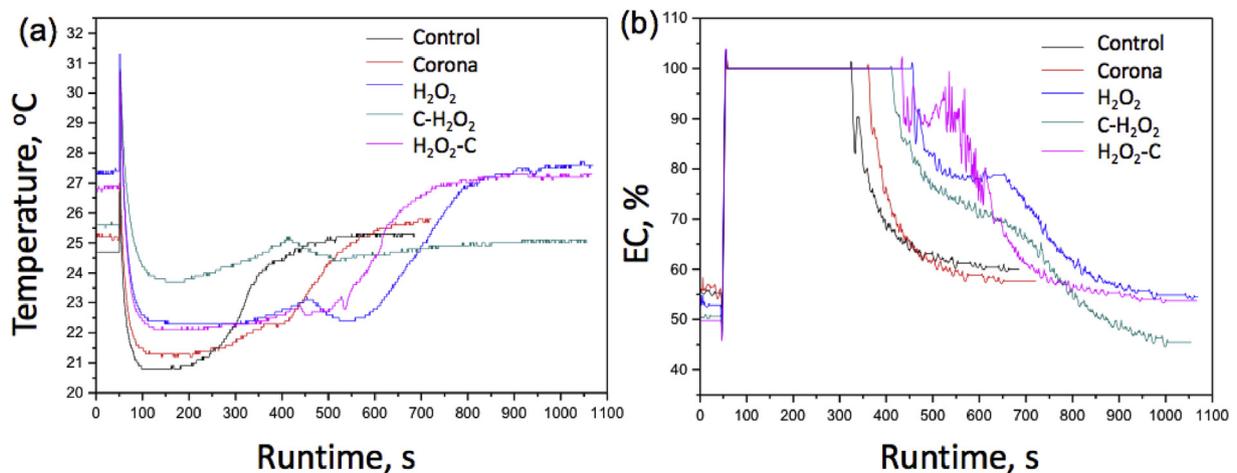


Fig. 5. The surface temperature of wool fabrics (a) and energy consumption of hotplate (b) in the dynamic mass transfer process.

them to accomplish the drying process (Fig. 5a and b).

The temperature and energy consumption in stage three fluctuates evidently with two zones for hydrogen peroxide treated and combined treated wool fabrics. The first stable zone is attributed to the evaporation of direct water and moisture in the fibrous structure, while the second zone corresponds to the further evaporation of indirect water and moisture in the fibers. The water/moisture in the fibrous structure is easy to evaporate as the water/moisture is in free state without strong connections to fiber surface. However, the water/moisture inside of fibers is strongly bonded with hydrophilic groups. Thus, the water/moisture in free state evaporates easily in the beginning of stage three, and then the water inside of fibers will be evaporated with extra energy consumed to break its bonding with hydrophilic groups. The dynamic mass transfer of surface modified wool fiber will have a profound impact on the real application of wool products. The products will need a longer time and a higher energy to equilibrium as the moisture stays firmly inside the fibers. Nevertheless, the surface temperature of surface modified wool products changes moderately as compared with untreated wool, suggesting that the products will feel warmer especially in the beginning stage of sweat transfer.

4. Conclusions

Surface modification has direct impact on the dynamic thermal and mass transfer of wool fabrics. The morphology of wool fibers has altered after surface modification with etched and broken scales by corona discharge treatment and damaged and peeled off scales by hydrogen peroxide treatment. Due to the enhanced wettability and wicking properties, surface modified wool fabrics showed lower water contact angles compared to that of pristine wool fabrics. Different MMT profiles were observed for surface modified wool fabrics, and larger wet areas on both sides of wool fabrics were obtained while only a droplet on the top surface was observed for pristine wool fabrics. In the dynamic heat transfer process, surface modified wool fabrics showed a lower surface temperature and less energy consumption of the hotplate than pristine wool fabrics, suggesting enhanced warmth retention rates of wool fabrics after surface modification. In the dynamic moisture transfer process, surface modified wool fabrics took longer time to accomplish the whole process and the evaporation stage had two separate zones

due to the enhanced water absorbing capacity after surface modification.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jtherbio.2019.102416>.

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