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Instrument and System for Evaluating Thermal Regulation Properties of Textiles

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Abstract

A test instrument was developed and the testing method was proposed to characterize the thermal regulation properties of textiles based on the mechanical device, microelectronics, sensors and control system. A series of indices were defined based on the typical heat flow-time curve and the raw data to characterize the thermal regulation performance of textiles. The measurement principle, the mechanical device and the evaluation method for the thermal regulation properties of textiles were introduced. Twelve types of fabrics made from different textile materials were tested. The one-way ANOVA analysis was conducted to identify the significance of the differences of the indices among the fabrics. The results show that each index is significantly different (P<0.05) among the different sample fabrics.

Keywords: *thermal regulation properties, instrument, evaluation, textiles*

1. Introduction

With the rapid development of economy and the improvement of people's life, people now care about not only a better visual effect but also wearing comfort when purchasing textile and clothing products. Clothing comfort generally includes three aspects: thermal-wet comfort, contact comfort and visual comfort [1-3]. Heat-moisture transfer performance of the textiles such as fabric is one of the key factors affecting clothing wearing comfort, which also decides the performance of some special functional fabric. The heat-moisture transfer performance of fabric is related to the thermal-wet comfort properties of clothing. Therefore, heat-moisture transfer properties of clothing and its evaluation method has become a research focus in the field of clothing comfort. The heat transfer properties are important attributes of heat-moisture transfer performance of textiles, especially under the dynamic wearing process during the dynamic contact between the skin and the clothing.

Heat transfer properties and thermal performance during the dynamic contact process between the skin and the clothing are referred to as thermal regulation properties of textiles, which greatly affect the clothing comfort and consumers purchasing behaviors.

According to the heat transfer principle, the heat dissipates from human body through convection, conduction, radiation and evaporation. In the previous studies, the heat transfer performance of the fabric was measured and evaluated based on the thermal equilibrium theory, and the fabrics were tested by measuring the heat loss or supplement within a certain time to get the heat transfer performance. Fourt proposed the test methods of thermal insulation properties of fabric [4].This test method keeps sample to cover on a hot plate with constant temperature to test and make the heat dissipation in the specimen orientation, which is called constant temperature cooling method. According to the heat needed to maintain the hot palte with constant temperature, it can be used to calculate the sample warmth retention rate, etc. In addition, there are cooling rate method [5], plate method [6], micro-climate method [7] and thermal manikin method [8] for the heat transfer performance evaluation of fabrics.

Extensive researches have been carried out for the thermal performance evaluation of clothing and textiles. Gagge A. P., Burton A. C. and Bazett H. C. presented the warm clothing insulation index – CLO, which associated with human physiological parameters, psychological, sensory and environmental conditions [9]. Mu Yao and Jian-yong Yu [10, 11] respectively analyzes the factors that influence the textile steady-state thermal properties of fabric using a self-developed heat transfer performance tester, and found that thickness of the fabric have

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greater impact on the thermal performance of the fabric. The thermal resistance and thickness of the fabric showed a good linear relationship. Jian-chun Zhang and Indu Shekar both studied the thermal resistance of textiles using the THERMOLABO-type tester developed by Japanese Kawabata. Jian-chun Zhang used the tester to test the thermal insulation properties of cold protective clothing and Indu Shekar studied the impact of wool fabrics on thermal resistance [12]. Fang-long Zhu et al developed a novel instrument which can measure radiation coefficient of protective fabrics under high convective and radiant heat flux [13]. Wei-zhong Gong, Vmbach and Pei-qing Jiang developed different micro-climate instruments successively. These micro-climate instruments can measure the parameters of five aspects: (a) Inside and outside air layer's temperature of fabrics micro-climate; (b) Inside and outside air layer's moisture of fabrics micro-climate; (c) Thermal resistance of the fabric; (d) Moisture resistance of the fabrics; (e) Equivalent thermal resistance of the fabrics [14-16].

Although, there are some standard methods and test instruments can be employed to measure the fabric heat transfer properties and thermal performance, but most of them can only be used to measure the fabric thermal properties under static conditions or equilibrium states, and can not simulate the thermal regulation process during clothing contacts with human skin. This paper reports the development of a new test instrument and system based on the mechanical device, microelectronics, sensors and control system for thermal regulation properties evaluation of textiles. The instrument can measure the thermal regulation properties by simulating the dynamic thermal contacts between the skin and textiles.

2. Test Principle and Evaluation Method

2.1. Test Principle

As shown in Figure 1, the mechanical device of the instrument consists of the following six main components:

(1) Lower measuring head 1;
(2) Heating plate 2;
(3) Upper measuring head 3
(4) Lifting equipment 4;
(5) Driving component 5;
(6) Instrument frame 6.

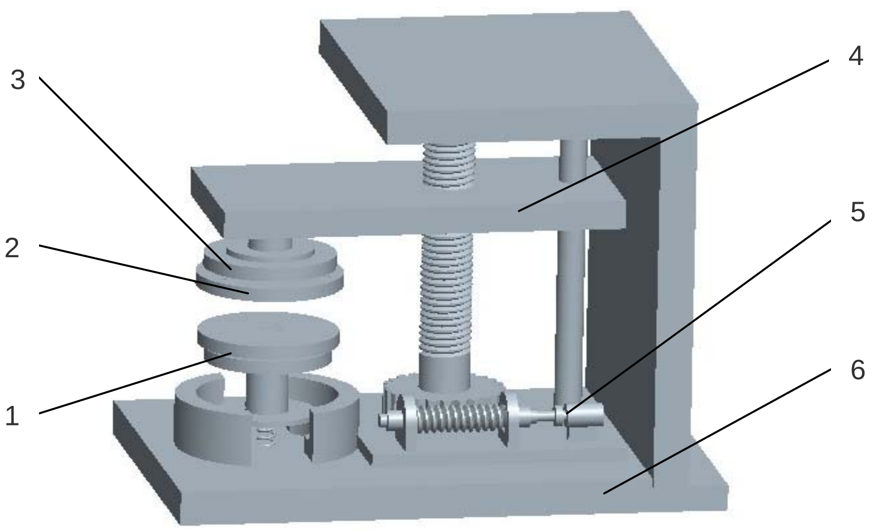
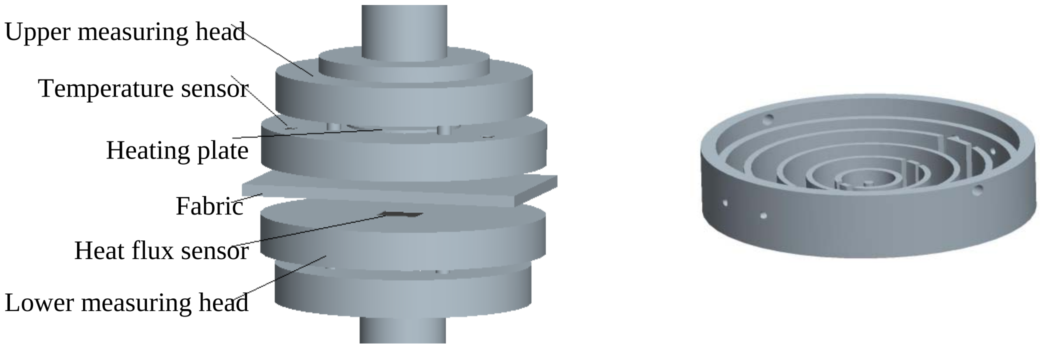


Figure 1. Mechanical Device of the Instrument System

The upper measuring head can be moved vertically and the motion is controlled by the lifting equipment and driving component. There are three kinds of sensors used for measuring the temperature of the upper and lower measuring heads, the heat flow passing through the fabric and the pressure load which is applied to the test sample fabric. As shown in Figure 2(a), three temperature sensors are evenly installed in both the upper measuring head and the lower measuring head for measuring the temperature changes of the two measuring heads. There are spring and pressure sensor installed between the lower measuring head and the instrument frame for measuring the pressure force applied to the test fabric. A heating plate is installed in the upper measuring head and is used to heat the head to keep constant temperature difference between the upper and lower measuring heads. In order to ensure the whole sample is heated uniformly and simultaneously, the annular heating wires are applied in the heating plate of the mechanical device as shown in Figure 2(b). A heatflux sensor is installed on the top side of the lower measuring head for the measuring of the heat flow.



(a) Measuring heads and sensors (b) Heating plate

Figure 2. Structure of Measuring Heads

Before testing, the upper measuring head is located at the initial position. When the measurement starts, the heating wires of the heating plate begin to heat to make the two measuring heads have the predetermined temperature difference. Then the upper measuring head moves down and fixes the sample between the free surfaces of the upper measuring head and the lower measuring head. The motor stops running and the upper measuring head stops moving down by a signal trigger which comes from a pressure sensor installed between the lower measuring head and the instrument frame, and the sample is kept at static condition. Meanwhile, the heatflux sensor starts to work and the test data begins to be recorded. Three minutes later, when the heat flow passing through the fabric is close to be steady, the heating plate stops heating, the motor starts to rotate in reverse, and the upper measuring head rises up and departs from the sample to return to initial position.

2.2. Evaluation Method

Figure 3 is a typical heat flow-time curve from the dynamic heat transfer testing. Derived from the measuring curves and the test data, four indices have been defined and calculated for evaluation of thermal regulation properties of textiles.

1) Maximum heat flow: Q_{MAX} ,

$$Q_{MAX} = \mathrm{q(t)}\big|_{MAX} \tag{1}$$

2) Heat flow at equilibrium state: q_E ,

$$qE = q(t)\big|_{t=t_E} \tag{2}$$

Where t_E is the time when the heat transfer is just from the dynamic state to the steady state and the heat flow becomes constant.

3) Thermal regulation ability: TRA,

$$TRA = \frac{\int_0^{t_E} q(t)_E \, dt}{t_E} \tag{3}$$

Where,

$$q(t)_E = \begin{cases} q(t) - q_E, & q(t) \geq q_E \\ 0, & q(t) < q_E \end{cases} \tag{4}$$

4) Relative thermal regulation ability: TRA_r (%),

$$TRA\_r = \frac{TRA}{q_E + TRA} \times 100\% \tag{5}$$

Indices TRA and TRA_r reveal the thermal regulation and buffering ability of textiles during the dynamic heat transfer.

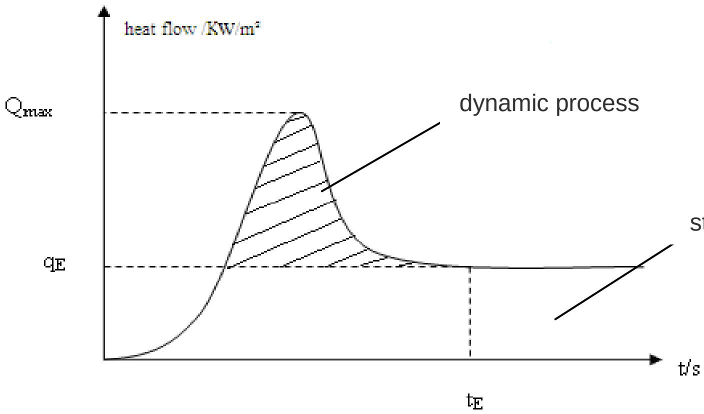


Figure 3. The Typical Heat Flow vs. Time Curve

3. Experiments Setup

Table 1. Fabric Structural Parameters

Sample code	Fabric construction	Mass/unit area (g/m^2)	Thickness (mm) at 4.14KPa
1#	Twill-brushed	290	0.57
2#	Corduroy	308	0.93
3#	Fancy weave	245	0.57
4#	Denim	359	0.75
5#	Denim-bleached	360	0.86
6#	Velvet	268	0.98
7#	Fleecy fabric- weft knitted	251	1.37
8#	Fleecy fabric- weft knitted	256	1.81
9#	Polar fleece	296	3.06
10#	Pile fabric-weft knitted	205	0.97
11#	Pile fabric-weft knitted	272	1.35
12#	Mesh fabric-warp knitted	96	0.32

Twelve types of fabrics with different structural features and made from different textiles were tested for the thermal regulation experiments. The sample was cut to the size of 180mm×180mm and any obvious wrinkles were removed. For each set of fabric, 5 pieces of specimens were cut for the testing. The fabric structural parameters are listed in Table 1. Before testing, all the specimens were kept in a conditioning room, controlled at 21±1°C and 65±2% RH according to ASTM D1776 for at least 24 hours.

4. Results and Analysis

All the specimens were tested on the instrument and system of thermal regulation properties by the same testing protocol according to the experiments setup. The mean values of the thermal regulation properties measurements are summarized in Table 2.

Table 2. The Mean Values of the Thermal Regulation Properties Measurements

Fabric	Heat flow Max Q_{MAX} (KW/m.m)	Thermal Regulation Ability TRA (KW/m.m)	Relative thermal regulation ability TRA_r (%)
1#	2.2796	0.312	18.67
2#	2.8341	0.5344	30.48
3#	2.0396	0.242	15.24
4#	2.2026	0.3577	22.79
5#	2.2774	0.3357	20.10
6#	2.5472	0.3591	20.75
7#	2.5312	0.5462	42.84
8#	1.2316	0.3157	42.53
9#	0.7873	0.2397	55.50
10#	1.896	0.2779	23.56
11#	2.6274	0.5145	33.49
12#	1.5261	0.092	6.81

A one-way ANOVA analysis was carried out to identify the significance of the differences of the evaluation indices among the fabrics using professional statistical software SPSS and the results are summarized in Table 3.

Table 3. One-way ANOVA Analysis Results of Evaluation Indices

Dependent Variable	Sum of Squares	df	Mean Square	F	Sig.
Q_{MAX}	20.574	11	1.870	72.178	0.000
TRA	0.988	11	0.090	36.580	0.000
TRA_r	1.042	11	0.095	70.838	0.000

The one-way ANOVA results indicate that each index is significantly different ($P<0.05$) among different fabrics in this study. Therefore, the fabrics' behaviors significantly affect the thermal regulation properties of all indices.

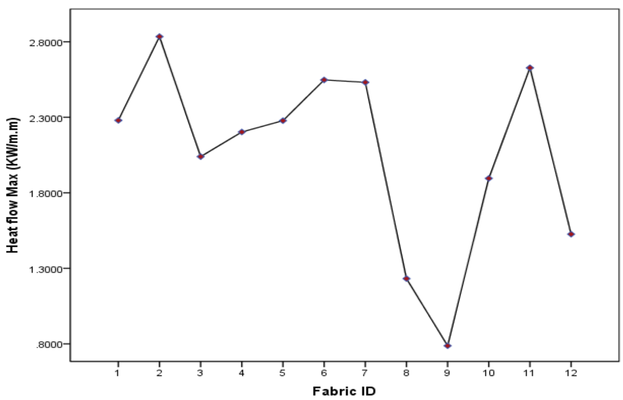


Figure 4. Mean Value of the Measurement Results of Heat Flow Max Q_{MAX}

Figure 4 is the mean value chat of the measurement results for the indices heat flow max Q_{MAX}. Fabric 2 has the highest value of heat flow, and is followed by fabric 11, where the Q_{MAX} is 2.834 and 2.627 (KW/m.m) respectively.

The measurement results of evaluation index TRA are shown in Figure 5. Fabric 12 has the lowest value of thermal regulation ability where TRA is 0.092 (KW/m.m), while fabric 7 is the best thermal regulation fabric since fabric 7 has the highest value of thermal regulation ability where TRA is 0.546 (KW/m.m).

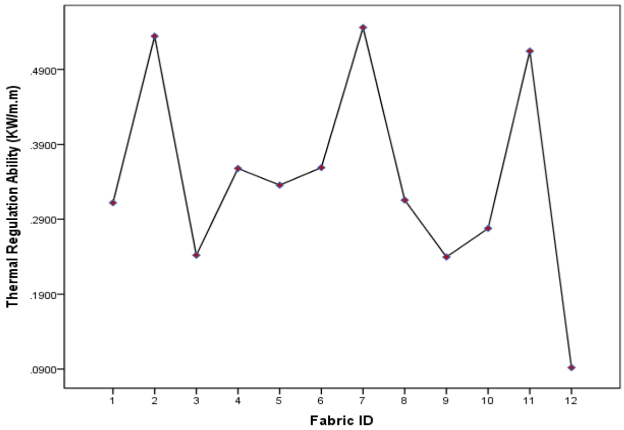


Figure 5. Measurement Results of Thermal Regulation Ability (TRA)

The measurement results of evaluation index TRA_r are shown in Figure 6. Fabric 9 is the best relative thermal regulation fabric compared with the heat flow at equilibrium state since fabric 9 has the highest value of relative thermal regulation ability where TRA_r is 55.5 (%), while fabric 12 has the lowest value of relative thermal regulation ability where TRA_r is 6.81 (%).

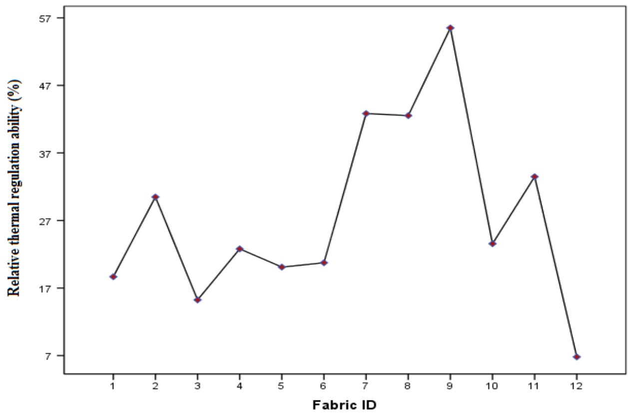


Figure 6. Measurement Results of Relative Thermal Regulation Ability (TRA_r)

5. Conclusion

Heat transfer properties and thermal performance during the dynamic contact process between the skin and the clothing are referred to as thermal regulation properties of textiles, which greatly affect the clothing comfort and consumers purchasing behaviors. A new instrument and system for thermal regulation properties evaluation of textiles was developed. The instrument and system can measure the thermal regulation properties by simulating the dynamic thermal contacts between the skin and textiles. Four indices were defined to evaluate the thermal regulation properties of the textiles derived from the raw data. Twelve types of fabrics with different structural features and made from different textiles were tested for the thermal regulation properties. The analysis of the variance results show that the instrument system is able to determine the significant differences in fabric thermal regulation properties to all indices with P level <0.05. The fabric 7 is the best thermal regulation fabric and has the highest value of thermal regulation ability.

Acknowledgements

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