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A study on the thermal comfort in sleeping environments in the subtropics—Measuring the total insulation values for the bedding systems commonly used in the subtropics

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Abstract

The total thermal insulation value of a bedding system significantly affects the thermal neutral temperature for sleeping environments and is therefore an important variable in the Comfort Equation developed for sleeping environments reported in a related paper. This paper reports on the measurement of the total insulation values for a wide range of bedding systems (through different combinations of bed, bedding and its percentage coverage over a human body, and sleepwear) commonly used in the subtropical regions using a thermal manikin. The total insulation values of the measured bedding systems varied greatly from 0.90 to 4.89 clo, depending upon bedding, bed and mattress, the type of sleepwear, and percentage coverage of body surface area by bedding and bed. The use of a Chinese traditional style bed—*Zongbang* bed can provide less insulation than the use of the conventional mattress commonly used in Hong Kong. The use of so-called air conditioning quilt (summer quilt) cannot help lower the total insulation significantly. On the other hand, some factors such as people sweating and moisture permeability of the quilts, etc., were not considered in the current study but may be further studied in future work.

Keywords: Total insulation value; Bedding system; Manikin; Thermal comfort; Sleeping environment

1. Introduction

It has been shown in a related paper [1] that the total thermal insulation value of a bedding system significantly affects the thermal neutral temperature for sleeping environments and is, therefore, an important variable in the Comfort Equation for sleeping environments. In order to evaluate various combinations of the environmental variables, which will achieve optimal thermal comfort for sleeping persons under steady state conditions (i.e., to solve Comfort Equation for sleeping environments), the total resistance, R_t, of bedding systems must be available. However, no database is currently available on the thermal insulation for bedding systems used for air conditioned sleeping environments in the subtropical regions except some documents such as ASHRAE Standard 55 [2] and ISO Standard 9920 [3] giving insulation values for clothing. Therefore, the thermal insulation provided by various bedding systems commonly used in the subtropics must be obtained through extensive laboratory experimental work.

A large number of previous studies on the thermal insulation of clothing have been reported [4–11]. Based on these studies, a complete full-scale database of the thermal insulation and evaporative resistance of clothing ensembles necessary for the use in various thermal comfort models for daytime was developed, and adopted by relevant standards (ISO Standard 9920 and ASHRAE Standard 55). There were also a limited number of previous studies on the thermal insulation provided by bedding systems, which were carried out using a manikin [12–14]. These studies resulted in a small-scale database of thermal insulation values for a variety of bedding systems. However, most of the reported studies were related to heated environments

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Nomenclature

a_i	area fraction of segment (i) related to whole body area A_{sk}, $a_i = a_{sk,i}/A_{sk}$, ND
A_C	percentage coverage of body surface area by bedding and bed, %
$F_{P\text{-}j}$	angel factor between manikin and surface j, ND
H_i	local heat flux of segment (i), W/m^2
H_{sk}	whole body heat flux, W/m^2
I_T	total insulation of a bedding system including the air layer around the covered body, clo
j	number of surface, ND
K	unit constant (6.45 clo W/(m^2 °C)), ND
R_t	total resistance of a bedding system including the air layer around a covered body, m^2 °C /W
t_a	ambient air temperature, °C
t_j	surface temperature of surface j, °C
t_o	operative temperature, °C
$\bar{t}_r$	mean radiant temperature, °C
$\bar{t}_{sk}$	mean skin temperature, °C
$t_{sk,i}$	local skin temperature of a segment (i), °C

where the objective was to increase thermal insulation value by a bedding system so as to lower indoor air temperature. Furthermore, the types of beddings studied were in generally based on those primarily used in the USA and Europe, and, therefore, not applicable to air-conditioned sleeping environments in the subtropics.

This paper reports on an experimental study on measuring the total insulation values for a wide range of bedding systems (through different combinations of bed, bedding and its percentage coverage over a human body, and sleepwear) commonly used in the subtropical regions using a thermal manikin. The experimental method is first introduced. This is followed by reporting selection of the components of a bedding system such as bedding, sleepwear, bed and mattress, etc. and measurement of the physical properties of the selected textiles. Thirdly, the results of measurement, which resulting in a small-scale database of the total insulation values provided by bedding systems commonly used in the subtropics, is reported. Finally, a number of issues related to the factors influencing the total resistance/insulation of a bedding system and the use of summer quilts are discussed.

2. Experimental method

The experimental work was based on a thermal manikin with geometry of a real human body in an environmental chamber. The purpose of the experimental work was to develop a database of the total insulation values (I_T) of bedding systems commonly used in the subtropics. The database obtained was used as an input to solve the Comfort Equation for sleeping environments, and may further be adopted by various standards such an ISO Standard or an ASHRAE Standard. The measurements and calculations of the total insulation values were carried out in accordance with the corresponding ISO [3] and ASTM [15] Standards.

The manikin shown in Fig. 1, Alex, is divided into 20 independent segments (Left/Right: foot, low leg, front thigh, back thigh, hand, forearm, upper arm, and pelvis, backside, face, crown, chest and back), each with its own temperature sensors, and heating and computer control system to approximately simulate the skin temperature distribution of a human being. In order to correctly simulate the thermal receptors all over the body of a human being, temperature sensing elements are distributed all over the manikin surface. The manikin is heated by the same wiring used for measuring. An individual proportional integrate (PI) controller is used to produce the required mean skin temperature in each body segment of the manikin. The mean skin temperature settings were 31 °C for hands and feet, and 35 °C for other body segments, respectively. Thus a mean skin temperature of

Fig. 1. The manikin (divided into 20 independent segments, each with its own heating and computer control system).

34.6 °C for the whole body (thermal neutral in a sleeping environment) was produced.

The manikin was placed with a supine position on a single bed with a dimension of 1900 (L) × 920 (W) mm in an environmental chamber. Besides a conventional air conditioning system to control the indoor air temperature and relative humidity, a wall panel cooling/heating system, which can be used to control the wall temperature, is also available in the environmental chamber. There are 10 wall temperature sensors distributed evenly in the wall panels.

For each experimental condition, both the indoor air temperature and the temperatures of internal surfaces of wall, ceiling and floor were all maintained constant at 22 °C, while the relative humidity inside the chamber at 50%. The air velocity was controlled at not greater than 0.15 m/s. During each test, the power input, the mean skin temperature of each segment, indoor air and panel wall temperature, and indoor relatively humidity were continuously monitored and recorded at an interval of 1 min. The mean value of each parameter was calculated based on at least 30 steady-state data. Fig. 2 shows an example of one measuring condition. The total thermal resistance (R_t) and insulation (I_T) of a bedding system, including the resistance or insulation from the air layer around the tested manikin, were calculated, respectively, as follows:

$$R_t = \frac{\bar{t}_{sk} - t_0}{H_{sk}} = \frac{\sum(a_i t_{sk,i}) - t_0}{\sum(a_i H_i)}, \tag{1}$$

$$I_T = KR_t \tag{2}$$

where K is unit constant, and equals to 6.45 clo W/(m^2 °C).

The operative temperature was calculated as the mean of air and mean radiant temperature based on that the difference between mean radiant and air temperature is small (<4 °C):

$$t_o = \frac{t_a + \bar{t}_r}{2}, \tag{3}$$

$$\bar{t}_r = \sum_{j=1}^{6} t_j F_{P-j}. \tag{4}$$

A test was also carried out with the nude manikin suspended horizontally in air to determine the air layer insulation, I_a, (fixed at 0.73 clo, exactly the same value as that obtained by McCullough et al. [12]).

3. Selection of bedding, sleepwear, bed and mattress

The components of a bedding system include bedding, bed and mattress, and the sleepwear used by occupants during sleep. The results of a previous study [16] showed that 92% of the respondents would wear sleepwear (47% used full-slip while the other 45% used half-slip sleepwear) and 90% would cover themselves with quilts (50%) or blankets (40%) during sleep. This helped determine the bedding items and sleepwear type to be used in experiments. Two types of summer quilt (i.e., so called locally air conditioning quilt, which, often made of polyester, is widely used by locals in air-conditioned sleeping environments), a blanket and a multi-purpose quilt as well as a full-slip and a half-slip sleepwear were purchased for use in experimentation. On the other hand, although a variety of mattress types are available, any conventional mattress (i.e., excluding a water bed or a thin cot) will provide considerably

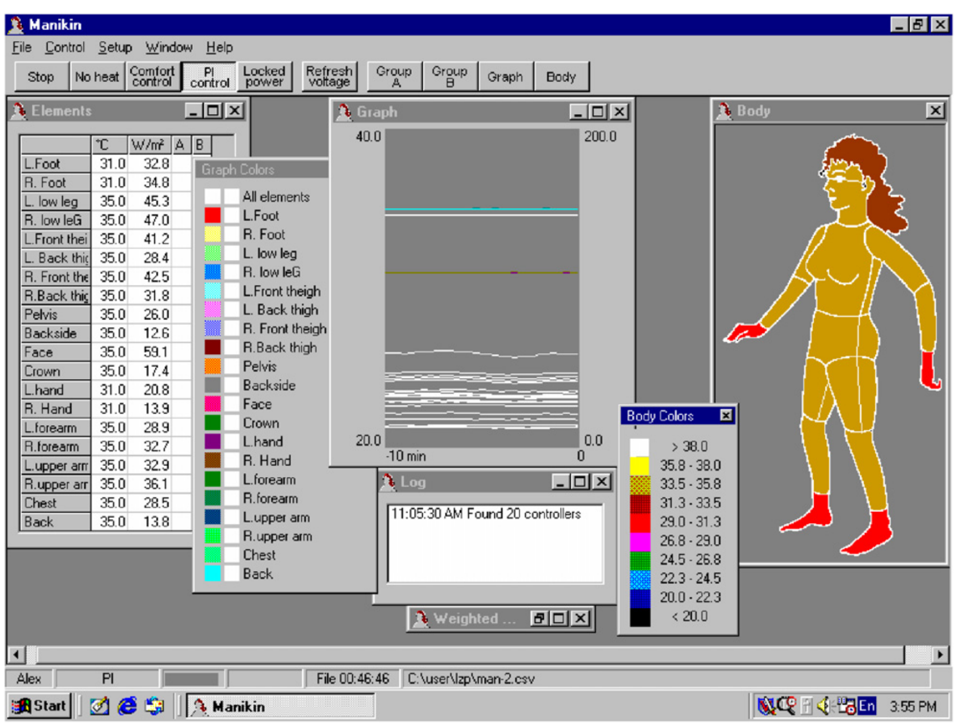


Fig. 2. Computer display of an experimental condition.

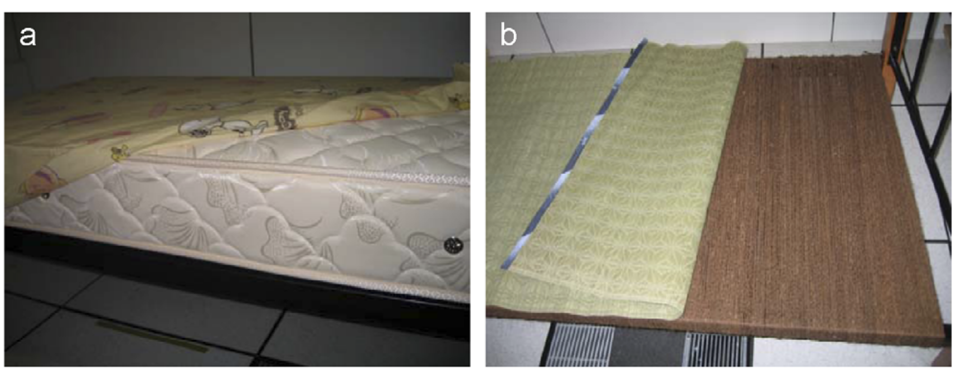
more local insulation than bedding. For all practical purposes, it can be assumed that there is no heat loss in steady state through the body surface in contact with a mattress. However, the firmness of a mattress might affect the amount of body surface area in contact with the mattress, but the resultant variation in insulation is minimal among conventional mattresses [12]. Therefore, only one conventional mattress was purchased for use in experimentation (shown in Fig. 3a). Furthermore, it is usually argued that because the area of contact between skin and a mattress is small and the mattress is thick, the heat loss through the mattress can be neglected [17]. In order to investigate the contribution of bed and mattress to the insulation of a bedding system, a Chinese traditional style bed (called *Zongbang* bed, shown in Fig. 3b), was also self-made using palm rope to provide a reference for comparison. This kind of *Zongbang* bed is widely used in the southern provinces in China, in particular in rural areas where air conditioning is not readily available.

4. Measurement of the physical properties of textiles

The bed sheet, quilt cover, blanket and sleepwear were laundered once according to the American Association of Textile Chemists and Colorists (AATCC) test method 135 [18] to remove any excess sizing from the fabrics. Weight per unit area of these bedding and sleepwear items was measured according to ASTM D 3776 [19]. The fabric thickness of each textile item was measured according to ASTM D 1777 [20] using a carpet thickness gauge meter (measuring range: 0–25 mm; accuracy: ±0.01 mm). The detailed measured characteristics of bedding items and sleepwear such as thickness, weight per unit area, fiber content, and fabric structure are shown in Table 1. Fig. 4 shows the blanket (B), the Summer Quilt 2 (Q2), the Summer Quilt 1 (Q1) and the Multi-purpose Quilt (Q3) from left- to right-hand side, respectively.

5. Experimental conditions

The total insulation value of a bedding system may be influenced by various components that make up the bedding system such as bed and mattress, bedding and sleepwear, etc. It is not useful to obtain the thermal insulation of an individual component in isolation, as these components will be used together as part of the bedding system. Therefore, the total insulation values for the different combinations of individual component shown in Table 2 were measured using the thermal manikin in the environmental chamber. In all experimental conditions, a



A conventional mattress | The *Zongbang* bed

Fig. 3. (a) A conventional mattress and (b) the *Zongbang* bed.

Table 1
Detailed measured characteristics of bedding items and sleep wear

Bedding item/sleepwear	Detailed description	Weight per unit area (kg/m^2)	Thickness (mm)
Blanket (B)	100% cotton	0.3308	3.03
Summer Quilt 1 (Q1)	Face: 100% cotton Filling: 100% polyester Back: 80% polyester, 20% cotton	0.5612	15.23
Summer Quilt 2 (Q2)	Filling: 100% feathery polyester Cover: Tracted polycotton	0.3096	7.62
Multi-purpose Quilt (Q3)	Filling: 100% polyester Cover: 70% polyester, 30% cotton	0.8390	23.17
Sheet 1	100% cotton	0.1133	0.96
Straw mat 2	100% straw	0.5064	1.45
Full-slip sleepwear (S1)	Long-sleeved, 100% cotton	—	0.46
Half-slip sleepwear (S2)	Short-sleeved, 100% cotton	—	0.83

Fig. 4. The Blanket (B), Summer Quilt 2 (Q2), Summer Quilt 1 (Q1) and Multi-purpose quilt (Q3) used in experimentation.

Table 2
Detailed combinations of individual components used in experimentation

Experimental condition No.	Bed type	
	Bed + conventional mattress + sheet 1 (M1)	*Zongbang* bed + straw mat 2 (M2)
1	Blanket (M1 + B)	Blanket (M2 + B)
2	Blanket + full-slip sleepwear (M1 + B + S1)	Blanket + full-slip sleepwear (M2 + B + S1)
3	Blanket + half-slip sleepwear (M1 + B + S2)	Blanket + half-slip sleepwear (M2 + B + S2)
4	Summer Quilt 1 (M1 + Q1)	Summer Quilt 1 (M2 + Q1)
5	Summer Quilt 1 + full-slip sleepwear (M1 + Q1 + S1)	Summer Quilt 1 + full-slip sleepwear (M2 + Q1 + S1)
6	Summer Quilt 1 + half-slip sleepwear (M1 + Q1 + S2)	Summer Quilt 1 + half-slip sleepwear (M2 + Q1 + S2)
7	Summer Quilt 2 (M1 + Q2)	Summer Quilt 2 (M2 + Q2)
8	Summer Quilt 2 + full-slip sleepwear (M1 + Q2 + S1)	Summer Quilt 2 + full-slip sleepwear (M2 + Q2 + S1)
9	Summer Quilt 2 + half-slip sleepwear (M1 + Q2 + S2)	Summer Quilt 2 + half-slip sleepwear (M2 + Q2 + S2)
10	Multi-purpose quilt + full-slip sleepwear (M1 + Q3 + S1)	—

feather pillow was placed under the manikin's head as shown in Fig. 5.

When people use bedding, they seldom cover their entire bodies (at least their heads are exposed). People can change their personal insulation by covering and uncovering parts of their bodies with bedding to achieve thermal comfort. To systematically study this effect, McCullough et al. [12] developed seventeen different configurations of the body surface coverage by bedding and bed, from the total coverage (100%) to no coverage (23.3% or nude on bed). Eight most commonly used configurations shown in Fig. 6 were selected for experimentation. The figure illustrates the placement of bedding on the manikin, with the percentage coverage (A_C) of body surface area by bedding and bed indicated for each configuration [12]. For each configuration of percentage coverage of body surface area shown in Fig. 6, the total insulation values of each combination of bedding, sleepwear, bed and mattress shown in Table 2 were measured.

6. Results

The results of measurements are given in Table 3. The total insulation values of the measured bedding systems ranged from 0.90 to 4.89 clo. All of the total insulation values include the insulations contributed by the pillow and the air layer surrounding the manikin.

6.1. Effect of the percentage coverage of body surface area by bedding and bed

Figs. 7–9 illustrate the effect of changing the percentage coverage of body surface area by bedding and bed (A_C) on the total insulation of a bedding system (I_T) at nude

Fig. 5. Examples of experimental conditions.

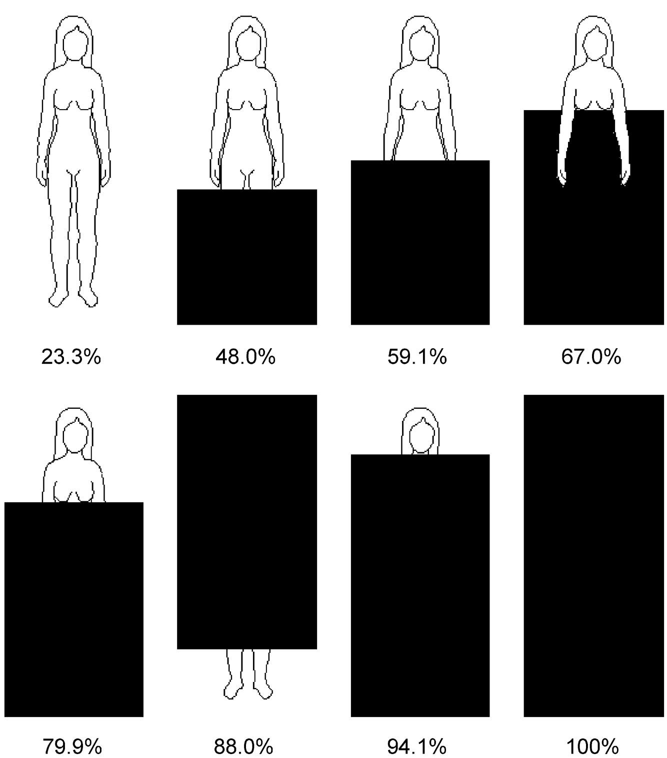


Fig. 6. Percentage coverage of body surface area by bedding and bed [12] used in experimentation.

Table 3
The total insulation values (clo) of the measured bedding systems

A_C (%)	23.3	48	59.1	67	79.9	88	94.1	100
M1 + Q1 + S1	1.57	2.15	2.72	2.88	3.27	3.99	4.56	4.77
M1 + Q2 + S1		1.84	2.24	2.41	2.81	3.32	3.73	4.06
M1 + B + S1		1.82	2.08	2.18	2.22	2.41	2.56	2.65
M1 + Q1 + S2	1.38	1.65	2.15	2.62	3.18	3.79	4.34	4.60
M1 + Q2 + S2		1.53	1.93	2.20	2.68	3.26	3.55	3.92
M1 + B + S2		1.43	1.76	1.80	2.07	2.36	2.40	2.58
M1 + Q1	0.98	1.16	1.43	1.90	2.44	3.68	4.03	4.47
M1 + Q2		1.14	1.42	1.69	1.98	2.95	3.03	3.62
M1 + B		1.07	1.24	1.45	1.65	1.98	2.11	2.23
M2 + Q1 + S1	1.31	1.63	1.97	2.32	2.57	3.08	3.32	3.64
M2 + Q2 + S1		1.61	1.93	2.19	2.42	2.66	2.97	3.12
M2 + B + S1		1.55	1.74	1.81	1.92	2.12	2.21	2.31
M2 + Q1 + S2	1.18	1.51	1.90	2.20	2.53	2.91	3.26	3.60
M2 + Q2 + S2		1.50	1.73	1.99	2.28	2.61	2.83	3.04
M2 + B + S2		1.46	1.62	1.64	1.87	2.02	2.10	2.19
M2 + Q1	0.90	1.09	1.35	1.83	2.06	2.67	3.00	3.26
M2 + Q2		1.07	1.27	1.58	1.81	2.34	2.50	2.76
M2 + B		1.04	1.18	1.30	1.45	1.74	1.84	1.90
M1 + Q3 + S1	1.57	2.39	2.86	3.08	3.53	4.15	4.66	4.89

(i.e., without sleepwear), full-slip and half-slip sleepwear conditions, respectively. It can be seen from the figures that A_C would affect I_T significantly. I_T would increase with the increase of A_C for all situations. For example, for the situation where the conventional mattress (M1) was used, when 48% of the body surface was covered, the I_T values when using the blanket (M1 + B) and the Summer Quilt 1 (M1 + Q1) were 1.07 and 1.16 clo, respectively, compared to 2.11 and 4.03 clo, respectively, when 94.1% of the body surface was covered. It can also be observed that when A_C

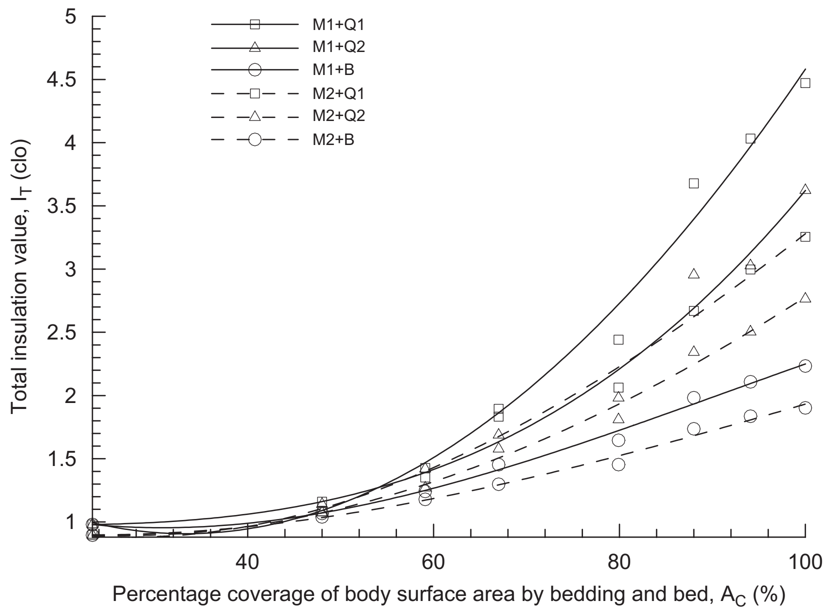


Fig. 7. The measured total insulation values provided by different bedding systems at different percentage coverage of body surface area by bedding and bed (nude condition).

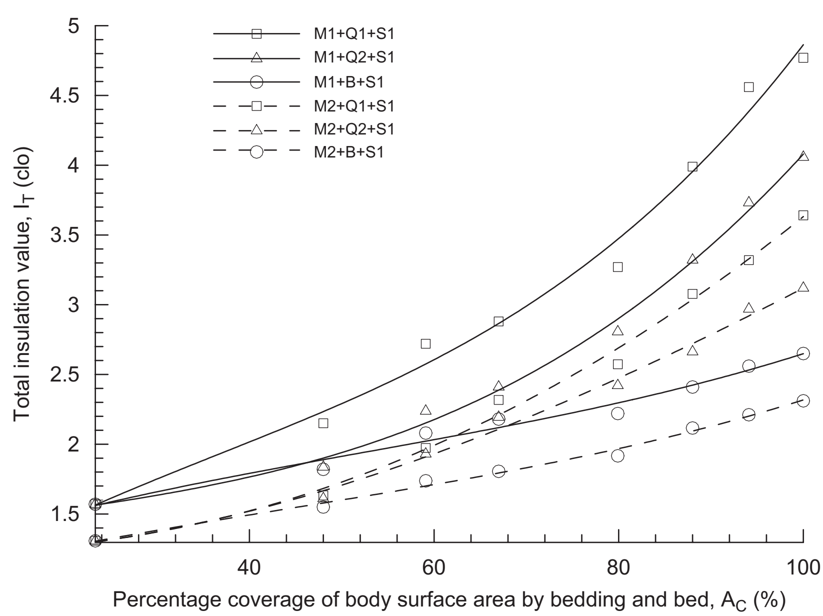


Fig. 8. The measured total insulation values provided by different bedding systems at different percentage coverage of body surface area by bedding and bed (full-slip sleepwear condition).

is small, the differences in I_T under different bedding systems are not significant. For example, at conventional mattress condition, when A_C was 48%, the I_T values when using the blanket (M1 + B), the Summer Quilt 2 (M1 + Q2) and the Summer Quilt 1 (M1 + Q1) were 1.07, 1.14 and 1.16 clo, respectively. However, with more and more body surface area covered by bedding, the differences in I_T under different bedding systems become evident. For example, at the same conventional mattress condition when the manikin was totally covered (100%), the I_T values when using the blanket, the Summer Quilt 2 and the Summer Quilt 1 were 2.23, 3.62 and 4.47 clo, respectively. The slopes of the data curves in the figures also indicate that as A_C increases, I_T rises at an increasing rate, in particular for the heavyweight bedding system (e.g., the Summer Quilt 1 (M1 + Q1)).

6.2. *Effect of bedding*

It can also be seen from Figs. 7–9 that comparing the I_T values when using the Summer Quilts 1 and 2, both of which were made up of polyester, the thicker (or heavier)

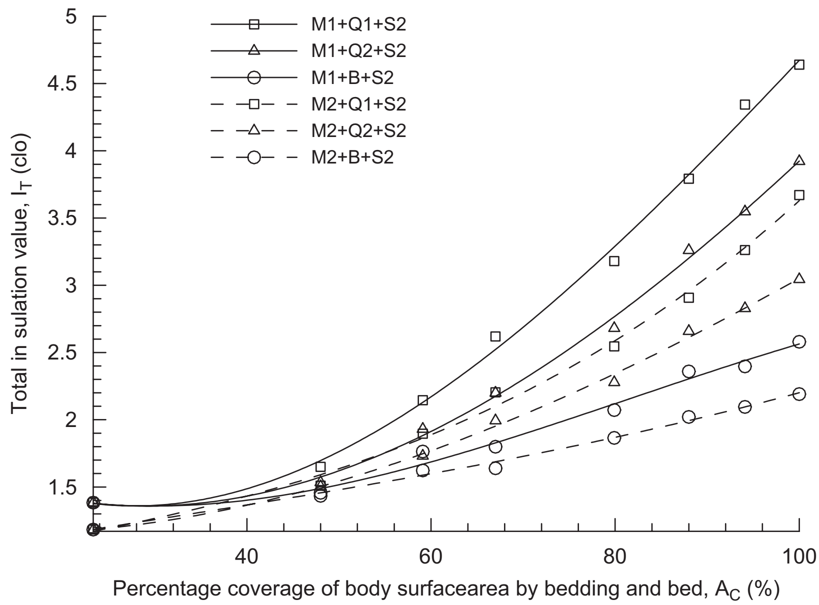


Fig. 9. The measured total insulation values provided by different bedding systems at different percentage coverage of body surface area by bedding and bed (half-slip sleepwear condition).

a summer quilt was, the higher the I_T value would be resulted in. This was understandable and consistent with common understanding. However, comparing the I_T values when using the blanket (made up of cotton) and the Summer Quilt 2, although the weight per unit area of the blanket was higher than that of the Summer Quilt 2, its thickness was less than that of the Summer Quilt 2 and, the measured I_T values when using the blanket were less than those when using the Summer Quilt 2. This implied that a bedding material had a limited influence on insulation, and that the insulation provided by a bedding component was mainly influenced by its thickness rather than its weight per unit area. This observation agreed well with the statement concerning the thermal insulation of clothing in ISO Standard 9920 [3]—"The type of material, however, has a limited influence on the thermal insulation. Instead the insulation is mainly influenced by the thickness and body area covered".

On the other hand, it should be noted that the difference in I_T using different bedding would also depend on A_C and the type of sleepwear. For example, it can be observed in Fig. 7 that at the nude condition, the bedding did not significantly affect I_T when A_C was less than 60%. However, the differences in I_T using different bedding increased when A_C was greater than 60%. For the sleepwear conditions shown in Figs. 8 and 9, the differences in I_T using different bedding started to become noticeable when A_C was greater than 50%.

Fig. 10 shows the comparison of the measured total insulation values when using the three different quilts under the conventional mattress and full-slip sleepwear condition in order to evaluate their effects on the total insulation. The Summer Quilt 1 and the relatively thinner Summer Quilt 2 were those commonly used in summer whilst the Multi-purpose Quilt 3 was a typical one commonly used in spring and autumn in Hong Kong (even in winter considering the subtropical weather condition). It can be observed from Fig. 10 that although the I_T values when using the Summer Quilt 1 were lower than those when using the Multi-purpose Quilt 3, the differences in the I_T values between using the Summer Quilt 1 and the Multi-purpose Quilt 3 ranged from 2% to 10%, which did not appear significantly large. On the other hand, the differences in the I_T values between using the Summer Quilt 1 and the Summer Quilt 2 ranged from 14% to 18%, due to different thicknesses (weights) of bedding.

6.3. *Effect of sleepwear*

Figs. 11 and 12 illustrate the comparison of the measured total insulation values resulted from different combinations of sleepwear and bedding when using the conventional mattress and *Zongbang* bed, respectively. It can be observed from the figures that for both conditions, the insulation values rose at a higher increasing rate when there was no sleepwear. This was particularly true when A_C was over 60%. It can also be seen from the two figures that the contribution of sleepwear to the total insulation would also depend on A_C and bedding. If A_C was high, the absolute increase in insulation value due to the addition of sleepwear would be smaller than if A_C was low. For example, in using the conventional mattress and the blanket, at 94.1% A_C, when a half-slip sleepwear was added to the nude manikin, I_T value increased from 2.11 (M1 + B) to 2.40 clo (M1 + B + S2)—a change of 0.29 clo, or 13.7%. For the same conventional mattress and the blanket, however, at 59.1% A_C, when the same sleepwear was added to the nude manikin, I_T value increased from 1.24 to 1.76 clo—a

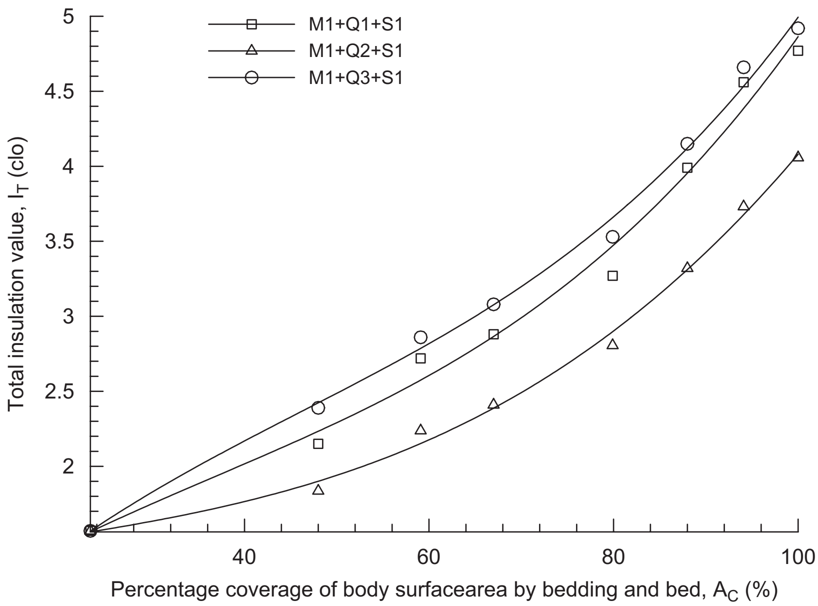


Fig. 10. The measured total insulation values when using the three different quilts under the conventional mattress and full-slip sleepwear condition.

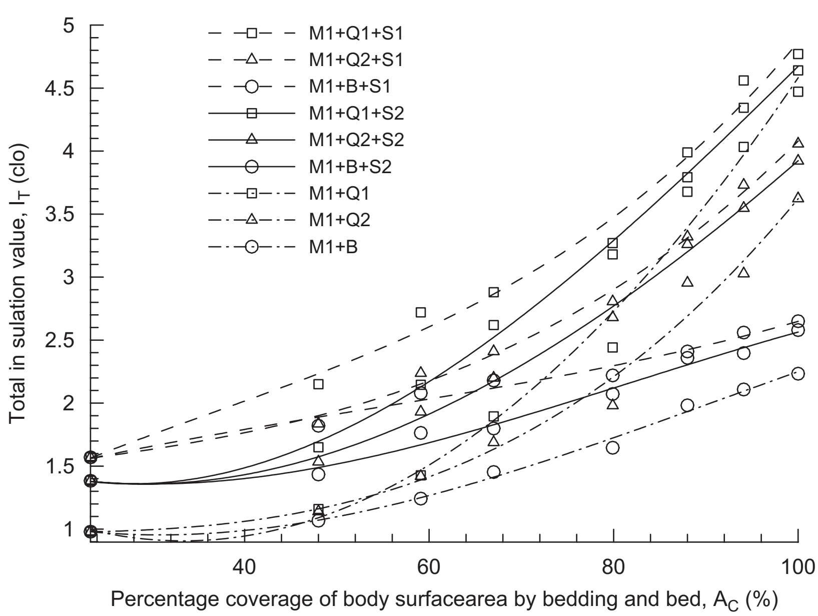


Fig. 11. The measured total insulation values provided by different combinations of sleepwear and bedding (conventional mattress condition).

change of 0.52 clo, or 41.9%. On the other hand, if the insulation contributed by bedding was high, the absolute increase in I_T due to the addition of sleepwear would be smaller than that when the insulation contributed by bedding was low. For example, in using the conventional mattress and the Summer Quilt 1, at 94.1% A_C, when a full-slip sleepwear was added to the nude manikin, I_T value increased from 4.03 (M1 + Q1) to 4.56 clo (M1 + Q1 + S1)—a change of 0.53 clo, or 13.2%. However, in using the conventional mattress and the Summer Quilt 2, at 94.1% A_C, when the same sleepwear was added to the nude manikin, I_T value increased from 3.03 (M1 + Q2) to 3.73 clo (M1 + Q2 + S1)—a change of 0.70 clo, or 23.1%.

6.4. Effect of bed and mattress

Fig. 13 shows the comparison of the measured total insulation values for both the conventional mattress and *Zongbang* bed under nude, full-slip and half-slip sleepwear conditions when A_C was 23.3% (i.e., without bedding). It can be seen from the figure that the use of *Zongbang* bed may provide less insulation than the use of conventional

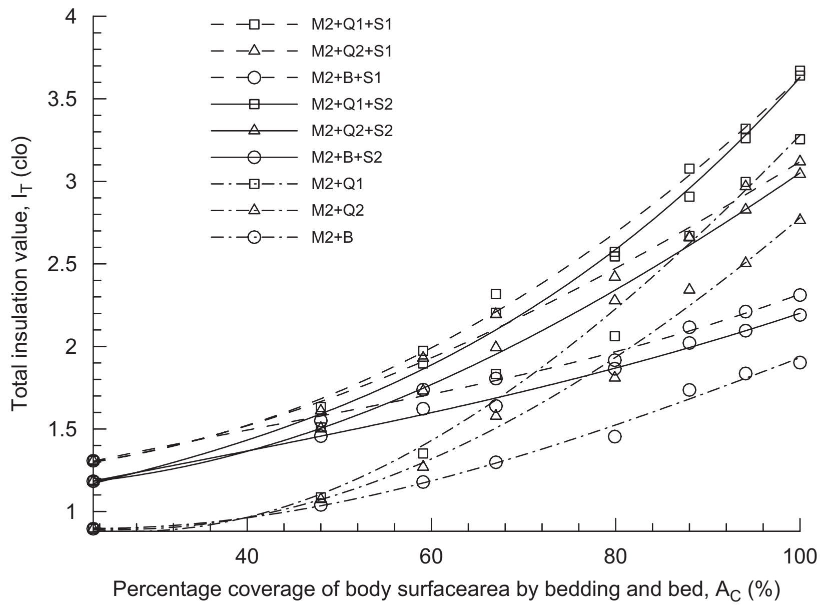


Fig. 12. The measured total insulation values provided by different combinations of sleepwear and bedding (*Zongbang* bed condition).

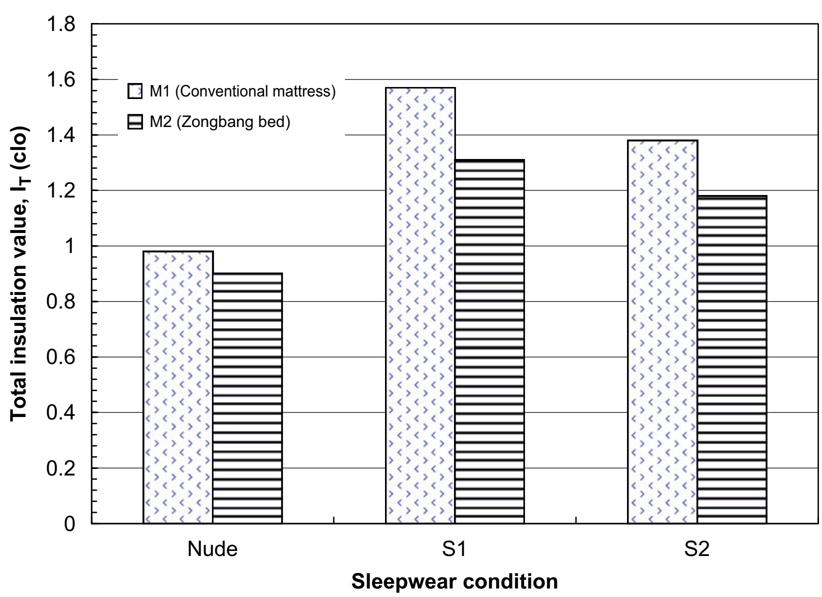


Fig. 13. Comparison of the measured total insulation values provided by using the conventional mattress and *Zongbang* bed under different sleepwear conditions (with $A_C = 23.3\%$).

mattress at all conditions (i.e., nude, full-slip and half-slip sleepwear). The differences in I_T between using the conventional mattress and *Zongbang* bed under nude, full-slip and half-slip conditions were 0.08, 0.19 and 0.13 clo, or 8%, 12% and 10% in terms of percentage differences, respectively.

Concerning the situations where bedding were used, it can be seen from the Figs. 7–9 that similar to situations for the effects of bedding and sleepwear, the contribution of bed and mattress to I_T would also depend on A_C, bedding and sleepwear. It can be observed from these figures that the differences in I_T between using the conventional mattress and *Zongbang* bed would increase with the increase *of* A_C. For example, when the Summer Quilt 2 was used, at 94.1% A_C, I_T value decreased from 3.03 clo when using the conventional mattress (M1 + Q2), to 2.50 clo when using the *Zongbang* bed (M2 + Q2)—a change of 0.53 clo, or 17.5%. For the same Summer Quilt 2, at 48% A_C, however, I_T value decreased from 1.16 clo when using the conventional mattress, to 1.07 clo when using the *Zongbang* bed—a change of 0.09 clo, or 7.8%. On the other hand, the higher the insulation contributed by bedding and sleepwear, the larger the absolute decrease in I_T due to the use of *Zongbang* bed and vice verse. For example, when the full-slip sleepwear and the Summer Quilt 1 were used, at 67.0% A_C, I_T value decreased from 2.88 clo when using the conventional mattress (M1 + Q1 + S1), to 2.32 clo when using the *Zongbang* bed (M2 + Q1 + S1)—a change of 0.56 clo, or 19.4%. However, when the half-slip sleepwear and the blanket were used, at 67.0% A_C, I_T value decreased from 1.80 clo when using the conventional mattress (M1 + B + S2), to 1.64 clo when using the *Zongbang* bed (M2 + B + S2)—a change of only 0.16 clo, or 8.9%.

7. Discussion

7.1. The factors influencing the total resistance/insulation of a bedding system

There are a number of factors that would influence the total resistance/insulation of a bedding system. The effects of the percentage coverage of body surface area by bedding and bed, and the components of a bedding system such as bedding, sleepwear, bed and mattress on the total resistance/insulation of a bedding system are discussed in Sections 6.1–6.4. It can also be noted that it is not useful to measure the thermal resistance from an individual component of a bedding system in isolation, as these components will be used together to form a bedding system and the contribution of one component to R_T or I_T will depend on A_C and the presence of other components making up the bedding system.

In addition, there are other factors that would influence the total insulation of a bedding system, such as air velocity, direction of airflow, posture and body figures of occupants, air relative humidity, sweating of people and the moisture permeability of the quilts, etc.

As the total insulation of a bedding system includes the surface insulation of the air layer, the air velocity, v, not only influences the value of convective heat transfer coefficients, h_c, and, hence the operative temperature, t_o, but also the total insulation of a bedding system through air layer insulation although the effect might be much smaller than that from other factors. When the air velocity increases, the total insulation value of a bedding system would decrease since the increased air velocity would enhance the convective heat transfer between a covered human body and its environment.

The direction of airflow, whether air flow is parallel to, or perpendicular to the major axis of a human body, may also influence the convective heat exchange between a human body and its environment. A previous experimental study showed that the differences in the convective heat exchange between the two different directions of airflow could be observed [21]. This is ascribed to the fact that the effective convection area of a human body is smaller when air flow is perpendicular to the major axis of a human body than that when air flow is parallel to the major axis of a human body. Considering the diminution of effective area when air flow direction is perpendicular to the major axis of a human body, Colin and Houdas [21] obtained different formulas to calculate the convective heat exchange between a human body and its environment.

Therefore, both the air velocity and the direction of airflow have an impact on the total insulation of a bedding system. However, their effects were not considered in this project since in practice the air velocity is limited to not greater than 0.15 m/s for air-conditioned sleeping environments. There are two reasons for this limitation. The first is that a higher velocity may cause draft (a local convective cooling) and local thermal discomfort since people are more thermally sensitive and consequently the risk of local discomfort is higher during sleep with lower metabolic rates and/or with less insulation. The second is that even for daytime applications, the precise relationship between increased air speed and improved comfort is not yet to be established although an elevated air velocity may be used to increase the maximum temperature for acceptable comfort if an affected occupant is able to control the air velocity. However, an occupant is obviously not able to control the air velocity when sleeping.

Posture and body figures of occupants may also influence the total insulation of a bedding system. The actual transport of sensible heat through a bedding system involves conduction, convection, and radiation. With different postures such as supine and side reclining, the effective conduction, convection and radiation areas of a human body will be different. Individuals with different body shape (thin or fat) may also result in different effective areas for conduction, convection and radiation heat transfer even if they are in same posture.

Furthermore, turning during sleep may also influence the total insulation of a bedding system since it will change the posture and the percentage coverage of the surface area by bedding and bed. In this study, it was assumed that people remained immobile during sleep. Limitations of this study included, therefore, the use of a rigid manikin to represent all human body types and the use of only one body position (i.e., supine); both could alter body contact with the bed/mattress, and consequently, heat transfer area. A person's body tissue will "spread out" when reclined, whereas a rigid manikin will not. Consequently, the total resistance of bedding systems as measured by using a manikin is probably on the lower side of actual values when a human subject of the same height and weight as that of the manikin is used. On the other hand, some factors such as relative humidity, sweating of people and moisture permeability of the quilts may also influence the total insulation of a bedding system. However, since the manikin cannot sweat, these were not considered in the current study but may be further studied in future work.

7.2. The usefulness of a summer quilt

A summer quilt, locally so-called air conditioning quilt, is expected to provide a lower thermal insulation than other types of bedding so that a relatively high indoor air temperature could be used in a bedroom. However, the results of the measurement suggested that the differences in the total thermal insulation between using the Summer Quilt 2 and the Multi-purpose Quilt 3 did not appear significantly large at only 2–10%. On the other hand, there existed noticeable differences (14–18%) in the total thermal insulation between using the Summer Quilt 1 and the Summer Quilt 2 because of their different thicknesses. The total insulation values when using both the Summer Quilt 1 and the Summer Quilt 2 were larger than that using the blanket. This implies that the use of a summer quilt cannot help lower insulation significantly, and therefore, its intended function is limited.

8. Conclusions

The total insulation (clo) values of various bedding systems commonly used in the subtropical Hong Kong have been measured using a thermal manikin in an environmental chamber, and a small-scale database of the total insulation values provided by bedding systems commonly used in the subtropics has been developed. The total insulation values of the measured bedding systems varied greatly from 0.90–4.89 clo, depending upon bedding, bed and mattress, the type of sleepwear, and percentage coverage of body surface area by bedding and bed. The lowest, 0.90 clo, occurred at naked condition using the *Zongbang* bed without any bedding, and the highest, 4.89 clo, at full-slip sleepwear condition using the conventional mattress, with the manikin 100% covered with the multi-purpose quilt, respectively. Furthermore, using the comfort equation reported in a related paper [1], the thermal neutral temperatures at 50% relative humidity for sleeping environments were 30.1 °C at 0.90 clo and 8.9 °C at 4.89 clo. This suggested that the differences in the total insulation would be very large if different bedding systems were used. Therefore, the bedding system used by a sleeping person has a substantial impact on thermal comfort. On the other hand, people have considerable flexibility in changing the total insulation value of a bedding system by altering the percentage coverage of body surface by bedding.

The use of a Chinese traditional style bed—*Zongbang* bed can provide less insulation than the use of the conventional mattress commonly used in Hong Kong. On the other hand, the use of so-called air conditioning quilt (summer quilt) cannot help lower the total insulation significantly.

The limitations of this study include that some factors, such as people sweating and moisture permeability of the quilts, were not considered on the measurement of the total insulation values for the bedding systems. However, these left-out factors may be further studied in future work.

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