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An effective method to determine bedding system insulation based on measured data

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Abstract

The thermal environment is an essential factor that affects sleep quality. In many circumstances, the bed microenvironment is more important than the ambient environment because of the large covered area of the human body and the close contact between the bedding system and the human body. The main objective of this research is to establish an effective method to determine bedding system insulation. A thermal manikin was used in the measurement of bedding system insulation. Three different types of quilts, which were filled with cotton, polyester and duvet respectively, were chosen to be tested. In total ten different quilts with different materials and weights were involved in the test. Four regular arrangements of covers were chosen with coverage rates of 94.1%, 85.9%, 70.6%, and 54.4% to test. A total of 64 bedding systems were tested to build an effective method to determine the bedding system insulation. On the basis of test data, the change of bedding system insulation with coverage was found to be nonlinear. Exponential fitting was applied to establish an insulation evaluation method for bedding system insulation. In addition, the effects of quilt cover and sleepwear on bedding system insulation were discussed and thermal insulation increment caused by quilt cover and sleepwear were estimated. The relationships between neutral indoor temperature and weight per unit area of the quilt for different coverage rates have been quantified based on existing subject experiments. This research provides an effective method to determine bedding system insulation, which can be widely used in thermal comfort research and HVAC system design.

Keywords

sleep environment;
bedding system;
thermal insulation;
thermal comfort

Article History

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1 Introduction

Humans spend almost a third of their lifetime sleeping (Aminoff et al. 2011). Many scientific studies have confirmed the important function of sleep in overcoming fatigue and recovering energy (Siegel 2005). Sleep deprivation may cause damage to body systems, resulting in mild cognitive impairment, increased risk of type 2 diabetes and cardiovascular disease, and an impaired immune system (Gangwisch et al. 2005; Pannain et al. 2012; Xie et al. 2013; Milewski et al. 2014; Rudnicka et al. 2017). Therefore, it is essential to improve human daily sleep through rational and effective methods. Compared with physiological and psychological therapy, environmental control is an effective method to potentially influence human sleep without health-related side effects. The thermal environment is an important factor affecting sleep quality. Since the 1970s many experimental studies have focused on the relationship between the thermal environment and sleep. In previous studies, sleep experiments were performed without any coverings. Haskell et al. (1981) conducted hot and cold exposure sleep experiments and found that a cold sleeping environment leads to less total sleep time, slow-wave sleep (SWS), rapid eye movement (REM) sleep, increased sleep onset latency (SOL), and more awakening times. A recent study also investigated the effects of heat and cold exposure on the sleep of subjects wearing short-sleeved sleepwear and covered with blankets (Lan et al. 2014). The results

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List of symbols

f	area fraction of the segment	Q_{sk}	total heat flow rate on the manikin surface (W/m^2)
i	number of the body-segment	q_{sk}	heat flow rate of the segment (W/m^2)
I	insulation of bedding system excluding quilt cover and sleepwear (clo)	R_T	total resistance of the bedding system (m^2·K/W)
I_s	insulation of sleepwear (clo)	R_b	thermal resistance between uncovered body and environment (K/W)
I_T	total insulation of bedding system (clo)	R_c	thermal resistance caused by covering (K/W)
ΔI_c	increment of bedding system insulation caused by quilt cover (clo)	R_m	thermal resistance caused by mattress (K/W)
ΔI_s	increment of bedding system insulation caused by sleepwear (clo)	t_o	operative temperature of the environment (°C)
K	unit constant equals 6.45 clo·W/(m^2·K)	t_{sk}	skin temperature of thermal manikin (°C)
P_c	coverage rate	w	weight per area of a quilt or other bedding system (kg/m^2)

indicated that the subjects took a longer time to fall asleep and experienced a shorter period of SWS when the room temperatures were moderately deviated from neutral. Some field studies also provide proof that the thermal environment affects sleep quality. Tsuzuki et al. (2015) conducted a survey in different seasons of a year to investigate the effects of seasonal illumination and ambient thermal environments on sleep in elderly men and found that the SOL in winter is higher than that in spring and autumn. The studies of Wang et al. (2015), Song et al. (2016), and Cao et al. (2022) affirm the negative effects of a cold environment on thermal sensation and comfort before sleep.

Fanger formulated the predicted mean vote (PMV) function to evaluate the thermal environment (Fanger 1970), which is recognized by ASHRAE Standard 55 (ASHRAE 2017) to guide HVAC system design. However, the PMV model has limitations and many scholars made different efforts with new models sprung up (Lai et al. 2020; Wu et al. 2021). The PMV index can only be applied to predict thermal sensation when subjects are awake. The thermal sensation differences between awake and sleeping person have been proven by Pan et al. (2012) and Zhang et al. (2018). The flexibilities of thermal adaption are also different between awake and sleeping person, especially the physiological and behavioral adaptations (Nicol et al. 2012). When humans are awake, they are aware of and capable of adjusting garment insulation and controlling the facilities (Zhang et al. 2022) to achieve temperature neutrality by adding or removing clothing. People who fall asleep, on the other hand, will have their temperature adaption abilities impaired (Bach et al. 2002). To optimize thermal comfort and sleep quality, it is critical to select beddings with proper insulation levels. The ambient environment, bedding system (including mattress, quilt, pillow, and sleepwear) and human body jointly build a microclimate for sleeping people, which can affect the human body directly. The effects of the thermal environment on sleep depend on bedding systems. Like the building envelope (Amraoui et al. 2021), the bedding system provides insulation between the ambient environment and the human body. Currently, there is few reference value that can be used directly on the thermal insulation of the bedding system, nor is the standard calculation method for bedding insulation.

Table 1 shows a comparison of the existing research measurements of bedding insulation. All researchers used thermal manikins to measure bedding system insulation. Although concluding some linear formulas in the research, McCullough et al. (1987) mainly focused on the covering of blankets which were widely used in western countries at that time. In the subsequent analysis, the linear relationship was found could not elucidate the changing of thermal resistance by the weight of coverings. Lin and Deng (2008) compared the thermal resistance differences between conventional mattress and zongbang bed, which is commonly used in southern region of China. Only four coverings were included in Lin and Deng's research and no calculation formula has been obtained. Lu et al. (2021) tested different bedding systems and provided fitting equations respectively for three bedding systems filled with silk, wool, and down. In Lu et al.'s research, the effect of different postures of thermal manikin on bedding system insulation has been investigated. Wilson and Chu (2005) investigated thermal insulation of selected eastern and western infant bedding combinations, and discussed insulation level differences in relation to environmental conditions among countries and between seasons. Wilson et al. (1999) also explored the estimation for thickness and thermal resistance of bedding assembly with experiments, and concluded that it was applicable to estimate the corresponding properties of flat beddings with measured values of single layers. Pan et al. (2010) applied a mathematical model to describe the bedding system. The bedding system was simplified to a trapezoid and the human body to a rectangle inside the

Table 1 Comparison of the existing measurement research of bedding insulation

	McCullough et al. 1987	Lin and Deng 2008	Lu et al. 2021
Type of mattress	Cotton mattress	Conventional mattress/Zongbang bed	Down mattress
Type of sheet	None	Cotton sheet/Straw mat	Cotton sheet
Number of covering	22	4	15
Number of sleepwear	4	2	0
Number of coverage	17	8	4
Type of sleep position	Supine	Supine	Supine/lateral

trapezoid. One of the variables used in these studies is bedding thickness under standard pressure, which is difficult to measure and then hard to use in practice.

The main purpose of this research is to establish a prediction method to evaluate bedding system insulation, which can be easily applied in thermal comfort research. Many standards have stipulated the testing procedure for the thermal resistance measurement that can provide valuable references for this study. ASTM-F1291 (ASTM 2010) provides method for measuring the thermal insulation of clothing using a heated manikin. ASTM-F1291 demands that the skin surface temperature of thermal manikin's each segment is kept at 35 °C and the minimum heat flow rate is 20±10 W/m^2. ISO 9920 (ISO 2009) requires that the skin surface temperature of each segment should be the same, ranging from 32 to 34 °C. The relative humidity requirements of ASTM-F1291 and ISO 9920 are the same at 30%–70%. ISO 23537 (ISO 2016, 2022) focuses on the thermal, mass and dimensional requirements for sleeping bags. It provides test methods and requirements of lower temperature limits for sleeping bags. As prescribed in ISO 23537-1:2022, the repeatability of the measurement on each sleeping bag shall be better than 4% (variation coefficient), which can be applied to our research.

2 Method

2.1 Testing objects

The total thermal resistance of the bedding system refers to the blocking effect (thermal resistance) of the bedding system composed of bed, mattress, sheet, pillow, coverings (such as quilt and blanket) and pajamas on the heat emission of the human body in lying state, and the unit is 1 clo (0.155 m^2·K/W). Different from the definition of clothing insulation, the bedding system insulation generally includes the thermal resistance of the air layer on the outer surface of the bedding system. The thermal environment inside bedding depends on the indoor thermal environment and the thermal property of the bedding system, which affects the thermal comfort of the human sleep state.

Based on our previous investigation about sleeping habits in China (Zhang et al. 2018), quilts filled with three different materials: polyester, down and cotton, were chosen to obtain the actual insulation data of commonly used bedding systems. Besides quilts, cotton sheet, cotton pillow, conventional mattress and two kinds of sleepwear were included in the testing bedding system. Cotton sheet, cotton pillow and conventional mattress were basic and constant condition. Specific data of testing objects are listed in Table 2. All the quilts are the same size (1.5 m × 2.0 m). Since in real sleep the proportion of the body surface area covered by the bedding system is variable, four common forms of coverage were chosen with the coverage rates of 94.1%, 85.9%, 70.6% and 54.4% to test. The data for coverage rates originate from the research of McCullough et al. (1987). Figure 1 shows the schematic of the four covering forms. A total of 64 bedding system groups were tested and used to build an effective method to determine the bedding system insulation, as listed in Table 3.

2.2 Testing procedure

Similar to clothing insulation testing, a thermal manikin, named Newton, was applied to the measurement of bedding system insulation. As shown in Figure 2, Newton is a thermal manikin with the geometry of the average Asian male body, which consists of 20 segments. Each segment has independent heating and computer control system. The skin surface temperature and heat flow rate of the 20 segments can be controlled separately. Table 4 also shows the skin surface area and the area factor of each segment.

According to existing standards and sleep research, the testing conditions of this study were determined to be 35 °C for each segment and 22 °C for ambient temperature, which are different from the previous measurement research of McCullough et al. (1987), Lin and Deng (2008). In their studies, the temperature setting of hands and feet is lower than other body segments. The mean skin temperature settings for hands and feet was 29.4 °C and for the whole body was 33.3 °C in McCullough's measurements. The

Table 2 Measured parameters of bedding items

Type	Number	Description	Total weight (kg)	Weight per area (kg/m^2)
Polyester quilt	P1	Filling: 100% polyester Cover: 100% polyester	0.966	0.322
	P2		1.544	0.515
	P3		2.372	0.791
	P4		2.774	0.925
Down quilt	D1	Filling: 100% down Cover: 100% cotton	1.495	0.498
	D2		1.904	0.635
	D3		2.946	0.982
Cotton quilt	C1	Filling: 100% cotton Cover: 100% cotton	1.940	0.347
	C2		2.894	0.665
	C3		3.988	1.029
Short-sleeved sleepwear	S1	100% cotton	0.248	—
Long-sleeved sleepwear	S2	100% cotton	0.586	—
Quilt cover	QC	100% cotton	0.956	—
Sheet	—	100% cotton	—	—
Pillow	—	Filling: 100% cotton Cover: 100% cotton	—	—
Mattress	—	Filling: 100% polyester Cover: 100% polyester	—	

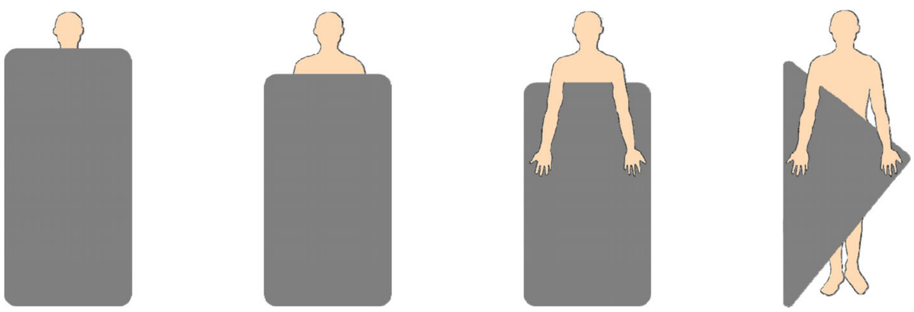

Fig. 1 The schematic of the four covering forms

Table 3 Tested bedding system groups

Quilt	Coverage rate	Quilt cover	Sleepwear	Sum
P1, P2, P3, P4 D1, D2, D3 C1, C2, C3	94.1%; 85.9%; 70.6%; 54.4%	×	×	40
P1, P2, P3, P4	94.1%; 54.4%	√	×	8
P1, P2, P3, P4	94.1%; 54.4%	√	S1	8
P1, P2, P3, P4	94.1%; 54.4%	√	S2	8
			Total sum	64

mean skin temperature settings were 31 °C for hands and feet and 35 °C for other body segments in Lin and Deng's measurements. Based on existing sleep thermoregulation research (Kräuchi et al. 1999; Lan et al. 2016; Zhang et al. 2019), the distal–proximal temperature gradient during sleep is close to zero, ranging from −1 to 0 °C. Consequently, we chose the uniform skin temperature for different segments as a better parallel with the actual situation. The relative humidity was controlled between 40% and 50%. Figure 3 shows the testing of a down quilt bedding system (without quilt cover and sleepwear) with coverage rates of 85.9% and 54.4%. Air temperature, globe temperature and relative humidity were continuously monitored and recorded during the whole test period.

2.3 Data processing

Every bedding system was tested repeatedly three times, which took about 3 hours. According to ISO 23537-1:2022

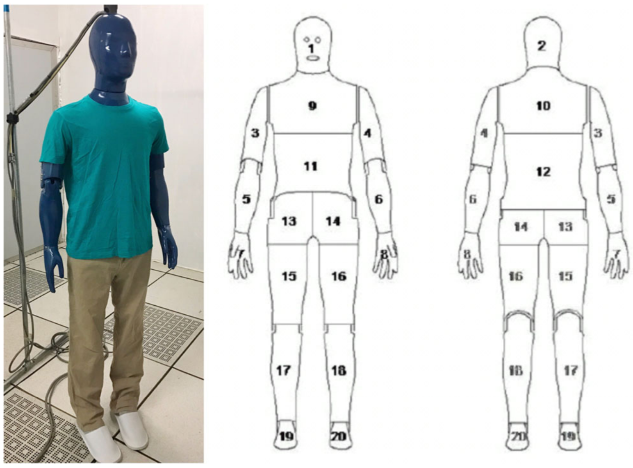

Fig. 2 The thermal manikin Newton

Table 4 The skin surface area and the area factor of each segment

No.	Segment	Area (m^2)	Area fraction
1	Face	0.047	0.028
2	Head	0.094	0.055
3/4	R/L Upper arm	0.069	0.040
5/6	R/L Forearm	0.061	0.036
7/8	R/L Hand	0.046	0.027
9	Chest	0.121	0.071
10	Shoulders	0.101	0.059
11	Stomach	0.119	0.070
12	Back	0.094	0.055
13/14	R/L Hip	0.081	0.047
15/16	R/L Thigh	0.127	0.074
17/18	R/L Calf	0.121	0.071
19/20	R/L Foot	0.060	0.035

(ISO 2022), the repeatability of the measurement on each bedding combination is better than 4%. The average value of three tests was regarded as the actual measured thermal insulation of the tested bedding system. The data recorded in the last five minutes of each test, when the manikin was in thermal equilibrium, were used to calculate total bedding system insulation. Figure 4 shows the testing data of thermal manikin's right upper arm when the bedding system was composed of P2, quilt cover and long-sleeved sleepwear with the coverage rate of 94.1%. The figure includes data from three tests of the bedding system. The shadow parts in the Figure 4 are the data used to calculate the thermal insulation. The bedding system insulations were calculated using Eq. (1).

$$I_{\mathrm{T}} = K \times \frac{\overline{t_{\mathrm{sk}}} - t_{\mathrm{o}}}{Q_{\mathrm{sk}}} = K \times \frac{\sum_{i=1}^{20} f_i \times t_{\mathrm{sk},i} - t_{\mathrm{o}}}{\sum_{i=1}^{20} f_i \times q_{\mathrm{sk},i}} \tag{1}$$

(a)

(b)

Fig. 3 Testing of a down quilt bedding system with different covering percentages: (a) 85.9%; (b) 54.4%

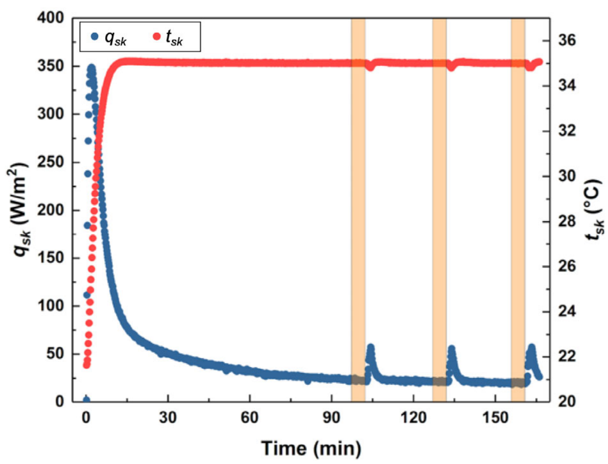

Fig. 4 The testing data of thermal manikin's right upper arm (P2, QC, S2, and 94.1%)

3 Results

3.1 Measured bedding system insulations

According to measured data and accepted heat transfer principles, the total insulation of different bedding systems was calculated. When the naked manikin lies flat on the mattress, the bedding system, consisting of air layers and mattress, has a measured insulation value of 0.95 clo. Table 5 shows the specific values of measured insulation data of different bedding systems. The higher weight per area and coverage rate, the higher the total bedding system insulation. The insulation of the three different kinds of bedding systems share a similar pattern of change with weight. The results show that bedding system insulation is hardly affected by the filling materials but has a strong relationship with weight per area and coverage rates.

3.2 Comparing the results of different filling materials

Figure 5 shows the comparison of the bedding system insulations with different filling materials under the same coverage rate. It can be concluded from the figures that the thermal insulations of bedding systems with different filling materials have no significant difference in this study. The correlation between the thermal insulation and the parameters of filling material type, filling weight, and coverage is analyzed with statistical methods. For the type of filling material, with the verification of normality test within each type and the homogeneity of variance test, no significant correlation to the thermal insulation is found via ANOVA. Then, for the filling weight and coverage, the Spearman correlation test is performed since the overall samples are not of a normal distribution, and the results for both parameters show significance at $p < 0.05$ level. The detailed indicators are presented in Table 6. In general, for the three influential factors concerned in this study, the thermal insulation is mainly affected by filling mass per unit area and coverage rate.

As shown in Figure 5, the influence of weight per unit area on bedding system insulation varies at different coverage rates. When the whole body of the manikin is covered with the only head exposed to the air, the higher the weight per unit area of the quilts, the higher the total thermal insulation of the bedding system. The change tendency of high coverage rate is more obvious than that of low coverage rates. As more and more body parts of the thermal manikin are exposed to the air (Figure 5), the influence of the weight per unit area on the total thermal insulation becomes less and less.

Table 5 Measured bedding system insulations

	94.1%	85.9%	70.6%	54.4%
P1	2.74	2.14	1.75	1.53
P2	3.30	2.55	2.02	1.70
P3	4.09	3.01	2.23	1.75
P4	4.39	3.06	2.40	1.78
D1	3.35	2.45	1.98	1.74
D2	3.95	2.76	2.28	1.80
D3	4.49	3.14	2.37	1.85
C1	3.70	2.80	2.21	1.71
C2	4.59	3.39	2.45	1.82
C3	4.89	3.47	2.57	1.85
P1+QC	2.81	—	—	1.56
P2+QC	3.51	—	—	1.77
P3+QC	4.24	—	—	1.83
P4+QC	4.55	—	—	1.94
P1+QC+S1	3.10	—	—	1.61
P2+QC+S1	3.71	—	—	1.80
P3+QC+S1	4.43	—	—	1.92
P4+QC+S1	4.61	—	—	1.99
P1+QC+S2	3.11	—	—	1.70
P2+QC+S2	3.73	—	—	1.92
P3+QC+S2	4.44	—	—	2.15
P4+QC+S2	4.65	—	—	2.23

3.3 Effects of quilt cover and sleepwear

Quilt covers are commonly used in China to keep the comforter clean, which can add two air layers to the bedding system and then increase the thermal resistance. Sleepwear has a fixed thermal resistance and also adds air layers in the bedding system, resulting in an increase in the thermal insulation of the total bedding system. The two kinds of sleepwear chosen in this study were measured using the same thermal manikin to determine their clothing insulation. The air layer insulation of the naked and standing thermal manikin is 0.65 clo. The short-sleeved sleepwear and long-sleeved sleepwear have insulation of 0.30 clo and 0.53 clo respectively. The effects of quilt cover (QC) and sleepwear (S1 and S2) on bedding system insulation were estimated by measuring the polyester filling bedding systems with a quilt cover and different sleepwear under the highest and lowest coverage rates of 94.1% and 54.4%. Figure 6 shows the measurement results. It can be concluded that the effect of bedding system insulation is no different whether short or long sleepwear is worn is no different when the coverage is high. The higher the weight per area, the less the increase in total insulation. When the coverage is low, the influence of short-sleeved sleepwear is small, and long-sleeved sleepwear can significantly increase the thermal resistance of the bedding system. Quantitative estimations on the change of bedding system insulation caused by quilt cover and sleepwear are demonstrated in Section 3.4.

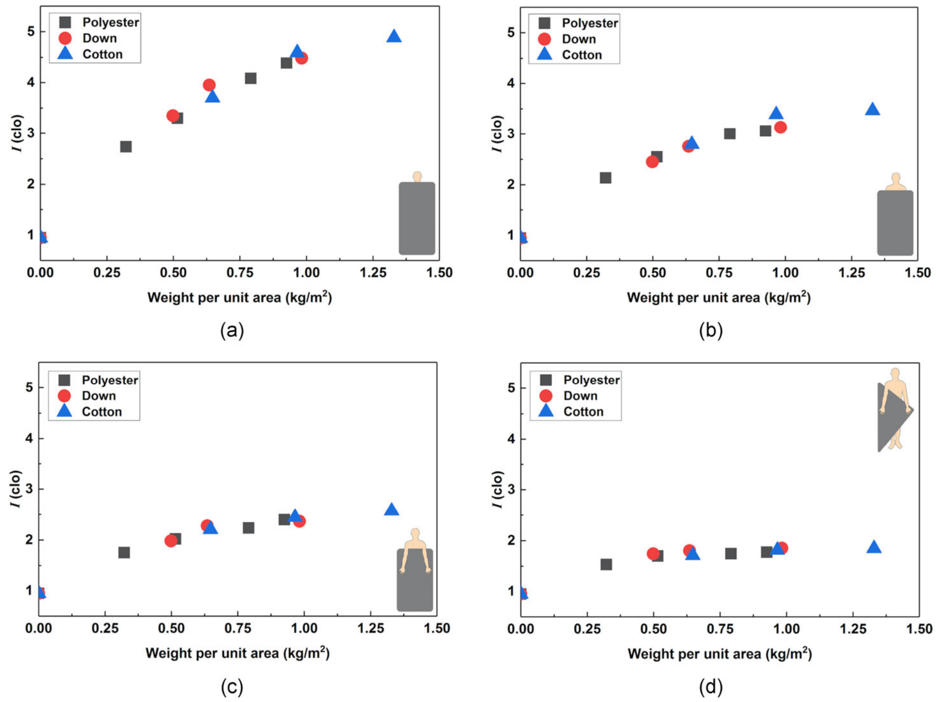

Fig. 5 Comparison of the bedding system insulations with different filling materials under the same coverage rate: (a) 94.1%; (b) 85.9%; (c) 70.6%; (d) 54.4%

Table 6 Correlation analysis of influencing factors and thermal insulation of bedding system

Influencing factors	Variable type	Test method	Correlation indicator/F-statistic	p value	Significance
Filling material	Categorical variable	ANOVA	0.722	0.493	Not significant
Filling weight	Numerical variable	Spearman	0.327	0.040	Significant
Coverage	Numerical variable	Spearman	0.918	< 0.001	Significant

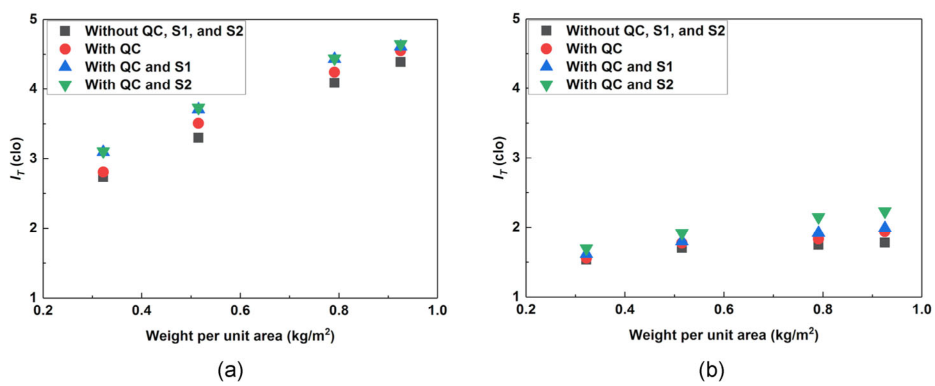

Fig. 6 The measurement results of bedding systems with or without quilt cover and different sleepwear under two body coverage rates: (a) 94.1%; (b) 54.4%

3.4 Establishment of a bedding system insulation calculation model

As analyzed in Section 3.2, the total thermal insulations of bedding systems with different filling materials (polyester, duck down, and cotton) have no significant difference in this study. Without considering the influence of the filling material, the thermal insulation of the bedding system (I) is a function of the weight per unit area of the quilt (w) and the coverage (P_c). The value range of the coverage rate is 54.4%–94.1%, and the value range of the weight per unit area of the quilt is 0.2–1.3 kg/m^2.

It can be seen from Figure 7 that the change of total bedding system insulation against weight per area is not

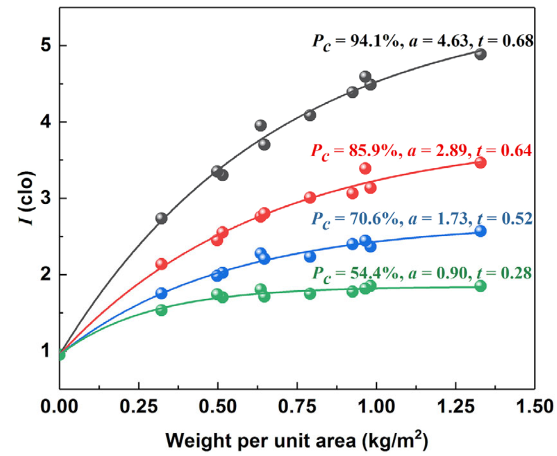

Fig. 7 First-order decay exponential fitting curve of bedding system insulation

linear. After sifting through possible functions, an exponential function was chosen to fit the measured data. Four fitting curves are shown in Figure 7, and the fitting correlation coefficients are above 0.99. Equation (2) is a first-order fitting formula. In the formula, 0.95 is a fixed intercept, derived from the thermal insulation of the bedding system with only the naked manikin lies flat on the mattress. The independent variable used in the fitting is the weight per unit area, and for the four coverage rates, four sets of fitting coefficients a and t are obtained.

$$I = a[1-\exp(w/t)]+0.95 \quad (2)$$

Further analysis of the fitting coefficients a and t shows the first-order decay exponential function relationship between fitting coefficients and the coverage rates, as illustrated in Figure 8. Equations (3) and (4) are the deterministic relational expressions of the fitting coefficients a and t. Therefore, under the condition of known coverage rate (P_c), the coefficients a and t can be determined. And

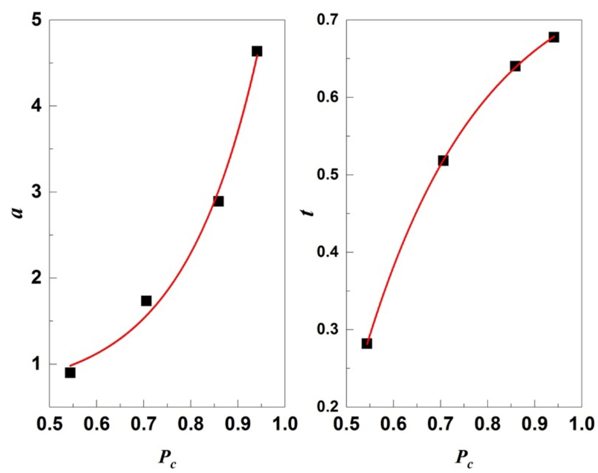

Fig. 8 Determination of fitting coefficients a and t

then the weight per unit area (w), a and t can be substituted into Eq. (2), to calculate the bedding system insulation.

$$a = 0.012\exp(P_c/0.162)+0.644 \quad (3)$$

$$t = -4.33\exp(-P_c/0.252)+0.782 \quad (4)$$

As analyzed in Section 3.3, the total thermal resistance of the bedding system will increase resulting from the increased air layer provided by the quilt cover. The thermal insulation increment caused by quilt cover is related to the weight per unit area and coverage rate. A function of the weight per unit area and coverage rate can be established to estimate the insulation increment. Equation (5) is the formula for estimating the thermal insulation increment by applying multiple linear regression fitting. The thermal insulation increment caused by sleepwear is related to the insulation of sleepwear. In the case of high quilt coverage, there is no difference in the increase of thermal insulation caused by the insulation of sleepwear. Meanwhile, the higher the weight per unit area, the less the increase in total thermal insulation. Compared with sleepwear with small insulation, sleepwear with higher insulation can significantly increase the bedding system insulation when coverage is low. Therefore, the thermal insulation increment caused by sleepwear is a function of weight per unit area, coverage rate, and sleepwear insulation. Equation (6) is the formula for estimating the thermal insulation increment caused by sleepwear by applying multiple linear regression fitting. It should be noted that when the bedding system does not contain a quilt cover or sleepwear, the thermal insulation increment should be zero.

$$\Delta I_c = f(w, P_c) = 0.146w + 0.168P_c - 0.1 \quad (5)$$

$$\Delta I_s = f(w, P_c, I_s) = -0.045w + 0.157P_c + 0.391I_s - 0.07 \quad (6)$$

In summary, the total thermal insulation of the bedding system can be calculated by adding the thermal insulation of the beddings (excluding the quilt cover and sleepwear), the thermal insulation increment of the quilt cover and the thermal insulation increment of the sleepwear, as shown in Eq. (7). Therefore, a bedding system insulation calculation model is established. Figure 9 shows the calculation flow chart of the model. The model should be applied in the range of P_c between 54.4% and 94.1%, w between 0.2 and 1.3 kg/m^2. The extrapolation of the model application interval needs further validation.

$$I_T = I + \Delta I_c + \Delta I_s = f(w, P_c, I_s) \quad (7)$$

According to this model, the bedding system composed of quilts made of porous and fluffy filling materials can be

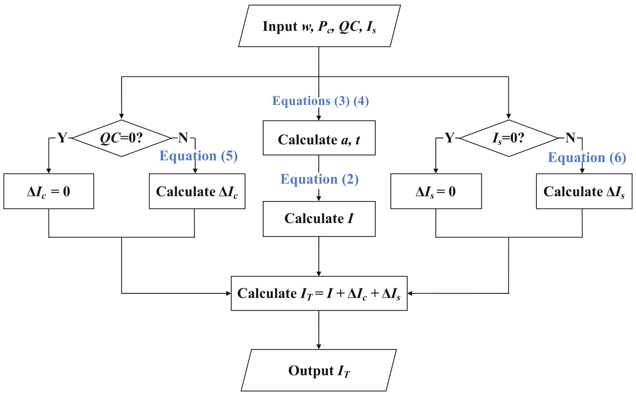

Fig. 9 Calculation flow chart

predicted under the conditions of known weight per unit area, coverage rate and sleepwear insulation. Compared with the measured results, the predicted results calculated by the model have high accuracy (Figure 10).

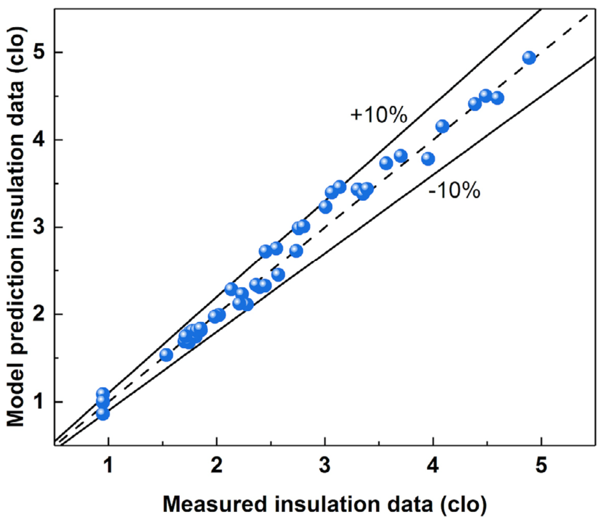

Fig. 10 Comparison of measured data and model prediction data

4 Discussions

4.1 Comparison to other studies

Some earlier studies mainly measured the insulations of polyester filling bedding. To ensure fair and valid comparisons, only polyester filling bedding types were investigated. The body surface coverage rate chosen in comparison was 94.1%. Long-sleeved sleepwear was included in the bedding system. In Pan's model (Pan et al. 2010), the total insulation of the bedding system is a function of the thickness of the quilt and body surface coverage rate. Figure 11 shows a comparison of our study and three existing studies, including two measurement studies and a model study. It can be concluded that the results of our study are in conformity with McCullough's measurement study (McCullough et al. 1987) and Pan's prediction model (Pan et al. 2010), but lower than the value of Lin's study (Lin and Deng 2008).

The aforementioned studies provide important basis for the bedding research. Meanwhile, further studies are needed since the number of different quilts and parameters considered before are limited. Appropriate mathematical descriptions on the effects of filling weight and coverage are also necessary to be addressed. In this study, a wider range of quilt weights with multiple types of filling materials are considered for various coverage conditions in the experiments. The obtained results are fitted as an exponential correlation for thermal insulation corresponding to weight per unit area. In addition, the effects of quilt cover and sleepwear on bedding system insulation were discussed and thermal insulation increment caused by quilt cover and sleepwear were estimated in our work.

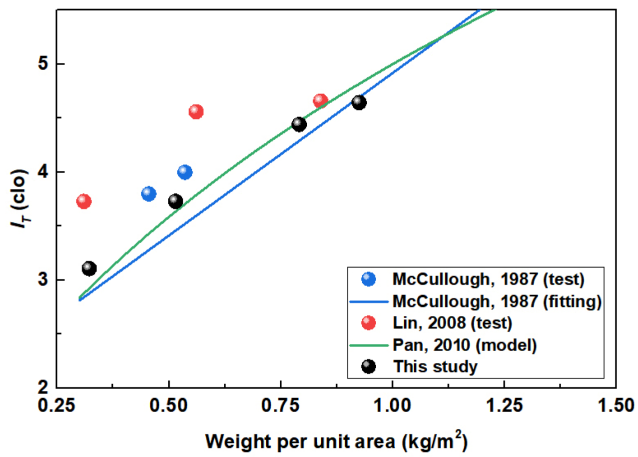

Fig. 11 Comparison with different studies (Lin and Deng 2008; Pan et al. 2010; McCullough et al. 1987)

4.2 Analogical analysis of nonlinearity of bedding system insulation

To better understand the nonlinearity of the change of bedding system insulation, an electrical analogy can be applied to the analysis. Pan et al. (2010) provided similar analysis in their study based on the assumption that the section of a human body is a rectangle and the shape of the bedding covering the human body is a trapezoid. Figure 12 shows the resistance nodes of a bedding system which can be divided into three portions: the resistance caused by covering (R_c), the resistance caused by mattress (R_m), and the resistance of the air layer between uncovered body and environment (R_b).

The total resistance of a bedding system can be calculated by Eq. (8). The heat transfer between the covered body and the environment includes three parts: conductive,

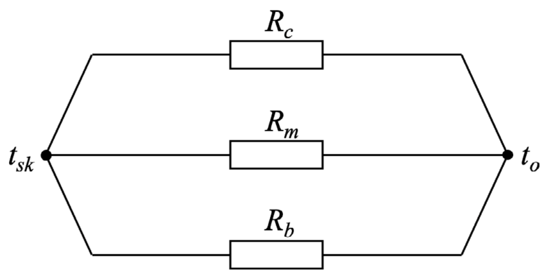

Fig. 12 Resistance nodes of the bedding system

convective, and radiative heat transfer between the body and the internal surface of the covering; heat conduction of covering; convective and radiative heat transfer between the external surface of the covering and environment. Under steady-state conditions, the conventional mattress can be assumed to be adiabatic. The R_m approaches infinite and Eq. (8) can be simplified to Eq. (9). Therefore, the resistance of the bedding system (R_T) is a nonlinear function of the covering resistance (R_c).

$$\frac{1}{R_T} = \frac{1}{R_c} + \frac{1}{R_m} + \frac{1}{R_b} \tag{8}$$

$$\frac{1}{R_T} = \frac{R_c R_b}{R_c + R_b} \tag{9}$$

4.3 Discussion on the effect of filling materials and sleeping posture

The quilts tested in the experiments of this study are randomly selected among the top-selling items from the e-commerce platform in China. Although there is no significant effects of the tested filling materials on thermal insulation of the bedding system in this study, further investigation should be conducted with more types and various specifications of filling materials for better illustration. McCullough et al. (1987) proposed linear fitting formulas of bedding system taking into account mainly thickness, weight, and the amount of body surface area covered by the bedding and clothing components, which is similar to our conclusion. Another research investigated three different bedding systems filled with down, wool, and silk (Lu et al. 2021). And the research confirmed the thermal resistance differences between the beddings filled with different materials. Whether the accurate calculation of bedding system insulation can ignore the material difference is inconclusive and needs further research.

In addition, the down feather quilts were expected to achieve high thermal insulation performances, while no significant advantage is observed in this study. Aside from the influencing factors considered in this study, the filling power (EN 2018) is also an essential parameter for down quilts. The higher of filling power, the higher of thermal resistance. Therefore, the tested duvets in this study may have a low filling power, resulting in thermal performance comparable to cotton and polyester beddings.

More studies are needed to explore the material difference and measure the insulations of bedding made of other materials. Considering that all the beddings used in this study are new, the attenuation of bedding insulation over time may also require further investigation. During the daily use, the fabric will absorb the moisture emitted by the human body and the moisture in the environment. Studies show that the thermal conductivity of fabrics like cotton and NOMEX, will increases 0.01 W/(m·K) along with the 10% increasing of relative moisture content absorbed in samples (Bogusławska-Baczek and Hes 2011; Hes et al. 2014).

The bedding system insulation can be affected by the sleeping posture. Lu et al. (2021) investigated the thermal resistance difference of supine, sideways and crouching sleeping using the same beddings. The result shows no significant difference between the thermal insulation obtained in supine and sideways posture. The crouching posture can provide highest thermal resistance because of the reduction of heat dissipation. Another research compared the thermal resistance difference of supine, prone and lateral posture (Zhu 2017). It can be concluded that supine posture provides highest insulation while side-lying posture provides lowest insulation, but the difference was not significant. More scientific research is needed in the future to clarify the effect of posture on thermal insulation.

4.4 The effect of bedding weight on comfortable indoor temperature

Based on the above tests and results, how can we choose appropriate bedding and set comfortable night bedroom temperatures in daily life? Our previous study provided a comfort zone of bedding insulation and air temperature on the basis of subject experiments (Zhang et al. 2020). According to the comfort zone, the relationships between neutral indoor temperature and weight per unit area were calculated. The curves in Figure 13 show the relationships between neutral indoor temperature and weight per unit area for different coverage rates.

It should be noted that the thermal insulation of the bedding is transformed into a relationship between the weight per unit area of the quilt and the coverage, without considering the thermal insulation increment caused by sleepwear. As illustrated in Figure 13, for the same quilt, the corresponding neutral temperature is different for different coverage rates. The differences in neutral ambient

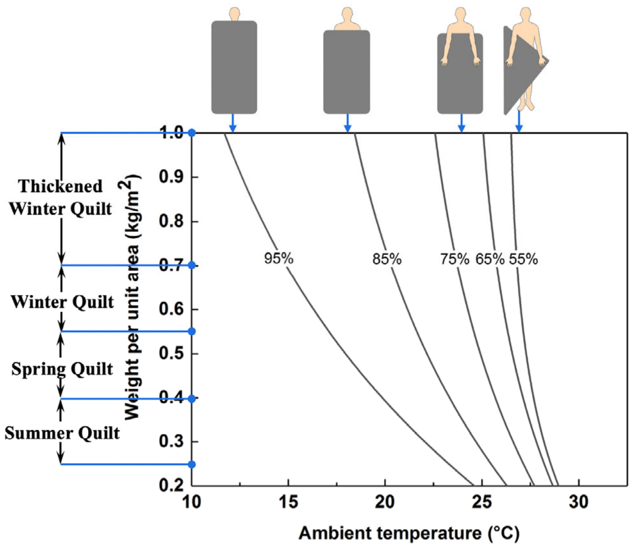

Fig. 13 The relationships between neutral indoor temperature and weight per unit area for different coverage rates

temperature corresponding to different quilts were greater at high coverage and less at low coverage. The comfort zone in Figure 13 has more intuitive features that can guide people in choosing the right quilt and ambient temperature in real life.

4.5 Limitations and future studies

Based on 64 sets of measured data of typical bedding systems, this study established the thermal insulation calculation method of the bedding system composed of fluffy-filled coverings, including the estimation of the thermal insulation increments caused by the quilt cover and sleepwear, using the weight per unit area, coverage rate, and sleepwear insulation as variables. However, there are some limitations in this study, and the research work can be continued in the following issues.

- Since the bedding used for testing in this study was brand new and the moisture absorption of the quilts with different filling materials was significantly different, the thermal insulation attenuation caused by the change in the fluffiness of the quilts overtime needs to be further investigated.
- In this study, the thermal insulation of bedding systems with three different filling materials (polyester, down, and cotton) was tested and no significant differences were found. However, the actual beddings people use may be filled with wool, silk, and even mixed material. More testing studies are required to determine the calculation method of thermal insulation of the bedding systems with different filling materials.
- Considering the thermal manikin's hard exterior and convenience for measurement, only the supine position was tested in this research. However, when people curl up in bed, the heat dissipation area will be reduced and the body heat dissipation decreases (Lu et al. 2021). More research is needed to determine the correction factors for thermal insulation calculations in other sleeping positions.

5 Conclusions

Based on measured data of 64 bedding system groups, this research has established an effective method to evaluate bedding system insulation, which can be applied to thermal comfort research and HVAC system design. Bedding system insulation can be determined by knowing the body surface covering area percentage, the weight per area of the insulation materials used in the quilt, the thermal insulation of sleepwear, and the bedding system having a quilt cover or not. Exponential fitting was chosen to fit the measured data and shows a perfect degree of fit. The effects of quilt cover and sleepwear on bedding insulation also have been investigated. We developed quantitative estimations on the increment of bedding system insulation caused by quilt cover and sleepwear. Further measurement and analysis are required to improve the bedding insulation evaluation method in light of filling materials and insulation attenuation.

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