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Heat Transfer in Single-side Napped Fabrics During Compression

Sujian Zhang [a], Yi Li [b,*], Junyan Hu [b], Xiao Liao [b], Haotian Zhou [c]

[a] *Jiangyin Polytechnic College, Jiangyin, Jiangsu 214400, China*

[b] *Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hung Hom Kowloom, Hong Kong*

[c] *Zhejiang University, College of Science, Mathematics and Applied Mathematics Hangzhou 310000, China*

Abstract

This paper presents a systematic analysis of the changes in thickness and the differences in the heat flux transfer for the two surfaces of selected single-side napped fabric, to explore the relationship between their heat flux and thickness during compression. The results showed that heat flow in the un-napped surface was greater than that in the napped surface when the fabric initially contacted the upper plate of a Fabric Touch Tester ($p < 0.05$); few differences of the heat flux between the un-napped and the napped surfaces measured separately with each surface facing upwards for each fabric type were observed when the pressure exceeded 0.6 Pa ($p > 0.05$); the heat flux was linearly correlated with thickness for both the un-napped surface and napped surface when the pressure exceeded 0.6 Pa (correlation coefficient $R^2 >$ 0.9); the gradients of the regression equation of heat flux-thickness gradually increased from the initial thickness point to the midpoint of the maximum pressure except for the first heat peak point of the un-napped surface. In conclusion, heat flux was significantly affected by the surface characteristics of the fabrics in the initial stages of compression but was then not affected by either the surface features or the fabric structures at higher levels of compression pressure. The conclusion could be useful in product development and in providing a guide for clothing wearing comfort.

Keywords: Thickness; Heat Flux; Napped Surface; Surface Measurement; First Heat Peak; Standard Pressure

1 Introduction

The heat and moisture transfer behaviors of clothing have been recognized as being critically important for human survival. Li et al. demonstrated that thermal-wet comfort counted for around 40% of overall wearing comfort [1]. In 1970, Fourt and Hollies [2] conducted a comprehensive study regarding clothing comfort and function, with special emphasis on thermal comfort.

*Corresponding author.
Email address: `tcliyi@polyu.edu.hk` (Yi Li).

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Schneider and Holcombe [3] studied fabric properties influencing coolness sensation. The fabric used was considered to be comprised of three layers: a dense core layer and two outer layers consisting of a predominance of air with a small number of protecting fibers. They explored the correlation between the thermal response (rate of temperature drop) of skin contacting a fabric and the outer layer thickness (thickness differences at just light pressures) of the fabric. The results showed that the thickness of the outer layers had a negative influence on the rate of subjective coolness perception and temperature on the skin surface during the fabric-skin contact. Li and Brown et al. [4] further investigated the relationship between the subjective perception of coolness and fabric properties. A range of 20 fabrics including micro-polyester lightweight fabrics and wool fleece fabrics were tested. It was found that the subjective perception of coolness was negatively related with the fabric porosity, fiber diameter, and fabric hairiness, but positively related with fiber hygroscopicity. Among those parameters, fiber hygroscopicity, fabric porosity, and fabric hairiness were the most important contributors. Fan et al. [5] investigated the effects of knitted fabric structure on coolness sensation. All the aforementioned studies only focused on the exploration of the relationships between coolness sensation and fabric thermal properties. Few publications regarding the heat transfer mechanism have been found. The human body is rarely in a static state. It is usually continually exposed to transients in physical activity and environmental conditions. Such changes may affect the fabric properties, which could eventually influence the heat transfer and human comfort. Fabric is prone to be compressed, bent and stretched during wearing. As a result, the heat and moisture transfer process between a fabric and skin should be greatly influenced by the contact areas of the fabric-skin contact, which is determined mostly by the surface features of the fabric.

In order to quantitatively evaluate the effects of fabric thermal properties, in 1977, Mecheels et al. [6] highlighted thermal resistance as a major factor. Nowadays, the most widely used index in the U.S. is the "*clo*", which was proposed by Gagge and his colleagues at the Pierce Foundation in 1941 [7]. Methods to measure heat transfer under steady-state conditions have also been developed in the past few decades. Well-known instruments includes the Flat-plate warmth Retaining Tester and the Kawabata Evaluation System [8-11]. Both have some limitations in the objective measurement of fabric touch sensation [12] and they can only test fabric thermal properties under static conditions. A new apparatus, named the Fabric Touch Tester (FTT) [13-16] has been developed to measure the mechanical and thermal sensory properties simultaneously and dynamically. It provides a research platform for objective assessments of both heat transfer and coolness sensation. The FTT can measure the changes in heat flux during the compression of fabrics. In order to conduct an objective and dynamic study of the effect of different fabric structures on heat transfer and coolness sensation, this study investigated a selection of single-side napped fabrics. This paper discusses the differences in the heat flux values and thicknesses of the different surfaces, the correlations between the heat flux values and the thicknesses during compression of the fabric, and then identifies a possible mechanism to explain the effects of fabric properties on thermal comfort.

2 Experimental

2.1 Structure of Thermal and Thickness Module in the FTT

The FTT consists of an upper plate and a lower plate. A heater installed in the upper plate was set to maintain a constant preset 10 °C temperature difference between the upper and lower plates. A heat flux sensor, installed in the upper plate as shown in Fig. 1 (a), was used to measure the heat flow during testing. The output parameters include the heat flux, the temperature differences between the upper and lower plate, and the thickness changes during compression [17].

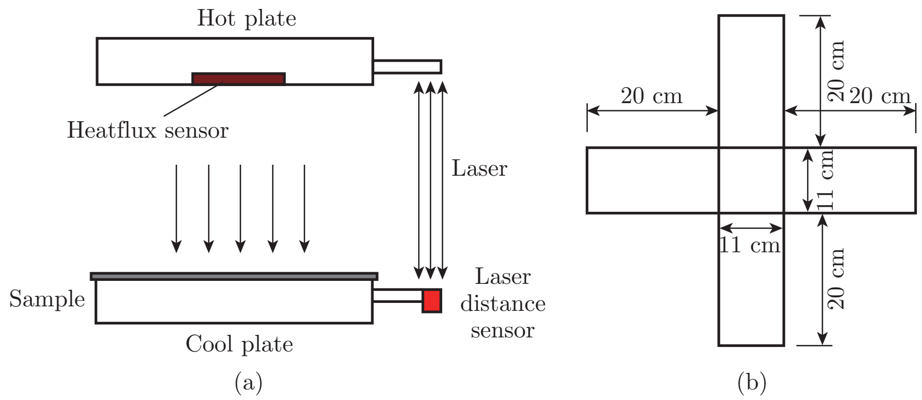


Fig. 1: Measurement principle of the FTT (a) and the dimensions of the cross shape of the sample (b)

After a 10 °C temperature difference was reached between the upper and lower plates, the upper plate was moved downwards to compress the test fabric, and then moved upwards after reaching the maximum compression force of 70 gf/cm^2. Thereby, each sample on the lower plate was compressed and then allowed to recover. The distance between the two plates was recorded by a laser displacement sensor for each fabric type and the compression pressures were measured by load cells underneath the lower plate [13-15].

2.2 Materials

In order to study the influence of the surface on the heat flux, six single-side napped samples were selected. Their specifications are listed in Table 1. Photographs of cross-sections through the samples of the samples are shown in Fig. 2. These included four woven fabrics and two knitted fabrics. All fabric types were cut into the sample shape shown in Fig. 1 (b). After conditioning at a constant temperature (20±1 °C) and relative humidity (65±2%) in the laboratory, the measurements were conducted using the FTT. Measurements were made on each fabric type with the un-napped surface facing upwards (un-napped surface - tested as the measured surface) and the napped surface facing upwards (napped surface - tested as the measured surface) 5 times.

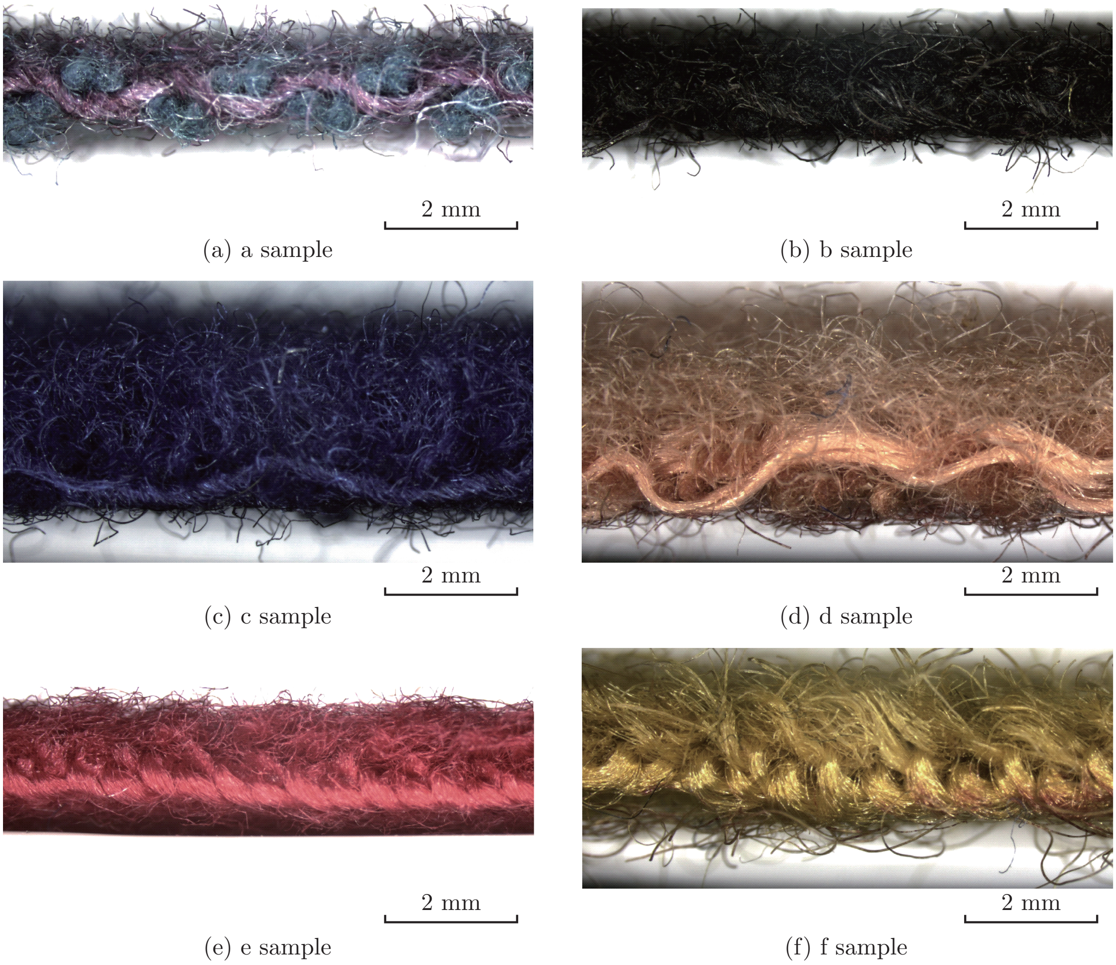
3 Results and Discussion

3.1 Comparison of Experimental Data for Un-napped and Napped Surfaces for Each Fabric Type

To eliminate random error, the original data was smoothed using the moving average method. When the parameter for the moving average for the sampling point was odd, the average value became the median of the moving average items. When the parameter for the moving average for the sampling point is close to the random fluctuation cycle of the raw data, instrumental error

Table 1: Sample descriptions

Fabric code	Weave	Yarn count (N)	Density (number/10 cm)	Composition	Weight (g/m^2)
a	2/2 twill	12	188×142	40 wool/60 polyester	340±1.0
b	2/2 twill	11	188×150	30 wool/70 polyester	356±3.7
c	sateen	10×12/2	180×126	5 wool/95 polyester	381±2.9
d	Alternative weave	9×32/2	330×188	30 wool/70 polyester	387±0.7
e	Weft plain	9	124×180	Cotton	313±3.1
f	Weft plain	16/2+150D	120×148	30 wool/70 polyester	449±7.2



(a) a sample (b) b sample (c) c sample (d) d sample (e) e sample (f) f sample

Fig. 2: Photographs of cross-sections through the samples

could be eliminated. According to the random wavelength for the raw data, the parameters for the moving average of thickness, pressure, heat flux was 31, 7, and 5 respectively.

The measurement of each sample thickness and heat flow values was made at four specific instances viz:

1. The point of initial thickness, the measurement of the initial thickness was difficult, but, as the thickness/pressure curve was relatively reproducible as shown in Fig. 3, this point was defined

as the position corresponding to the initial increase in pressure; the graphs of pressure and heat flux plotted against thickness are shown in Fig. 4;

2. The first peak point of heat flux, this corresponded to the position at which the first heat flux peak appeared during the compression process as shown in Fig. 5, (for some samples, the value measured at this point was sometimes the maximum heat flux value over the entire compression process);

3. The point of standard pressure, this was where the pressure reached 0.6 Pa;

4. The midpoint of the maximum pressure, this was when the fabric type had been compressed under the maximum pressure for 10 s and was the midpoint position during this period of application of maximum pressure as shown in Fig. 6.

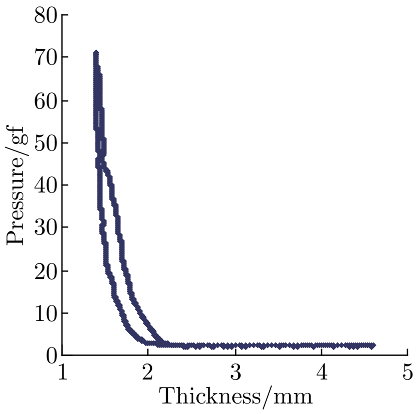


Fig. 3: Curve of pressure against thickness for sample e

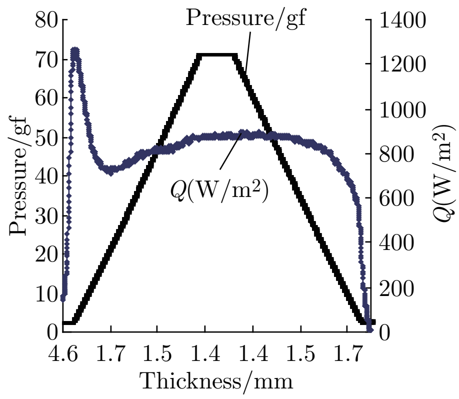


Fig. 4: Curve of pressure and heat flux against thickness for sample e

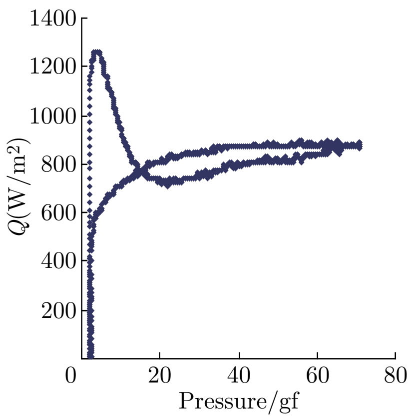


Fig. 5: Curve of heat flux against pressure for sample e

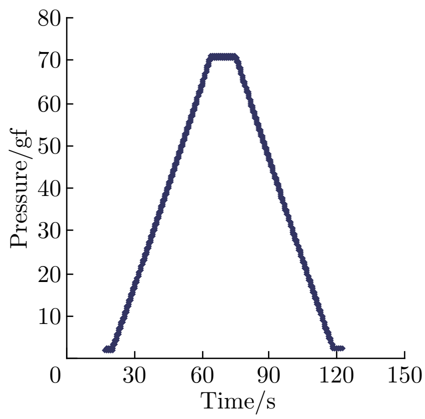


Fig. 6: Curve of pressure against time for sample e

The maximum heat flux reflects the coolness-warmth perception when touching the fabric [18], the greater this value is, the cooler is the fabric feeling. The thicknesses and heat flows in the four positions were compared.

The differences in the thicknesses that were measured for the un-napped and napped surfaces are presented as histograms (shown in Fig. 7). Analysis of the raw data revealed that the differences in thickness between the un-napped and napped surfaces for the same fabric types at a particular

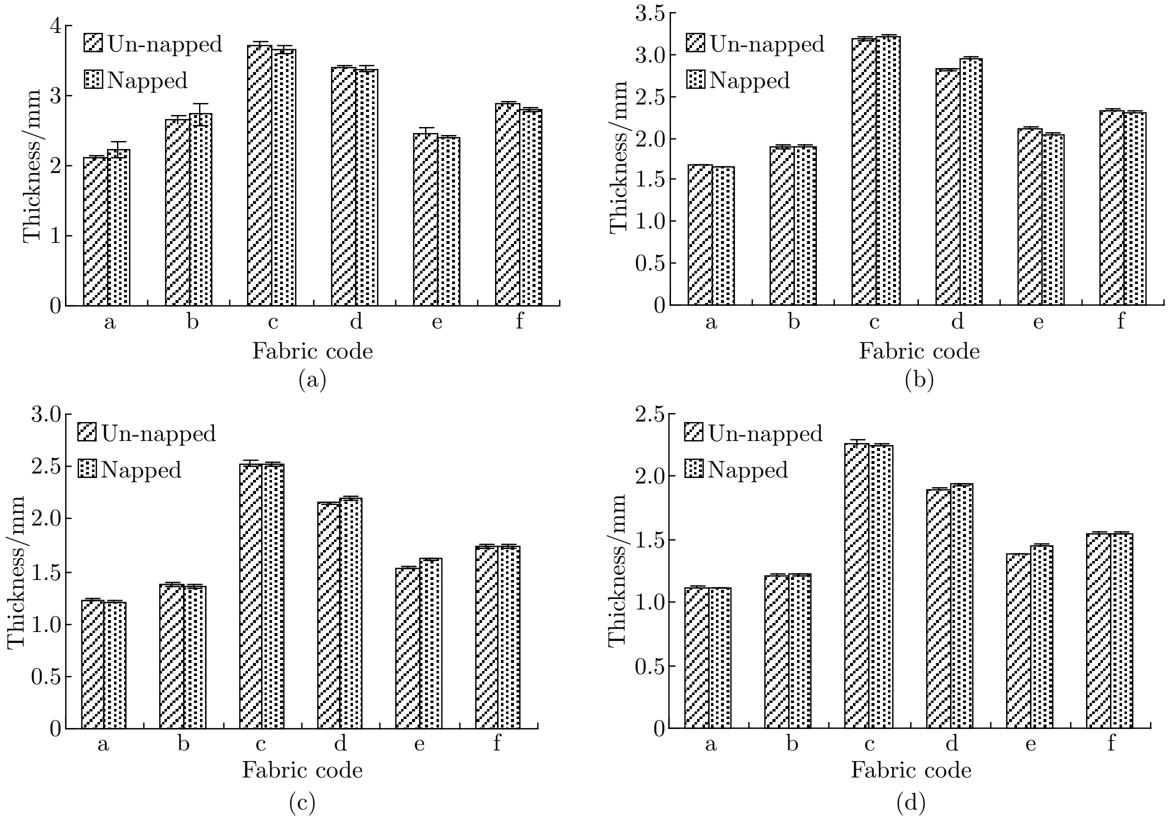


Fig. 7: Comparison of the thickness for the un-napped and napped surfaces: (a) initial thickness, measured surface P = 0.928; (b) thickness in the first heat peak, measured surface P = 0.750; (c) thickness at standard pressure, measured surface P = 0.122; (d) thickness at midpoint of the maximum pressure point, measured surface P = 0.065

position were small i.e. the thickness value of the un-napped surface was not significantly different to the napped surface at a particular position for the same species ($P > 0.05$). The thickness of the fabrics gradually decreased as the pressure value increased (shown in Fig. 8). The percentage decrease in thickness is shown in Table 2. During the compression process, the percentage decrease in the thickness of the fabric between that measured at the standard pressure and the initial

Table 2: Percentage decrease in thickness

Fabric code	Initial thickness (mm)	Percentage decrease in thickness between the first heat peak and the initial thickness (%)	Percentage decrease in thickness between the standard pressure and the first heat peak (%)	Percentage decrease in thickness between the midpoint of the max-pressure and the standard pressure (%)
a	2.109	20.3	27.0	8.8
b	2.658	28.6	27.8	11.2
c	3.726	14.3	21.0	10.3
d	3.399	17.0	23.8	11.7
e	2.467	14.4	27.4	10.0
f	2.880	19.1	25.6	10.7

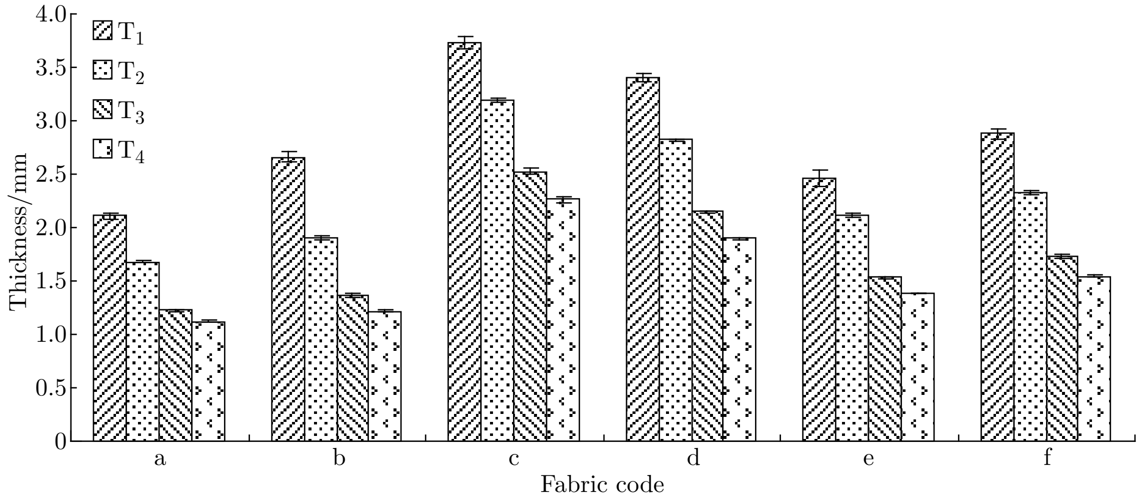


Fig. 8: Thickness of un-napped surface facing upwards at the four measurement points: T_1 represents the initial thickness; T_2 represents the thickness at the first heat peak; T_3 represents the thickness at the standard pressure; T_4 represents the thickness at the max-pressure midpoint

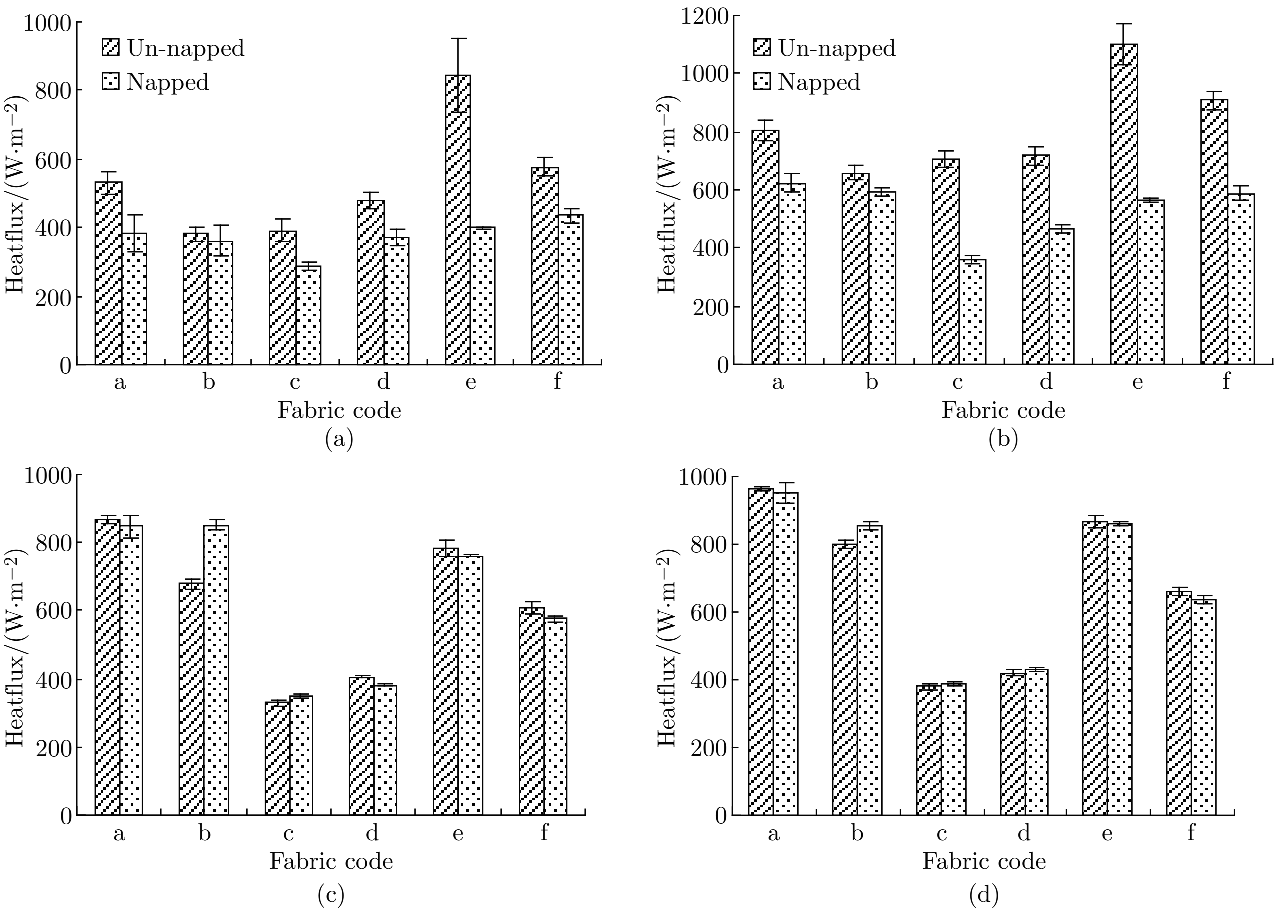


Fig. 9: Comparison of the heat flux for un-napped and napped surfaces: (a) the initial thickness point, measured surface P = 0.000; (b) the first heat peak point, measured surface P = 0.000; (c) the standard pressure point, measured surface P = 0.765; (d) the midpoint of the maximum pressure point, measured surface P = 0.642

thickness was up to about 40%, the thickness decrease between the midpoint of the maximum-pressure and the standard pressure was small (about 10%).

Differences in the heat flow measured with the un-napped surface facing upwards and the napped surface facing upwards are shown in Fig. 9. At the position of initial thickness and the first heat flux peak, the heat flow with the un-napped surface facing upwards was greater than that for the napped surface facing upwards by amounts ranging from 10% – 95% depending on the fabric types. This implied that the un-napped surface was cooler than napped surface to the touch. At the position corresponding to the standard pressure, the heat flux differences between the un-napped and napped surfaces facing upwards for the same fabric types were small, except for fabric b. At the position of the midpoint of the maximum pressure, the heat flow differences between the surfaces for the same fabric types were almost negligible. From ANOVA of the original data using Minitab, (Minitab is a statistics package, it was developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in 1972 [19]), the heat flux values for the un-napped surface facing upwards was significantly different to the values for the napped surface facing upwards at the positions of initial thickness and the first heat flux peak for the same fabric types ($p < 0.05$). The heat flux values for the un-napped surface facing upwards were not significantly different to those for the napped surface facing upwards at the positions of standard pressure and the midpoint of the maximum pressure for the same fabric types ($p > 0.05$). This showed that the heat flux was dependent on the surface that was touched in the single-side napped fabric when the fabric was initially touched, and that the heat flux was no longer dependent on the side that was touched after a certain amount of compression. This was clearly due to the state and amount of nap on the un-napped and napped surfaces.

3.2 Analysis of the Relationship between the Heat Flow and Thickness Values

The relationship between the heat flow and thickness values for the un-napped surface for the six fabric types is illustrated in Fig. 10. Similarly the relationship between the heat flow and thickness values for the napped surface for the six fabric types is shown in Fig. 11. Linear functional equations and correlation coefficients (R^2) relating heat flow to thickness, corresponding to the four measurement positions, are shown in Table 3.

At the initial thickness position, the respective linear correlation coefficients R^2 (0.2247, 0.4222) indicated a low correlation between heat flux and thickness, showing that the heat flux was affected by other factors, such as the fabric structure and fiber properties, in addition to being affected by the thickness. At the position corresponding to the first heat peak, the respective linear correlation coefficients R^2 (0.0762, 0.8879) showed a large difference. When the fabric types were placed with the un-napped surface facing upwards, the coefficient R^2 was small (even less than the value at the initial thickness) implying that the correlation between the heat flux and the thickness was weak. The variations in heat flux were large at this position. When the fabric samples were placed with the napped surface facing upwards, there was a negative linear correlation between the heat flux and thickness, which indicated that that surface state and the first peak of heat flux were interrelated. The respective linear correlation coefficients R^2 and regression equations at the positions of standard pressure and the mid-point of the maximum pressure also indicated a negative linear correlation between heat flux and thickness, indicating that the heat flux was increasingly negatively linearly related to the thickness after applying a

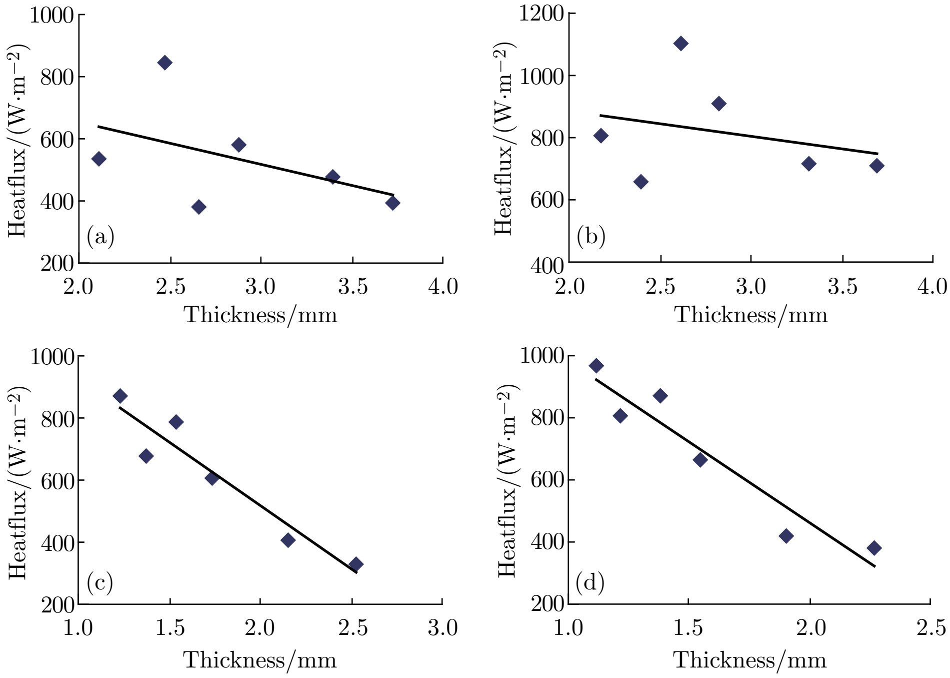


Fig. 10: Linear correlations between the heat flux and thickness for the un-napped surface: y is the heat flux (W/m2) and x is thickness (mm) at four positions. (a) the initial thickness point $R^2 = 0.2247$, (b) the first heat peak point $R^2 = 0.0762$, (c) the standard pressure point $R^2 = 0.9117$, (d) the midpoint of the maximum pressure $R^2 = 0.9098$

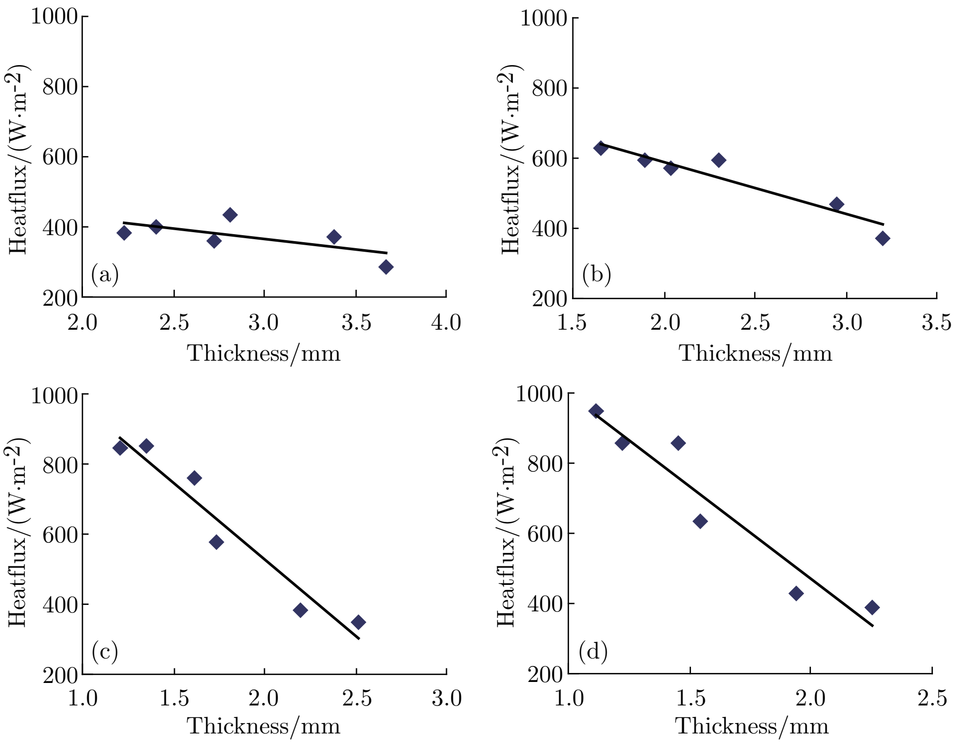


Fig. 11: Linear correlations between the heat flux and thickness for the napped surface: (a) the initial thickness point $R^2 = 0.4222$, (b) the first heat peak point $R^2 = 0.8879$, (c) the standard pressure point $R^2 = 0.9315$; (d) the midpoint of the maximum pressure $R^2 = 0.9143$

Table 3: Linear functional equations and correlation coefficient (R^2) relating the heat flow to thickness at the four measurement positions

Measurement position			Linear functional equations	R^2
a	Initial thickness position	Un-napped surface	$y = -134.45x + 919.65$	0.2247
		Napped surface	$y = -57.725x + 538.73$	0.4222
b	The first heat peak position	Un-napped surface	$y = -79.723x + 1002.7$	0.0762
		Napped surface	$y = -150.11x + 889.58$	0.8879
c	The standard pressure position	Un-napped surface	$y = -406.87x + 1327$	0.9117
		Napped surface	$y = -438.16x + 1403.8$	0.9315
d	The midpoint of the maximum-pressure	Un-napped surface	$y = -523x + 1503.8$	0.9098
		Napped surface	$y = -525.58x + 1519.9$	0.9143

certain pressure. It also indicated that heat change and fabric structure were irrelevant under these conditions. Comparing the linear correlations at the four specific positions, the slopes of the regression equations increased from the initial thickness to the midpoint of the maximum pressure except for those at the first heat peak with the un-napped surface facing upwards. The explanation for this is that, with a decrease in the thickness of the air layer in the fabric, there was bigger increase in the heat flux with decreasing thickness such that the influence of thickness on heat flux also increased.

- At the position of standard pressure, by comparing the linear functional equations for the un-napped surface $y = -406.87x + 1327$ (shown in Table 3 — position c for the un-napped surface) and the linear functional equations for the napped surface $y = -438.16x + 1403.8$ (shown in Table 3 — position c for the napped surface), the percentage difference of the x coefficient was 7.1%, the percentage difference of the constant term was 5.5%;

- At the position of the mid-point of the maximum pressure, by comparing the linear functional equations for the un-napped surface $y = -523x + 1503.8$ (shown in Table 3 — position d for the un-napped surface) and the linear functional equations for the napped surface $y = -525.58x + 1519.9$ (shown in Table 3 - position d for the napped surface), the percentage difference of the x coefficient was 0.5%, the percentage difference of the constant term was 1.1%.

Under the standard pressure, the thickness — heat function percentage difference for the un-napped and napped surfaces was less than 8%. Under the midpoint of the maximum pressure, the thickness — heat function deviation for the un-napped and napped surface was further reduced. This shows that heat flux was increasingly influenced by thickness and decreasingly influenced by the surface characteristics as the pressure on the fabric increased.

3.3 Discussion

A single-side napped fabric can be considered to be comprised of three layers: a dense core, a napped layer, and un-napped layer, as illustrated for a simple woven fabric in Fig. 12. When the upper plate of the FTT initially contacts the napped layer, because the fibers and pile are longer and, hence, trap more air in the napped layer than in the un-napped layer, and the air thermal conductivity is less than that of the fiber, heat transfer is slow from the upper plate to the lower plate though fabric, consequently the value of heat flux sensed is small as shown in Fig. 12 (a). When the upper plate of the FTT just contacts the un-napped layer, because the fiber thermal conductivity is greater than that of the air, the heat transfer is fast from the upper plate to the lower plate through the fabric, the value of the heat flux sensed is large, as shown in Fig. 12 (b). Hence, the thermal conduction through contact with the napped layer with the longer pile and a greater amount entrapped air is smaller than that through contact with the un-napped layer with shorter pile and less entrapped air. Consequently the smoother (less napped) is the fabric surface; the cooler is the feeling when the fabric is touched. Under compression, the air in the pile/napped layer is gradually expelled; the density of the pile layer becomes closer to that of the core layer, therefore the difference between the heat transfer of the napped surface and the un-napped surface gradually decreases.

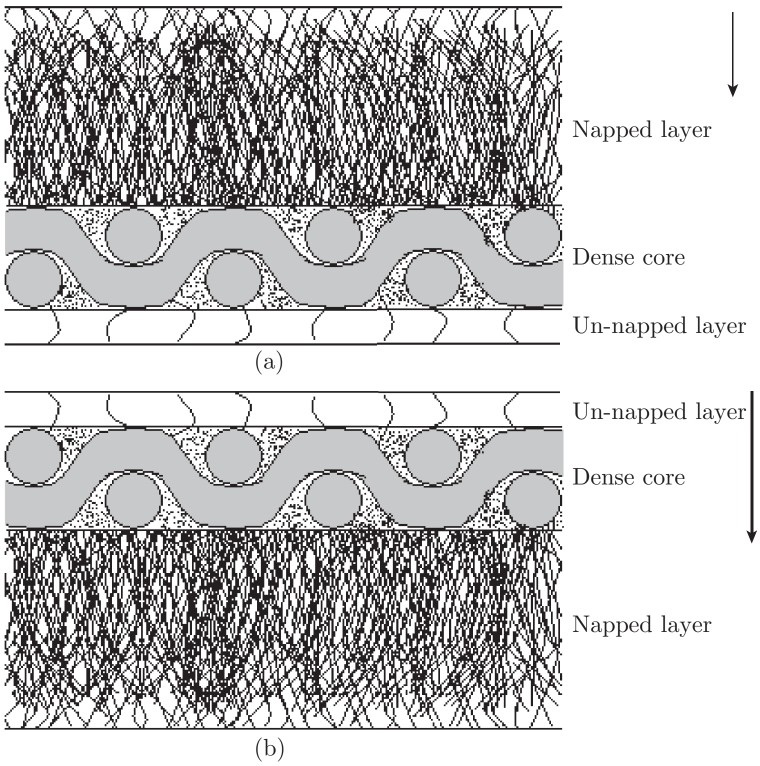


Fig. 12: Schematic diagram of a single-side napped fabric: (a) the upper plate of the FTT contacts the napped layer, (b) the upper plate of FTT contacts the un-napped layer

In the process of compressing fabric on the FTT, the heat flux of the sample first rapidly increased, there was a peak in the heat flux for the un-napped surfaces of the samples (shown in Fig. 4), then, the heat flux slowly increased as the fabric thickness decreased under the pressure. As the upper plate of FTT was slowly raised, the pressure on the fabric gradually decreased, the thickness of the fabric on FTT gradually increased and the heat flux gradually decreased. There were differences in the heat flux changes for the different fabrics with their napped surface facing upwards and their un-napped surface facing upwards. In particular, there were obvious differences in the position of the first heat peak. The respective linear correlation coefficients R^2 (0.0762, 0.8879 shown in Table 3) for the heat flux plotted against thickness for some of the samples at the first heat peak position (shown in Table 3) reflected the differences between their napped surface and their un-napped surface. The graphs and the respective linear correlation coefficients R^2 (0.2247, 0.4222 shown in Table 3) for the heat flux plotted against thickness for some of the samples (shown in Figs. 10, 11) at the initial thickness position reflected dispersion. These showed that the surface states and the types of fabric had great effects on the heat flux when the fabric was just touched.

4 Conclusions

Thickness differences in the un-napped and napped surfaces for the same fabrics were small ($P > 0.05$, shown in Fig. 7) under the same pressure corresponding to the first heat peak observed in the FTT. Under compression, the percentage decrease in the thickness of the fabric was up to about 40% during the initial stage of compression. At the position of initial thickness measurement and the first heat flux peak, the heat flow with the un-napped surface facing upwards was greater than that with the napped surface facing upwards, At the position of standard pressure and midpoint of the maximum pressure, the heat flux difference between the un-napped and napped surfaces facing upwards for the same fabric was small ($P > 0.05$, shown in Fig. 9). At the initial contact stage, the heat flux was related to the surface of the single-side napped fabric touched. However after a certain amount of compression, the heat flux was no longer related to the surface of the fabric that was touched.

Analysis of the correlation between the heat flux and thickness indicated that, at the position of initial thickness, the correlation between heat flow and thickness was not obvious. At the first heat peak, the correlation between the heat flux and the thickness with the un-napped surface facing upwards was negligible because the correlation coefficient R^2 was small (0.0762). However, at the first heat peak, the heat flux and the thickness with the napped surface facing upwards was linearly correlated. At both the positions of standard pressure and the midpoint of the maximum pressure, the heat flux was linearly correlated with the thickness when both the un-napped or napped surfaces were facing upwards, (the correlation coefficient $R^2 \approx 0.9$). This demonstrated that the heat flux was affected by other factors, such as the fabric structure and fiber properties, in addition to the thickness at the initial contact stage but, the heat flux was no longer dependent on fabric structure after applying a certain pressure. The slopes of the respective regression equations increased from the initial thickness to the midpoint of the maximum pressure with the exception of the first heat peak for the un-napped surface. This can be explained by the fact that, with a decrease in the air layer in fabric, there was increase in the influence of thickness on heat flux. The difference between the correlation coefficient for heat flux and thickness for the un-napped and napped surfaces was further reduced as the fabrics became more compressed. This showed that the heat flux was increasingly influenced by the fabric thickness, whereas the influence of the surface characteristics gradually decreased.

The coolness-warmth of a fabric to the touch greatly depends on the amount of air in the fabric. The smoother (un-napped) is the fabric surfacethe lesser is the air entrapped in the fabric surfacethe greater is the heat flux though the fabric; the cooler is the feeling when the fabric is touched. Under compression, the air in the pile/napped layer is gradually expelled; the difference between the heat transfer of the napped surface and the un-napped surface gradually decreases and, consequently, the influence of fabric thickness on heat transfer gradually increases.

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