Investigation of thermal insulation of cold protective clothing under different underwear and ambient conditions

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ABSTRACT – REZUMAT

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In this study, the thermal insulation of cold protective outerwear under various clothing combinations and ambient conditions was estimated using a thermal manikin. A series of cold protective outerwear, worn with various types of underwear, were evaluated in a conditioned room to explore the dependence of outerwear thermal insulation on the underwear. Besides, statistical studies were utilized to study the effect of ambient temperature on the thermal insulation performance of cold protective clothing ensembles. The thermal insulation of outerwear was observed to be different when it was measured with various fit styles, thicknesses and combinations of underwear. These discrepancies can be attributed to the variation in the air gap between clothing layers and the presence of stagnant air within the porous clothing. Furthermore, the ambient temperature was found to be a dominant factor affecting the thermal insulation performance of the clothing ensembles with high air content, as the airflow inside the porous material may be aggravated by the larger temperature difference between the clothing and the environment. Based on this study, ambient conditions for the assessments of different kinds of clothing can be divided into five groups, simulating the actual-used scenarios. The findings of this study are anticipated to enhance the comprehensiveness of thermal insulation evaluations for clothing systems and assist in the identification of optimal clothing choices for diverse ambient conditions.

Keywords: *clothing thermal insulation, underwear, cold protective outerwear, fit, ambient conditions*

Investigarea izolației termice a îmbrăcămintei de protecție exterioară pentru diferite tipuri de lenjerie de corp și condiții ambientale

În acest studiu, izolația termică a îmbrăcămintei de protecție exterioară în diferite combinații de articole și condiții ambientale a fost estimată folosind un manechin termic. O serie de articole de îmbrăcăminte de protecție exterioară, purtate cu diferite tipuri de lenjerie de corp, au fost evaluate într-o cameră condiționată pentru a explora dependența izolației termice a îmbrăcămintei exterioare asupra lenjeriei de corp. În plus, studii statistice au fost utilizate pentru a studia efectul temperaturii ambientale asupra performanței de izolare termică a ansamblurilor de îmbrăcăminte de protecție exterioară. S-a observat că izolația termică a îmbrăcămintei exterioare este diferită atunci când a fost măsurată cu diferite stiluri de ajustare pe corp, grosimi și combinații de lenjerie de corp. Aceste discrepanțe pot fi atribuite variației spațiului de aer dintre straturile de îmbrăcăminte și prezența aerului stagnant în interiorul îmbrăcămintei poroase. Mai mult, s-a constatat că temperatura mediului ambiant este un factor dominant care afectează performanța de izolare termică a ansamblurilor de îmbrăcăminte cu conținut ridicat de aer, deoarece fluxul de aer din interiorul materialului poros poate fi afectat de diferența mai mare de temperatură dintre îmbrăcăminte și mediul exterior. Pe baza acestui studiu, condițiile ambientale pentru evaluările diferitelor tipuri de îmbrăcăminte pot fi împărțite în cinci grupuri, simulând scenariile utilizate în mod real. Se anticipează că rezultatele acestui studiu vor spori exhaustivitatea evaluărilor de izolare termică pentru sistemele de îmbrăcăminte și vor ajuta la identificarea alegerilor optime de îmbrăcăminte pentru diverse condiții ambientale.

Cuvinte-cheie*: izolație termică a îmbrăcămintei, lenjerie de corp, îmbrăcăminte de protecție exterioară, corespondență, condiții ambientale*

INTRODUCTION

Clothing thermal insulation property is an important factor affecting human thermal comfort [1, 2]. In some extremely cold conditions, the physiological function of humans gradually diminishes when the clothing cannot provide sufficient thermal insulation [3]. Therefore, the thermal property of clothing should be accurately measured to keep human thermal comfort in various ambient conditions.

Some researchers worked on the clothing thermal insulation performance by perceptual assessment [4, 5]. Although such subjective assessment is meaningful to understand the perceptions of subjects, it tends to be less reproducible and can expose the subjects to dangerous conditions. Therefore, objective methods were developed to measure clothing thermal insulation. The guarded hotplate method is widely adopted to estimate the thermal insulation of fabric [6, 7]. As it is limited to measuring the thermal properties of clothing, thermal manikins are further adapted to estimate the thermal insulation of the whole clothing system [8, 9]

Thermal manikins are considered the most effective tools to estimate clothing thermal insulation. Several standards have addressed the measurement specification of the thermal insulation using a thermal manikin, since clothing thickness, size, fit and test conditions can influence the thermal insulation performance of the clothing system [10–13]. Cold protective outerwear is always worn with underwear to keep human thermal comfort. The fit styles, combinations and structure of underwear may cause differences in the thermal insulation of outerwear, while the influence introduced by underwear on the deduced outerwear thermal insulation was rarely studied. In addition, testing conditions, such as ambient temperature and relative humidity, are usually kept constant for different kinds of clothing. However, it was reported that the clothing thermal insulation performance can be influenced by the ambient conditions as the airflow in the porous clothing can be enhanced due to the higher temperature difference between human skin and ambient conditions [7].

In the present work, a series of studies was employed to estimate the effect of underwear on the thermal insulation of cold protective outerwear. Besides, the dependence of thermal insulation performance of clothing on the ambient temperature was also investigated. Based on the statistical analysis of winter temperature and humidity of 298 major cities in China, ambient conditions for the assessments of various clothing ensembles were further proposed to simulate the actual-used scenarios. The obtained results could be useful for more accurately evaluating the thermal insulation of clothing systems and help to choose the most suitable clothing for various ambient conditions.

MATERIALS AND METHODS

Samples

A total of seven underwear and nine outerwear (manufactured by K-Boxing Co., Ltd, China) with the same clothing size L were selected in this study. The size of the experimental samples fitted the dimension of the thermal manikin appropriately. Table 1 presents the detailed characteristics of samples, including manufacturing method, structure, colour, fit, material, mass density, thickness and porosity. Samples U1~U7 are underwear and samples O1~O9 are outerwear. Softening finishing was applied to all underwear samples. All samples were dark-coloured to minimize the influence of colour on radiative heat transfer.

Method

The thermal insulation performance of clothing was measured using a thermal manikin (LD-1, Laizhou Electronic Instrument Co., Ltd., China) [8,14]. As shown in figure 1, the front and back of the testers are two independent curved elements. Different sizes of clothes can be measured by adjusting the chest, waist and hem circumferences. The middle parts are testing plates encircled by the guarded plates at the

Table 1

CHARACTERISTICS OF TESTING ENSEMBLES

No.	Product name	Manufacturing method/colour/structure	Material	Density (g/m^2)	Thickness (mm)	Porosity (%)
U1	V-neck sweater	Knitting; Navy; Regular fit	48^S/2/S 100% W	231.4	0.86	79.62%
U2	Round-neck sweater	Knitting; Black; Regular fit	30^S/2/S 100% C	228.6	0.81	81.67%
U3	Crewneck thick cardigan	Knitting; Black; Regular fit	30^S/2/S 100% W	318.2	1.22	80.24%
U4	Crewneck thin cardigan	Knitting; Black; Regular fit	48^S/2/S 100% W	239.2	0.84	78.43%
U5	Turtleneck sweater	Knitting; Black; Regular fit	30^S/2/S 100% W	332.9	1.21	79.16%
U6	Shirt	Woven; Black; Tight fit	120^S/2/S 70% C/26% N/4% SP	187.3	0.27	51.27%
U7	Crewneck thick sweater	Knitting; Black; Loose fit	30^S/2/S 84.5% C/15.5% T	427.9	1.54	81.66%
O1	Medium-long jacket	Navy; Loose fit	100% Cotton	434.7	0.36	-
O2	Suit	Black; Low collar; Tight fit	80% C/20% V;	758.5	1.13	-
O3	Medium-long down coat	Navy; Thick; Regular fit	Surface: 100% T; Filling: 90% Duck down	540.0	16.40	-
O4	Medium-long down coat	Navy; Thick; Loose fit		523.6	16.72	-
O5	Short down coat	Navy; Thick; Regular fit	Surface: 100% T; Filling: 80% Duck down	532.7	12.33	-
O6	Short down coat	Navy; Thick; Loose fit		521.6	12.73	-
O7	Short wadded jacket	Black; Thick; Regular fit	Surface: 100% T; Filling: 100% Cotton	446.8	11.75	-
O8	Short wadded jacket	Black; Thick; Loose fit		418.3	11.92	-
O9	Tweed coat	Navy; Low collar; Tight fit	54.8% W/45.2% T	855.3	7.12	-

Note: C: Cotton; N: Nylon; SP: Spendex; T: Polyester; V: Viscose; W: wool

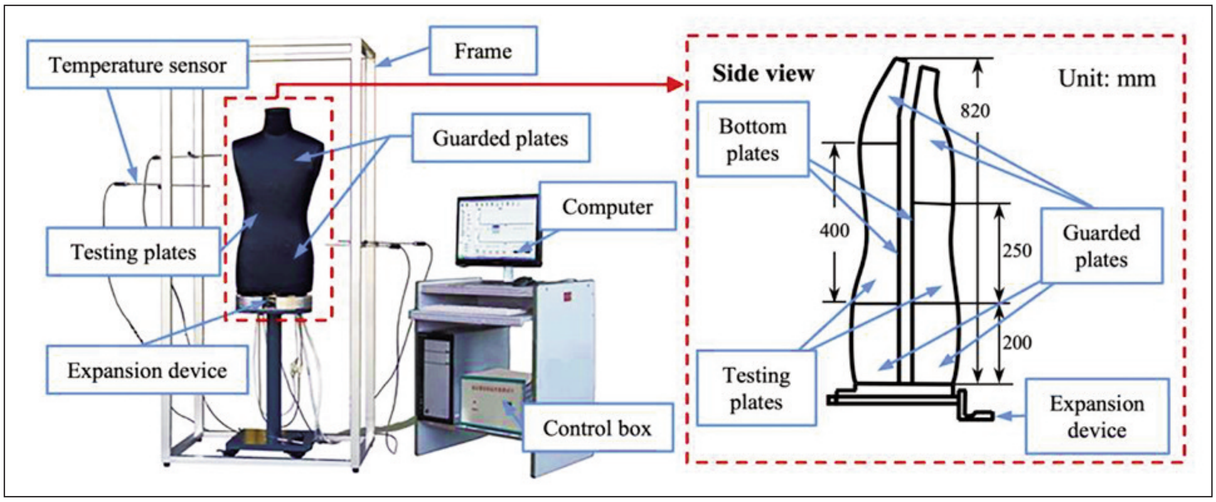

Fig. 1. The structure of LD-1 thermal manikin

neck and waist and the inside surfaces between the front and back elements are bottom plates. The temperature of all plates is controlled at 33±0.2°C to simulate the temperature of the human skin surface. The guarded and bottom plates can effectively reduce the heat dissipation from the collar and low hem of clothing. Moreover, four temperature sensors are fixed 15~30 cm away from the tester to measure the ambient temperature. During the experiment, the generated heat flux of the testing area and associated temperatures are recorded at given intervals.

Measurements for the outerwear thermal insulation with various underwear

According to the clothing thickness, styles and combinations, the outerwear samples were divided into thin outerwear used in cool areas or in spring/autumn (such as sample O1 and O2) and thick outerwear used in cold areas or in winter (such as sample O3), and separately worn with the single thin underwear and two combined underwear to simulate the actual-used scenarios. Three types of outerwear (sample O1~O3) with different thicknesses and styles were selected as typical samples to investigate the dependence of thermal insulation of various outerwear on underwear. The combinations of outerwear and corresponding underwear are shown in table 2.

Table 2

THE CORRESPONDING UNDERWEAR FOR DIFFERENT KINDS OF OUTERWEAR

Case	Outerwear	Underwear
Cool area or spring/autumn	O1/O2	U1, U2, U4, U6, U7
Cold area or winter	O3	U6U1, U2U3, U2U5, U2U7

Clothing ensembles used in cold area and cool areas were conducted in a room with temperatures of 15°C and 55% RH and 22°C and 65% RH, respectively, simulating the indoor conditions of winter and spring/autumn in Yangtze River Delta of China. The ambient temperature and relative humidity in each test were kept constant within ±1°C and ±4%, respectively.

The total thermal insulation I_T (m²·°C/W), effective insulation I_{clu} (m²·°C/W) and intrinsic insulation I_{cl} (m²·°C/W) are determined as follows:

$$I_T = \frac{A_s\,(T_s - T_a)}{H} \quad (1)$$

$$I_{clu} = I_T - I_a \quad (2)$$

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \quad (3)$$

where T_s and T_a are the mean temperature of skin and environment (°C), respectively; H is heat generated from the testing plates (W); A_s is the total surface area of test plates (m²); I_a is thermal insulation of the air layer on the surface of the nude thermal manikin; f_{cl} is clothing area factor.

Intrinsic insulation of clothing ensemble I_{cl_e} (m²·°C/W) can be estimated based on the insulation of individual clothing as [11]:

$$I_{cl\_e} = I_{clu\_o} + I_{clu\_u} \quad (4)$$

where I_{clu_o} and I_{clu_u} are intrinsic insulation of outerwear and underwear (m²·°C/W), respectively.

Measurements for the clothing thermal insulation under various ambient conditions

Seven kinds of cold protective outerwear (O3~O9) worn with underwear ensemble U2U3 were selected to study the effect of ambient temperature on the clothing's thermal insulation performance. Four types of temperature (–10°C, 0°C, 10°C and 20°C) were adopted to simulate various environmental conditions. It was found that although the relative humidity was set at a constant level (65±4%), the actual value was measured at 57±4% for –10±1°C, 61±4% for 0±1°C, 72±4% for 10±1°C and 65±4% for 20±1°C, respectively, as relative humidity cannot be controlled under 10°C. Consequently, winter conditions of 298 major cities in China for 30 years were further investigated to analyse suitable testing environments including temperature and relative humidity for different clothing.

RESULTS AND DISCUSSION

Effect of underwear on thermal insulation performance

Thermal insulation of underwear

Five types of single underwear and four types of underwear ensembles (table 2) were selected to estimate the influence of underwear clothing properties on outerwear thermal insulation. The fit styles of underwear were different, such as tight fit, regular fit and loose fit. Table 3 shows the intrinsic insulation of nine different underwear. The intrinsic insulation of four underwear ensembles was closed with a maximum difference of 9.0%. The insulation of single underwear was different, with the minimum and maximum values 0.0397 m^2·°C/W (sample U6) and 0.0716 m^2·°C/W (sample U7), respectively. This was mainly due to different clothing fit and thickness. Sample U6 was the thinnest sample with the tightest fit and sample U7 was the thickest sample with the loosest fit.

Thermal insulation of cold protective outerwear used in cool area

Two kinds of spring/autumn outerwear, loose fit (sample O1) and tight fit (sample O2), were measured with the corresponding underwear (table 2) to obtain its intrinsic thermal insulation. The thermal insulation was plotted as shown in figure 2, respectively.

In the case of loose-fitting sample O1, as shown in figure 2, *a*, the I_{cl_e} of various clothing ensembles shows similar values, with the minimum value 0.185 m^2·°C/W and maximum value 0.191 m^2·°C/W. It was interesting that although the I_{cl_u} of tight-fitting underwear U6 was lower and the I_{cl_u} of loose-fitting underwear U7 was higher than that of other single underwear (table 3), the thermal insulation of their corresponding clothing ensembles was close to other combinations. This is due to that the thickness of the air gap between the tight-fitting underwear U6 and loose-fitting outerwear O1 was wider than that of other ensembles, leading to additional thermal insulation [15]. Besides, the thickness of the air gap between underwear U7 and O1 was thinner due to the loose-fitting structure of sample U7, and thus the I_{cl_e} of U7+O1 was similar to other ensembles. It suggested that the underwear fit exerted little influence on the thermal insulation of clothing ensembles when outerwear was loose-fitting.

However, the intrinsic insulation (I_{cl_o}) of outerwear O1 measured with different underwear was slightly different, with a maximum difference of 18.3%. Statistic significant test (ANOVA) was further adapted to observe the difference among the I_{cl_o} of outerwear O1 measured with five kinds of underwear. The results indicated that the I_{cl_o} of outerwear O1 measured with U6 and U7 was significantly different from the insulation measured by other underwear at a 95% confidence level. Besides, no significant difference was found in regular-fitting underwear U1, U2 and U4. The results implied that the combination way affected the thermal insulation of outerwear. This significant difference was mainly caused by the obvious difference in thickness and fit styles of U6 and U7.

In the case of tight-fitting sample O2, the thickness of the microclimate air gap among clothing layers was much thinner due to the tight structure of outerwear.

Table 3

THE THERMAL INSULATION OF UNDERWEAR

Parameters	Underwear ensembles				Single underwear				
	U2U3	U2U5	U6U1	U2U7	U1	U2	U4	U6	U7
I_{cl_u} ×10^{-2} (m^2·°C/W)	9.00	9.56	9.74	9.89	6.40	5.90	5.93	3.97	7.16
CV (%)	5.1	3.5	2.9	5.0	6.6	8.8	7.1	5.5	7.0

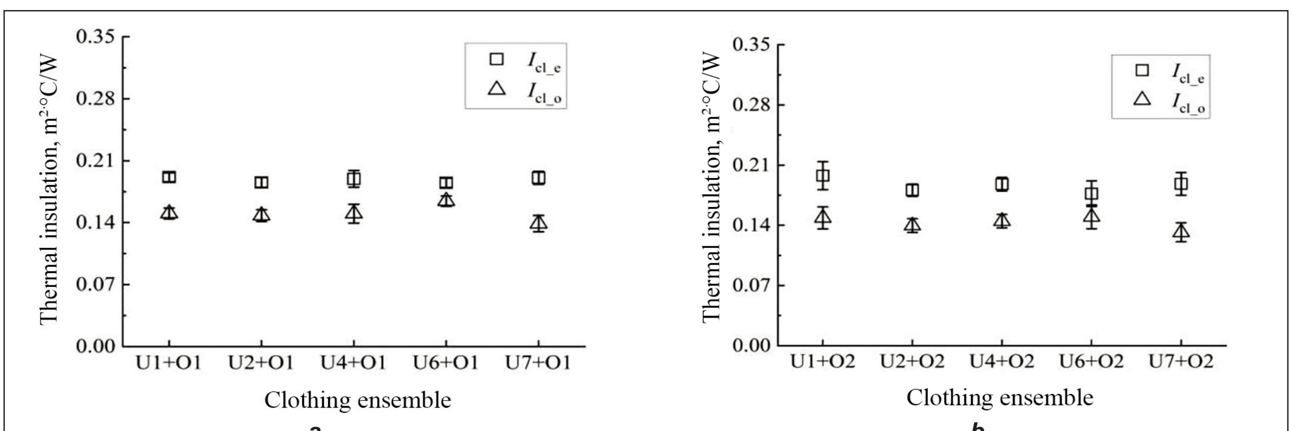

Fig. 2. The thermal insulation of the outerwear sample and its clothing ensembles for sample: *a* – O1; *b* – O2

The results showed that only the I_{cl_o} of outerwear O2 measured with underwear U7 was significantly different from the insulation measured by other single underwear at a 95% confidence level. This was because the thermal insulation of underwear U7 was higher as the presence of a thick air gap between the skin and underwear caused by the loose-fitting structure [16]. While the loose-fitting underwear U7 was in close contact with the skin when it was worn with tight-fitting outerwear, and thus the I_{cl_o} of outerwear O2 deduced from the thermal insulation of underwear U7 was lower, as shown in figure 2, *b*.

Thermal insulation of cold protective outerwear used in cold areas

Outerwear O3 was down clothing used in cold conditions. As presented in figure 3, it was found that the I_{cl_o} deduced from the thermal insulation of various underwear ensembles was similar, with a maximum difference of 3.4%. It was found that the difference between the I_{cl_o} measured with underwear ensembles U2U5 and U2U7 was significantly different at a 95% confidence level. Besides, no significant difference can be detected in the I_{cl_o} of sample O3 measured with other underwear ensembles. I_{cl_u} of underwear U2U7 was higher than that of other underwear ensembles, while the I_{cl_e} of clothing ensemble U2U7+O3 was lower (table 4). This implied that the thickness of down outerwear O3 was compressed when it was worn with sample U2U7 due to the loose-fitting structure of underwear U7, thus resulting in a reduction of still air content in the filling material of sample O3.

The above results indicated that the estimated thermal insulation of the outerwear worn with different fit styles (tight fit, regular fit, and loose fit) and thickness of underwear may exhibit variations. These variations were attributed to differences in the air gap between clothing layers and the presence of stagnant air within the porous clothing, even when the size of the underwear closely matched that of the thermal manikin. Therefore, it is crucial to take into account not only the size but also the fit style and thickness of the underwear during the thermal insulation testing for outerwear.

Testing conditions for various clothing

Effect of ambient temperature on thermal insulation performance

Humans will perceive different thermal sensations when they wear the same clothing ensemble in different ambient conditions. Four different temperature conditions were adopted to examine the influence of ambient temperature on clothing thermal insulation. Outerwear with different thicknesses and fit styles was selected. Sample U2U3 was used as underwear worn with outerwear.

Figure 4 shows the dependence of clothing total thermal insulation (I_T) on the ambient temperature. The I_T of ensembles with filling material (U2U3+O1~O8) was at least 25.0% higher than that of without filling material (sample U2U3+O9) due to the high still air content inside the filling material, as it was reported that the thermal conductivity of air in relative static state was much smaller than that of fibres [17]. Besides, it was found that the I_T of each ensemble kept an approximately constant value when the ambient temperature increased from –10°C to 10°C, after which it slightly rose and the value of I_T increased up to 17.2% when the ambient temperature increased to 20°C except for the ensemble sample U2U3+O9. It is of interest to note that the clothing's porous structure and fit influenced the clothing's thermal insulation in diverse ambient conditions The outerwear O9 was the only one tight fit and without filling material and its fibres contacted closely with each other. The microclimate air gap in ensemble sample U2U3+O9 was thin. The chest circumference of sample O9 was 1.079 m, slightly wider than that of the thermal manikin (0.960 m). While the chest circumferences of the other outerwear ranged from 1.141 m to 1.194 m, representing a 0.062 m to 0.115 m increase compared to sample O9. Therefore, the air content within the clothing system of ensemble sample U2U3+O9 was low. The results implied that the heat flux transferred through ensemble U2U3+O9 in different temperature conditions was mainly by conduction and the ambient temperature exerted little influence on the thermal insulation, which was in agreement with

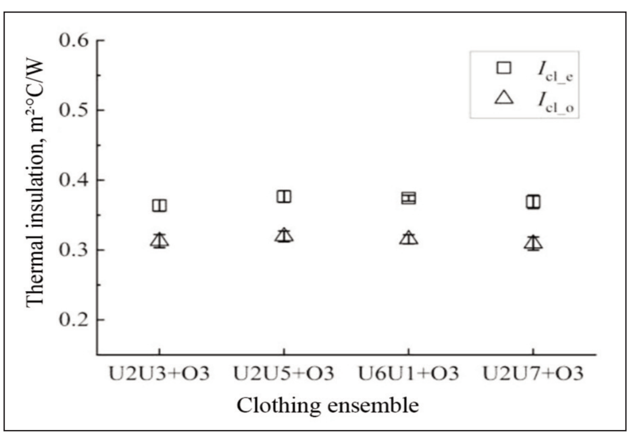

Fig. 3. The thermal insulation of outerwear sample O3 and its clothing ensembles

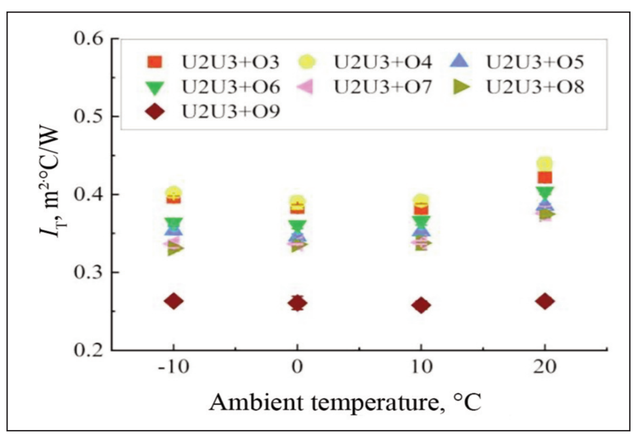

Fig. 4. Clothing total thermal insulation under various temperature conditions

Table 4

RECOMMENDED TESTING CONDITIONS FOR DIFFERENT KINDS OF CLOTHING						
Clothing type	**I_T**		**Winter condition**		**Testing condition**	
	(clo)	**(m^2·K/W)**	***T* (°C)**	**RH (%)**	***T* (°C)**	**RH (%)**
Clothing used in extremely cold conditions	4.8~5.9	0.739~0.911	$-20 \le T \le -10$ (42 cities)	24 cities > 60% RH	–15±2	-
Thick down coat, thickly wadded jacket, etc	3.7~4.8	0.567~0.739	$-10 < T \le 0$ (87 cities)	59 cities 40~60% RH	–5±2	-
Wadded jacket, thin down coat, etc	2.5~3.7	0.395~0.567	$0 < T \le 10$ (119 cities)	110 cities > 60% RH, in which 64.5% of cities 75~85% RH	5±2	80±4
Jacket, suit, tweed coat, etc (without filling material)	1.4~2.5	0.223~0.395	$10 < T < 20$ (41 cities)	40 cities > 60% RH, in which 80% of the city 70~80% RH	12±2	75±4
Thermal underwear	<1.4	<0.223	Common conditioned room		20±2	65±4

the previous work [7]. The increasing thermal insulation of other ensembles was believed to be associated with decreasing convection inside the filling material and microclimate air gap as the temperature difference decreased, leading to smaller equivalent conductivity [18].

Recommended testing conditions for clothing

Ambient temperature has a major influence on the clothing's thermal insulation performance according to the previous section. Besides, as the relative humidity cannot be controlled in low-temperature conditions, the influence of the relative humidity on the thermal insulation performance was not experimentally investigated. The relative humidity may affect the clothing's thermal properties, especially for the textile with a high moisture regain [19].

To determine the testing conditions for various kinds of clothing, the average winter temperature and relative humidity of 298 major cities in China during the 30 years were analysed [20], as illustrated in figure 5. In addition, the winter temperature represents the average temperature of the coldest month in one year. Besides, it was reported that the most comfortable and healthy relative humidity for the human body was 40%~60% [21], the environmental relative humidity was divided into three levels, dry feeling (less than 40%), comfortable feeling and healthy (40%~60%) as well as wet feeling (more than 60%). The classification of ambient temperature and humidity for various kinds of clothes was developed according to the temperature-humidity distribution, as shown in table 4. The total thermal insulation of the clothing ensemble was (I_T) calculated by equation 1 and the heat dissipation per unit area was set to be 1 MET (58.2 W/m^2). It means that when a human is exposed to different conditions, the heat dissipation of the body surface is maintained at about 58.2 W/m^2 to keep comfortable by wearing clothes with different thermal properties [22]. As a result, the testing condition was developed for various clothing as shown in table 4.

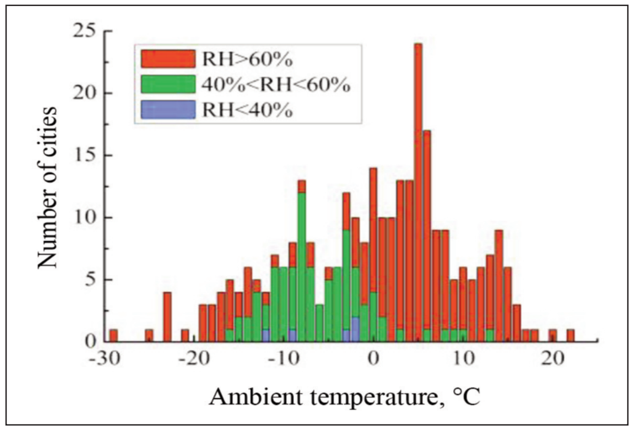

Fig. 5. Temperature-humidity distribution in China

CONCLUSIONS

A series of tests were carried out to investigate the influence of underwear on the measurements of clothing insulation of cold protective outerwear. The study reveals that even when the size of the underwear was suitable for the thermal manikin, variations in the thermal insulation of the outerwear may still occur. These fluctuations were caused by the discrepancy in the air gap between clothing layers and variations in the stagnant air within the porous fabric, as the fit styles and thicknesses of corresponding underwear were different. Consequently, in thermal insulation testing for outerwear, it is crucial to consider not only the size of underwear but also appropriate styles and thickness.

We also examined the influence of ambient temperature on the thermal insulation of clothing ensembles. Thermal insulation of clothing with filling material was observed to increase with ambient temperature from 10°C to 20°C since the convection inside the clothing system was decreased. Thermal insulation of a tight-structure clothing system was observed nearly unchanged, as the fibres of such clothing contacted closely with each other. Then testing ambient conditions for various clothing was divided into 5 groups according to the analysis of winter environment.

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