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An Experimental Study on Human Thermal Comfort with Thermal-Conductive Bed during Sleep in Summer

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Abstract: Sleep is vital for human health, while sleep quality is affected by indoor thermal environments. This study aims to investigate human thermal comfort with a thermal-conductive bed during sleep in summer. A series of experiments were conducted in a climatic chamber of a university. Subjects slept on a thermal-conductive bed, with or without the supply of water cooling them by flowing through the pipes embedded in the bed. The supply water was set at 20, 25, 28, and 30 °C. The indoor temperature was set at 32 °C. The bed surface temperature (back, buttock, thigh, and calf) and the subject's skin temperature were measured. Questionnaires after waking up the next morning were conducted. The results show that when there was no water supply in the pipes of the thermal-conductive bed, the bed surface temperature was 0–1.5 °C higher than the indoor temperature, and subjects felt slightly warm. When the supply water temperature was 28 or 30 °C, subjects felt thermally comfortable during a night's sleep. This study demonstrates that the proposed thermal-conductive bed with supply water temperatures of 28–30 °C can create a comfortable sleep environment for residents who have no air-conditioning systems in summer, which can also help save building energy.

Keywords: thermal comfort; thermal-conductive bed; sleep comfort; thermal environment

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1. Introduction

People spend approximately one-third of their lifetime sleeping. Sleep can help people recover from physical and mental fatigue caused by daytime activities, which is essential to help the body restore energy to maintain physical function [1,2]. Sleep quality and sleep thermal comfort could be strongly affected by indoor thermal environments [3–5]. A comfortable thermal environment is vital to short sleep latency and obtaining deep sleep [6]. Thus, to obtain higher work or study efficiency during the daytime, air conditioners are adopted in residential bedrooms in many buildings [7]. According to a survey in Shanghai, 90% of 800 families used air conditioners during the whole sleep time in summer [8]. In Hongkong, where the hot and humid summer lasts for over four months, 68% of 554 respondents kept their air conditioners running all night [9]. As a result, a large amount of energy was consumed. In China mainland, the electricity consumption of air conditioners accounted for over 30% of the total power consumption of residential buildings in summer [10]. In Hongkong, the proportion of electricity usage from residential air conditioners in 1971 accounted for 14.6%, while it increased to 30.4% in 1996 and 45% in 2011, respectively [11,12].

Nevertheless, many discomfort complaints were found when air conditioning systems were used, especially in summer [13,14]. A study in Hongkong showed that around 60% of the respondents experienced waking up even if they turned on air conditioners. They felt cold or warm during sleep [9]. Kim et al. [15] showed similar results that occupants in Korea were exposed to either high or low indoor temperatures during sleep. Air temperatures that deviated from the neutral temperature would raise the frequency and duration of wakefulness and reduce slow wave sleep (SWS) and rapid eye movement sleep [16]. By estimating thermal comfort and sleep quality before and after sleep, Pan et al. [17] found that the requirements for thermal comfort of sleeping people differ from that of waking people. It has been investigated that sleep quality was affected by cold exposure or moderate heat in a constant thermal environment [18].

Undoubtedly, heating, ventilation, and air conditioning (HVAC) systems play a vital role in creating comfortable indoor thermal environments in modern buildings. However, the high level of thermal comfort certainly needs much more energy [7]. For the reason of economic development and environmental protection, energy consumption in buildings has attracted people's attention [19,20]. Hoyt et al. [21] and Zhang et al. [22] pointed out that every 1 °C increase in the set-point temperature for cooling can roughly reduce 10% energy consumption of an air conditioning system. Under these circumstances, methods to both save energy and improve thermal comfort have been explored, such as a personalized ventilation system. In China, electric fans are widely accepted as an effective method to improve the thermal environment and save energy in summer [23,24]. In a study conducted by He et al. [24], the fan-use rate was 80% at the environmental temperature of 30 °C.

Furthermore, the methods to improve thermal comfort during sleep have attracted the attention of some researchers in recent years. Okamoto-Mizuno et al. [25] performed a series of experiments to confirm the effect of head cooling on human sleep stages and body temperature. The obtained results show that the whole-body sweating rate was significantly decreased by the use of a cooling pillow during sleep under humid heat conditions. Irshad K. et al. [26] conducted a field study on sleeping comfort in a test chamber with a thermoelectric air-cooling system. The results show that the subjects felt comfortable and had a better sleep quality in a thermoelectrically cooled room at a power input of 720 W. Yu et al. [23] studied the proper electric fan control strategy in summer sleep thermal environments. The results indicate that the dynamic air supply control strategy of the fan, which was stabilizing–falling–stabilizing–rising–stabilizing, can improve sleep quality. Another similar study found that when the indoor temperature was below 32 °C, providing appropriate air velocities could alleviate the thermal discomfort of occupants during sleep [27]. Furthermore, He et al. [24,28] conducted a series of experiments on subjects' thermal comfort with desk fans in a hot–humid environment. They found that desk fans made more than 80% of subjects feel acceptable at 28 and 30 °C. In addition, He et al. [29,30] also found that the radiant cooling desk reduced warm sensation and increased both comfort and acceptability of subjects in hot environments.

Moreover, Pan et al. [31] designed a bed-based task/ambient conditioning (TAC) system, which was defined as the environmental conditioning system that allowed occupants to independently control their local thermal micro-environments in buildings. The results indicate that the application of the bed-based TAC system would help to attain obvious energy savings. In order to investigate the effect of TAC on the local body of sleeping people, Lan et al. [32] designed a bedside personalized ventilation (PV) system to provide fresh and cool air directly to the head and face of sleepers. After using the bedside PV system, people felt cool, and their skin temperature dropped. As reported in Nunneley SA et al.'s studies [33,34], cooling the head reduces thermal stress more effectively than cooling any other area of the body. Furthermore, Krauchi et al. [35] indicated that the skin temperature of the foot was important for good sleep. It has to be maintained at a relatively high temperature to facilitate the rapid onset of sleep.

As indicated by the above-mentioned studies, local cooling can improve human thermal comfort during sleep in summer. However, some problems remain unresolved. For example, the application of the TAC system to sleeping environments in real buildings helps reduce energy consumption; however, the bulky air ducts and ventilation plenums of the TAC system may cause inconvenience to occupants [31]. Moreover, although the TAC system was improved by removing the air ducts [36–38], it might still cause a cold draft. Furthermore, during the application of the bedside PV system to sleepers, the ventilation time could be continuous for 7 h or more. In a study by Xia et al. [39], headache or dizziness were reported when people were exposed to air currents for a long time. Additionally, some diseases, such as pains in joints, rheumatism, or colds, might be caused by air drafts during night sleep [40]. For air conditioning systems based on ceiling radiant cooling panels (CRCP), the main way of exchanging heat with internal heat sources in a sleep environment is radiation. Although the CRCP-based air conditioning systems could avoid the cold draft, condensation was observed from time to time due to the high level of humidity [41]. Moreover, radiant heat transfer was not as efficient as convective or conductive heat transfer, and the radiant cooling systems consumed more energy. For example, He et al. [42,43] indicated that the radiant cooling desk consumed cooling energy 89.9, 104.4, and 130.7 W at 28, 30, and 32 °C, respectively.

In this paper, a thermal-conductive bed that directly cools sleeping users was proposed. The main purpose aims to study the effects of the proposed bed on human thermal comfort during sleep in summer, as well as its energy-saving potential. Firstly, the configuration of the thermal-conductive bed was described. Then, a series of experiments were performed in a climatic chamber during the hot summer of 2021. During the experiments, subjects' thermal sensation and thermal comfort votes were recorded by answering questionnaires. Furthermore, the skin temperature of different body areas of the subjects was measured. Finally, the energy-saving potential of the thermal-conductive bed was discussed. This study provides a potential solution for energy efficiently improving human thermal comfort during sleep in summer, especially for those people who have no air conditioning indoors.

2. Methodology

2.1. Description of Thermal-Conductive Bed

Figure 1 shows the configuration of a thermal-conductive bed. A water tank (No. 21 in Figure 1a) was installed to supply the required water to the thermal-conductive bed. The supply of water sent to the thermal-conductive bed was provided by a circulating water pump (No. 18 in Figure 1a). The bedstead was equipped with both bedhead pipe and bed-end pipe with a diameter of 15 mm for supply water circulation. The stainless-steel pipes, which have the characteristics of good thermal conductivity and low cost, were used for the pipes. The pipes were installed in the upper panel of the bed to circulate cold water so that the bed could cool the human body lying on it. The bottom of the bed panel was empty. The inlet-water pipe was divided into two branches after passing through the main solenoid valve (SV). One branch was connected with the inlet of the bedside pipe. The other was connected to the inlet of the bed-end pipe. The outlet pipes of the two branches merged after the SV. Thermometers were installed on the supply and return pipes to measure the water temperature. Moreover, a bed frame (No. 3), which was made of sturdy and corrosion-resistant wood, was used to support the pipes.

The space between the pipes was filled with heat insulation material (No. 14 in Figure 1c), and the bottom of the pipes was padded with a heat insulation plate (No. 15 in Figure 1c) to reduce the transfer of cold energy to the cavity of the bed. The temperature of water in the return pipe can be adjusted by adjusting the opening of valves 9 and 10.

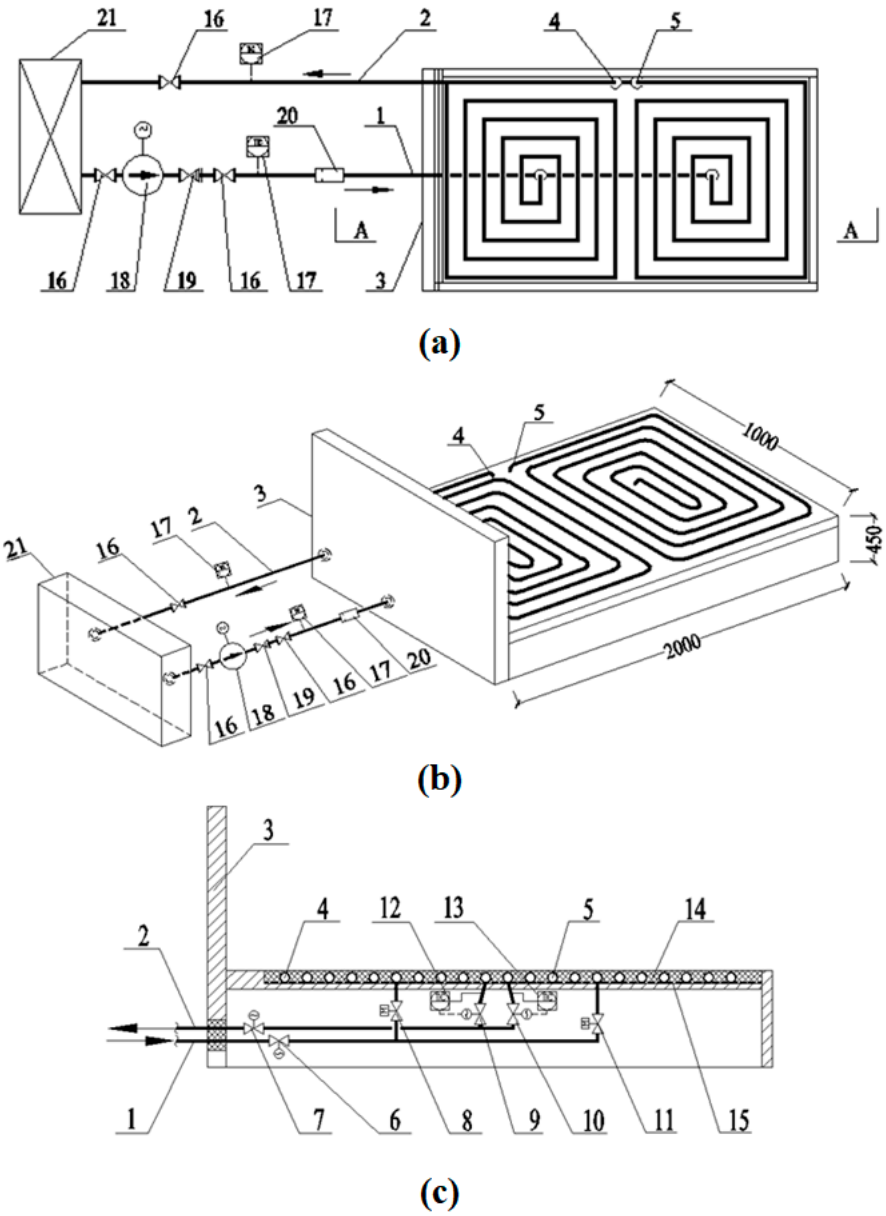

Figure 1. The configuration of the thermal-conductive bed used in this study: (**a**) the layout; (**b**) the axonometric view; and (**c**) the A-A sectional view. The numbers in the figure and the names are one-to-one correspondence are as follows: 1. Supply pipe; 2. Return pipe; 3. Bed frame; 4. Bedside water pipes; 5. Bed-end water pipes; 6. Solenoid valve on inlet pipe; 7. Solenoid valve on outlet pipe; 8. Solenoid valve on bedside supply pipe; 9. Solenoid valve on bedside return pipe; 10. Solenoid valve on bed-end return pipe; 11. Solenoid valve on bed-end supply pipe; 12. A thermometer in bedside return pipe; 13. A thermometer in bed-end return pipe; 14. Insulation material; 15. Heat insulation plate; 16. Shutoff valve; 17. Thermometer; 18. Water pump; 19. Non-return valve; 20. Flowmeter; 21. Water tank.

The size of the thermal-conductive bed was 2 m (length) × 1 m (width) × 0.45 m (height). The thickness of the bed plate was set at 0.05 m, and the pipe spacing was 0.085 m. The thickness of the human body was assumed to be 0.18 m. The water flows along the direction over the length of the bed, and the heat conduction of the body is vertical to the direction of water flow. The heat between the human body and the bed was mainly transferred by heat conduction, and then, the heat was carried away by water in the form of convection heat transfer, assuming that the physical body came into contact with the bed surface completely. The mathematical description of the problem can be expressed as follows:

$$c_p \times m \times \delta t_w = q \times A \tag{1}$$

$$q = K \times \left(t_s - t_w\right) \tag{2}$$

In which

$$K = \frac{1}{R_t + \frac{1}{h}} \tag{3}$$

$$R_t = \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} \tag{4}$$

$$h = \frac{Nu \times \lambda_w}{H} \tag{5}$$

$$Nu = 0.023Re^{0.8}Pr^{0.4} \tag{6}$$

where q is heat dissipation between the human body and the bed, in W/m^2; δt_w is a temperature rise of cold water, in °C; A is the contact area between the human body and bed, in m^2; t_w is average water temperature, in °C; t_s is average skin temperature, in °C; h is the convection heat transfer coefficient between the bottom of the bedplate and water, in W/(m^2·K); c_p is the specific heat at a constant pressure of water, in J/(kg·K); m is flow mass of water, in kg/s; R_t is the total thermal resistance of bed cushion, in (m^2·K)/W; λ_i and δ_i are thermal conductivity (in W/(m·K)) and thickness of mattress (in m), respectively; Nu, Re, Pr are Nusselt number (dimensionless), Reynolds number (dimensionless), Prandtl number (dimensionless), respectively; λ_w is a thermal conductivity of water, in W/(m·K); H is the equivalent diameter, that is, the height of the aqueduct, in m. The mattress consisted of one single material with thermal conductivity of 0.15 W/(m·K), and the thickness was 0.05 m.

2.2. Experiment Conditions

The experiment was conducted in a thermal-conductive bed placed in a climatic chamber with dimensions of 4.2 m × 3 m × 2.6 m in summer, as shown in Figure 2. The climatic chamber was located at the College of Resource and Environment and Safety Engineering at Hunan University of Science and Technology, Xiangtan, China. Xiangtan is located in the central south of China. According to the code for thermal design of civil buildings in China (GB 50176-2016) [44], Xiangtan belongs to the Hot-Summer and Cold-Winter (HSCW) Zone. The chamber was equipped with an air conditioning system to maintain constant indoor air temperature, humidity, and air velocity throughout the experiment.

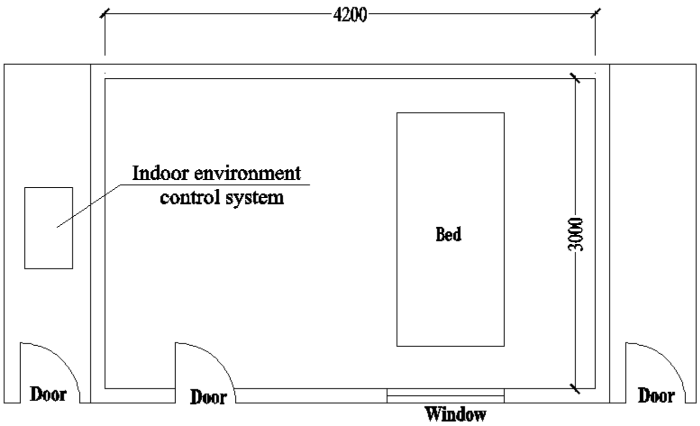

Figure 2. The layout of the climatic chamber.

A warm indoor environment (air temperature: 32 ± 0.5 °C, RH: 70 ± 5%, air velocity: 0.1 ± 0.02 m/s) was set in the chamber. The lights were turned off after the subjects fell asleep. The acoustical environment was acceptable, according to the subjects' responses. Five conditions with different supply water temperatures were defined, as listed in Table 1. It should be noted that the water temperature refers to the temperature of supplied water in pipes at the inlet of the bed head, obtained from thermometer No. 17, as shown in Figure 1.

Table 1. Experimental information.

	Indoor Air Temperature (°C)	Indoor RH (%)	Air Velocity (m/s)	Supply Water Temperature (°C)
Case 1	32 ± 0.5	70 ± 5	0.1 ± 0.02	without water
Case 2	32 ± 0.5	70 ± 5	0.1 ± 0.02	20
Case 3	32 ± 0.5	70 ± 5	0.1 ± 0.02	25
Case 4	32 ± 0.5	70 ± 5	0.1 ± 0.02	28
Case 5	32 ± 0.5	70 ± 5	0.1 ± 0.02	30

2.3. Subjects

A total of 12 subjects (age: 22.5 ± 2.5 years old; height: 170.5 ± 4.5 cm; weight: 68.7 ± 14.8 kg) participated in the experiments. They were all male students of Hunan University of Science and Technology. Since wearing only a few clothes and attaching temperature sensors to the skin (especially the chest area) during the experiment were very inconvenient for females, no female students were recruited for the experiments. Before the experiment began, each subject was inquired whether he was willing to participate in the experiment. Oral consent was obtained from each subject who was willing to participate in the experiment, and they were told that they could quit at any time during the experiment. The subjects have lived in Xiangtan, China, for more than one year. The Pittsburgh Sleep Quality Index (PSQI) questionnaire was used to evaluate the sleep quality and sleep disorders of each subject within one-month intervals [45]. The results showed that each participant was without sleep disorders. A candidate who had a PSQI global score of less than 5, which indicated no sleep disorder, was suitable for the experiment. All the subjects were in healthy condition. In the 24 h before participating in the experiments, they did not smoke and do strenuous exercise, or drink alcohol or coffee. They wore short-sleeved T-shirts and shorts without bed coverings. The clothing insulation was 0.2 clo. The thermal-conductive bed was covered with a thin blanket, and the upper layer was covered with a mat. Moreover, a simple oral explanation of the purpose and procedure of the experiment was given to each subject by the researchers before the experiments were conducted.

2.4. Measurement and Questionnaires

During the experiments, subjects' local skin temperature, bed surface temperature, thermal environment parameters, inlet and outlet water temperature (the temperature of the water entering and exiting the pipes), and inlet water flow rate were continuously measured and recorded throughout the whole night of the experiments. As for the measurement of bed surface temperature, four points on the thermal-conductive bed surface which contacted with the back, buttock, thigh, and calf of the human body were selected as the measurement points. Table 2 illustrates the detail of the instruments used in this experiment. All of the instruments had been calibrated before the measurement.

In this study, the human body was divided into five areas: shoulder; chest; abdomen; thigh; and calf. The body surface of each area included the upper part exposed to indoor air and without covering with the quilt (U), the back part in touch with the mattress (B), and the parts on both sides of the physical body (S). On the upper surface of the body, the skin temperature of the chest, abdomen, thigh, and calf were measured. On the back of the body, the skin temperatures of the back, right thigh, and right calf were measured. On the side of the body, the skin temperatures of the left shoulder, left abdomen, left thigh, and left calf were measured. The iButton sensors were attached to the skin surface by medical adhesive tape. Figure 3 shows one of the investigated subjects lying on the thermal-conductive bed in the climatic chamber after the sensors were attached. It should be noted that after attaching the iButton sensors to the human body, subjects wore short-sleeved T-shirts and shorts, as Section 2.3 described.

Table 2. The measured parameters and used sensors.

Parameter	Sensor	Type	Accuracy	Measurement Range
Skin temperature	iButton sensors	DS 1922L	±0.5 °C	−40–85 °C
Bed surface temperature; Inlet/outlet pipe water temperature	K-type thermocouples with data logger	LabQuest2	0.5 °C	0–45 °C
Air temperature	Thermo-hygrometer	TR-72Ui	±0.3 °C	0–50 °C
Relative humidity	Thermo-hygrometer	TR-72Ui	±5%	10–95%
Inlet water flow rate	Floater flowmeter	LZT-1002 M	±0.5 L/min	1–7 L/min

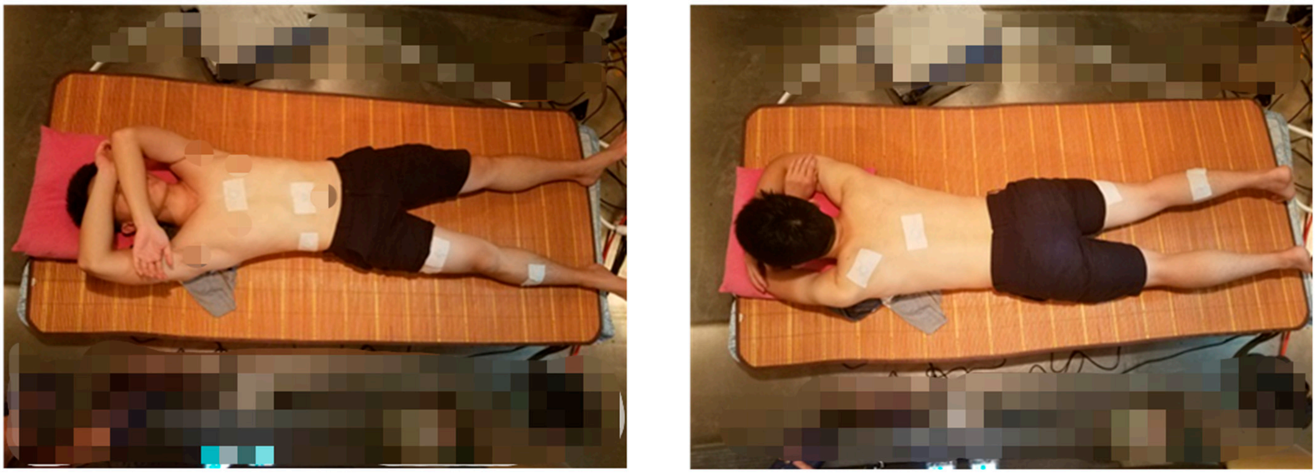

Figure 3. One of the investigated subjects lay on the thermal-conductive bed after the sensors were attached (after attaching the iButton sensors to the human body, subjects wore short-sleeved T-shirts and shorts).

The temperatures of the bed surface beneath the back, buttocks, thigh, and calf of subjects were measured with temperature sensors, and the water temperatures of the inlet and outlet were monitored. During the experiment, two sets of independent data acquisition equipment (LabQuest2) were used for measurement. Data loggers (Thermo Recorder TR-72Ui) were used to measure the indoor air temperature and RH around the bed, located 0.5 m from the bed surface. By regulating the opening of valves No. 9 and 10, as shown in Figure 1, the temperature of the supply water can be adjusted accordingly.

2.5. Questionnaires

Human thermal comfort was affected by the adaptability and expectation of the thermal environment [46,47]. Therefore, the proper indoor temperature could not be assessed simply by thermal sensation votes (TSV). In this study, the questionnaires mainly consisted of the following two parts: (1) a pre-sleep survey; and (2) a survey after waking up the next morning. In part (1), the subjects reported their physical and psychological state during the continuously measured day. It was conducted after the subjects reached the climatic chamber and adapted to the environment. In part (2), the subjects reported their thermal sensations and thermal comfort when they woke up the next morning. Table 3 presents the scales of subjective responses in the questionnaire. A seven-point scale suggested by ASHRAE Standard 55 [48] was used to rate subjects' thermal sensations. A five-point scale was adopted to assess subjects' thermal comfort.

Table 3. Scales of subjective responses in the questionnaire.

Thermal Sensation Votes (TSV)						
Cold −3	Cool −2	Slightly cool −1	Neutral 0	Slightly warm +1	Warm +2	Hot +3
Thermal comfort votes (TCV)						
Comfortable 0	Slightly uncomfortable 1	Uncomfortable 2	Very uncomfortable 3	Extremely uncomfortable 4		

2.6. Experimental Procedure

Measurement sensors were settled before the subjects arrived at the climatic chamber. The sleep schedule was consistent with the subjects' usual sleep time. The experimental procedure is described below:

(1) 22:00 Subjects reached the climatic chamber and were accommodated in the thermal environment for 30 min;
(2) 22:30 Subjects filled out the before-sleep survey questionnaire for physical and psychological status during the day;
(3) 22:35 The iButton sensors were attached to specified areas of the skin of subjects, as shown in Figure 3;
(4) 22:40 Check and adjust the equipment to make them display and record normally;
(5) 23:00 Turn off the lights after observing that the subject did not move their body frequently;
(6) 7:00 After the subjects woke up, they were asked to answer questions about their thermal sensation and thermal comfort for sleep.

2.7. Data Analysis

In this study, the mean skin temperature of the upper area (MST_U), the back area (MST_B), and the side area (MST_S) of a human body were calculated by weighing the area coefficients of each surface area. The calculation formulas are listed below:

$$MST_U = a_1 T_{chest\text{-}u} + a_2 T_{abdomen\text{-}u} + a_3 T_{thigh\text{-}u} + a_4 T_{calf\text{-}u} \tag{7}$$

$$MST_B = b_1 T_{back\text{-}b} + b_2 T_{thigh\text{-}b} + b_3 T_{calf\text{-}b} \tag{8}$$

$$MST_S = s_1 T_{shoulder\text{-}s} + s_2 T_{abdomen\text{-}s} + s_3 T_{thigh\text{-}s} + s_4 T_{calf\text{-}s} \tag{9}$$

where $T_{chest\text{-}u}$, $T_{abdomen\text{-}u}$, $T_{thigh\text{-}u}$, and $T_{calf\text{-}u}$ are the skin temperatures of the upper parts of the chest, abdomen, thigh, and calf, respectively; $T_{back\text{-}b}$, $T_{thigh\text{-}b}$, and $T_{calf\text{-}b}$ represent the skin temperatures of the back, the back parts of thigh and calf, respectively, and $T_{shoulder\text{-}s}$, $T_{abdomen\text{-}s}$, $T_{thigh\text{-}s}$, and $T_{calf\text{-}s}$ represent the skin temperatures of around the shoulder, the side parts of abdomen, thigh, and calf, respectively. Table 4 illustrates the ratios of body surface area (a, b, s) according to references [49,50].

Table 4. Surface area ratios of the calculated skin temperature.

No.	Upper (a)	Back (b)	Side (s)
1	0.27	0.54	0.03
2	0.22	0.26	0.26
3	0.36	0.2	0.36
4	0.15	/	0.33

3. Results

3.1. Bed Surface Temperature under Different Water-Supplied Conditions

The bed surface temperature of the thermal-conductive bed was measured under experimental conditions described in Section 2.2. Figure 4 shows the bed surface temperature distribution in different cases. As for the same sites of the bed surface, the bed surface temperature when there was no water flowing through the pipes was 1.8–9.3 °C higher than when the supply water temperature was set at 20, 25, 28, or 30 °C. Specifically, when there was no water flowing through the pipes, the bed surface temperature varied from 32 to 33.5 °C, which was 0–1.5 °C higher than the indoor temperature (32 °C) due to the heat from the subjects. When the supply water temperature was raised from 20 °C to 25 °C, the surface temperature of the thermal-conductive bed changed significantly. Specifically, when the supply water temperature was 20 °C, the bed surface temperature varied from 23 to 26 °C. When the supply water temperature was 25 °C, the bed surface temperature varied from 29 to 30 °C. However, the variation in bed surface temperature was slight when the water temperature increased from 25 to 30 °C. Specifically, when the supply water temperature was set at 25, 28, and 30 °C, the bed surface temperature varied from 29 to 31 °C. Furthermore, a decreasing trend of the surface temperature from the bedhead to the bed-end was observed. The results indicate that when the supply water temperature was from 25 to 30 °C, the bed surface temperature was relatively stable (29–31 °C).

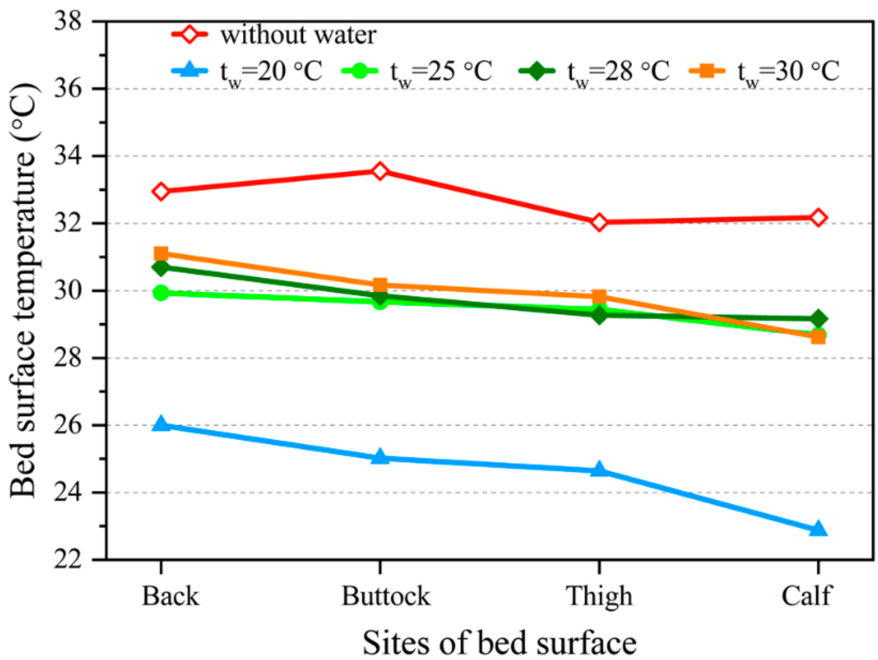

Figure 4. The surface temperature distribution of thermal-conductive bed under different cases.

3.2. Skin Temperature under Different Supply Water Temperatures

The mean skin temperature (*MST*) of different body segments (the upper, the back, and the left side of the human body) under experimental conditions calculated from

Equations (7)–(9) is shown in Figure 5. The linear fitting lines of *MST* throughout the night are also presented.

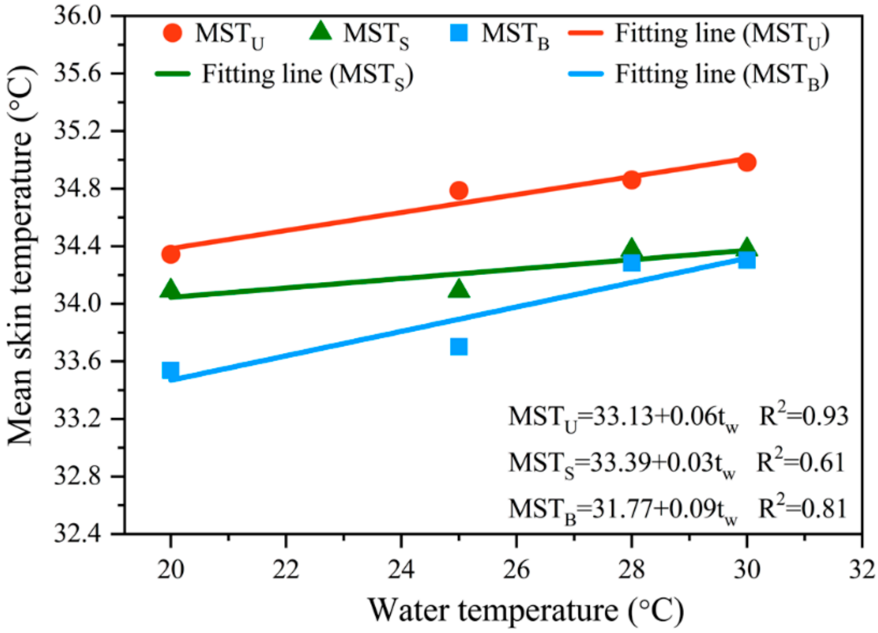

Figure 5. The correlation between the mean skin temperature and the water supply temperature.

As illustrated in Figure 5, MST_U varied from 34.3 to 35.0 °C, and MST_B varied in a range of 34.1–34.4 °C. MST_S was more fluctuating with a difference of 0.8 °C under experimental conditions. It can be seen that MST_U, MST_B, and MST_S increased stably with the rise of supply water temperature. Both MST_B and MST_S were lower than MST_U under various test cases. When t_w was 20 °C, the difference between MST_U and MST_S reached 1.08 °C. As t_w increased to 28 °C, the difference between MST_U and MST_S decreased to 0.58 °C. Moreover, when t_w increased to 28 °C, MST_S and MST_B tended to be consistent, which could be due to the side and back areas of the body being closer to the bed than the upper body areas.

Based on the linear regression functions developed for *MST* and supply water temperature (t_w), the correlation between the two parameters was found. The sensitivity between the two correlated parameters can be reflected by the slope value. It was shown that t_w was most sensitive to MST_B, followed by MST_U and MST_S.

3.3. Correlation between TSV, TCV, and Supply Water Temperature

The temperature of supply water in the pipes of the thermal-conductive bed has an important impact on the thermal sensation. Too high or too low a temperature of supply water makes people feel uncomfortable. In this study, subjects who voted "Cold", "Cool", or "Slightly cool" were regarded as having cool sensations. Then, the percentages of cool sensation (the proportion of the subjects having cool sensations to the total subjects) in the back, buttock, and thigh was calculated. Moreover, the linear fitting method was used to determine the correlation between thermal sensation vote (TSV) and supply water temperature (t_w). The results are presented in Figure 6. The regression model is listed below:

$$\varnothing_{cool} = 2.67\text{-}0.089t_w,\ R^2 = 0.89 \tag{10}$$

where $\varnothing_{cool}$ is the percentage of the subjects having cool sensations in the back, buttock, and thigh to the total subjects, and R^2 is the coefficient of determination.

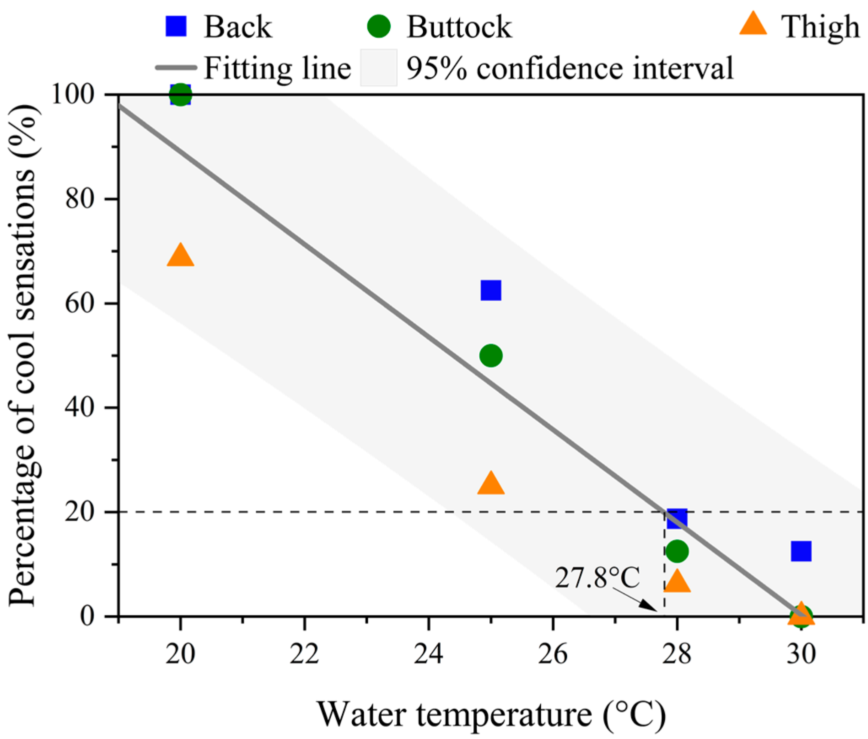

Figure 6. The correlation between the percentage of cool sensations and the supply water temperature. The percentage of cool sensations refers to the percentages of subjects voting "Cold", "Cool", or "Slightly cool".

As shown in Figure 6, the percentage of subjects with cool sensations showed a strong negative correlation with the supply water temperature (R^2 = 0.89). When the supply water temperature increased by 1 °C, the percentage of subjects with cool sensations decreased by 8.9%. Specifically, when the supply water temperature was set at 20 °C, 100% of subjects had cool sensations in the back and buttock areas, and 70% of subjects had cool sensations in the thigh. When the supply water temperature was set at 28 °C, less than 20% of subjects had cool sensations in the back, buttock, and thigh. In other words, the lowest temperature of supply water was expected to be above 27.8 °C. Furthermore, it is indicated that the back area of the human body was more sensitive to the supply water temperature. For example, when the supply water temperature was 28 °C, the percentage of cool sensations in the back was higher than the percentages in the buttock and thigh (back:19%; buttock:13%; thigh: 6%). This could be explained by a larger contact area around the back with the thermal-conductive bed than the other two body areas.

Furthermore, subjects who voted "Slightly uncomfortable", "Uncomfortable", and "Very uncomfortable" were regarded as feeling thermal discomfort. Then, the percentages of thermal discomfort (the proportion of the subjects feeling thermal discomfort to the total subjects) in the back, buttock, and thigh were calculated. Moreover, the correlation between thermal discomfort and the supply water temperature is illustrated in Figure 7. The regression model is listed below:

$$\varnothing_{dsicomfort} = 2.76\text{-}0.091 t_w,\ R^2 = 0.91 \quad (11)$$

where $\varnothing_{discomfort}$ is the percentage of the subjects feeling thermal discomfort in the back, buttock, and thigh to the total subjects.

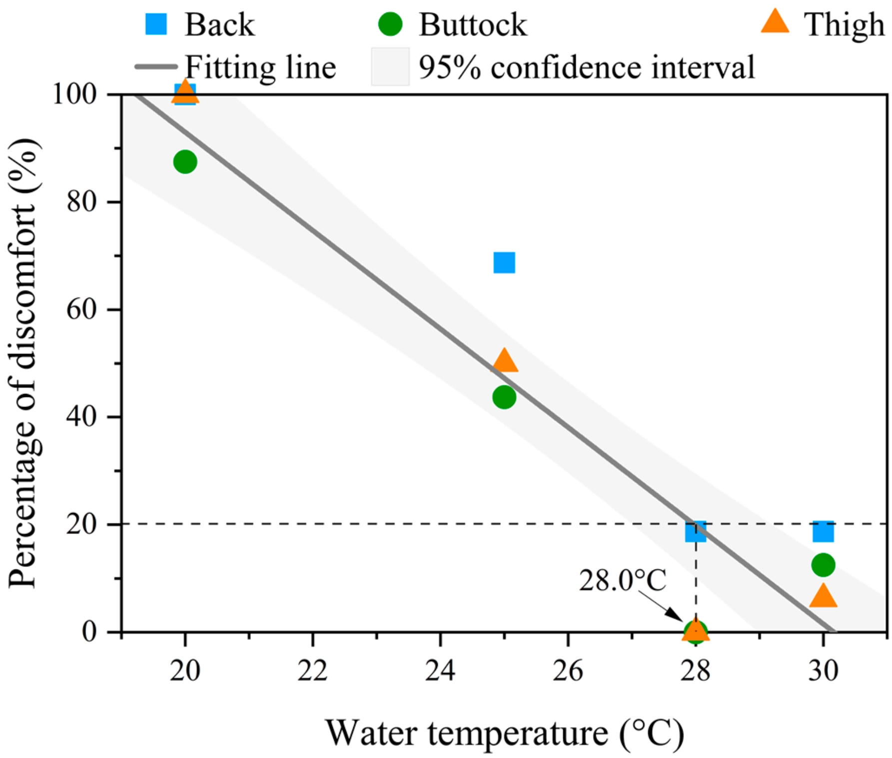

Figure 7. The correlation between the percentage of thermal discomfort and the supply water temperature. The percentage of thermal discomfort refers to the percentages of subjects voting "Slightly uncomfortable", "Uncomfortable", or "Very uncomfortable".

As shown in Figure 7, the percentage of subjects feeling thermal discomfort showed a strong negative correlation with the supply water temperature (R^2 = 0.91). When the supply water temperature increased by 1 °C, the percentage of subjects with cool sensations decreased by 9.1%. To be specific, when the supply water temperature was set at 20 °C, 100% of subjects had cool sensations in the back and buttock areas, and 88% of subjects had cool sensations in the thigh. When the supply water temperature was set at 28 °C, less than 20% of subjects had thermal discomfort in the back, buttock, and thigh. Namely, the lowest supply water temperature was expected to be greater or equal to 28 °C.

According to the above results, subjects felt thermally comfortable when their back was cool at a water supply temperature of about 28 °C. Therefore, it is suggested that t_w around 28–30 °C is suitable for a thermal-conductive bed in this study. In such conditions, MST_U, MST_B, and MST_S could be, respectively, in the range of 34.7–35 °C, 34.1–34.3 °C, and 34.2–34.4 °C.

3.4. Thermal Sensation and Comfort

Similar to the results presented in Section 3.3, the proportions of the subjects' local and overall thermal sensation and comfort votes were calculated. Figure 8 illustrates the proportions of local and overall thermal sensation votes. The thermal sensation votes varied under different water-supplied conditions. The subjects voting "Neutral" accounted for the highest proportion when the supply water temperature was 28 or 30 °C. Specifically, in terms of no-water conditions, more than 75% of the subjects felt slightly warm or warm in the areas of the calf, thigh, buttock, back, and shoulder, and 75% of the subjects felt neutral in the part of the abdomen. The overall thermal sensation votes were slightly warm (40%) and warm (60%). When the supply water temperature was 20 or 25 °C, more than 55% of the subjects felt slightly cool in the areas of the calf, thigh, buttock, back, abdomen, and shoulder. When the supply water temperature was 28 or 30 °C, more than 85% of the subjects felt neutral in the areas of the calf, thigh, buttock, back, abdomen, and shoulder.

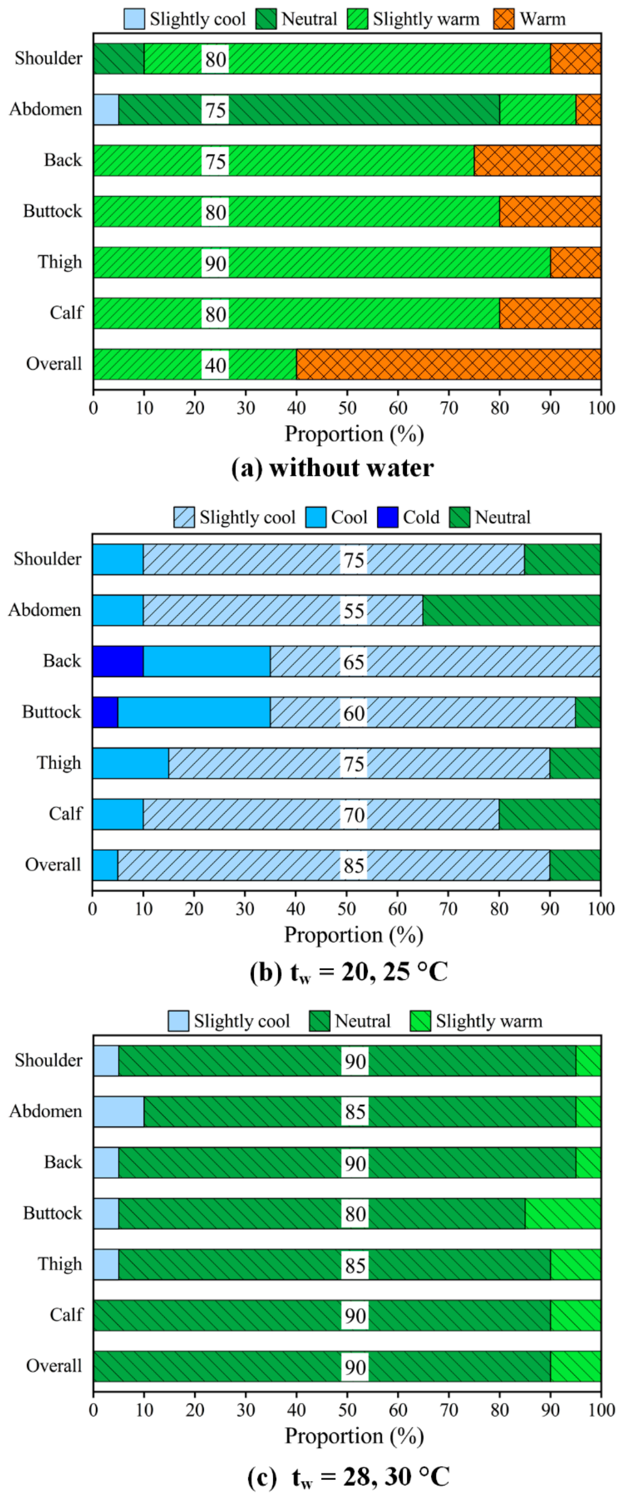

Figure 8. The proportions of thermal sensation vote with different supply water temperatures.

The proportion of thermal comfort votes under different water-supplied conditions is presented in Figure 9. The proportion of the subjects feeling comfortable with the supply water temperature at 28 or 30 °C was much higher than when without water or the supply water temperature at 20 or 25 °C. Specifically, in terms of no-water condition, only 5% of the subjects felt comfortable in the areas of the shoulder and abdomen. The overall thermal comfort votes were uncomfortable (65%). When the supply water temperature was 20 or 25 °C, less than 30% of the subjects felt comfortable in the shoulder, buttock, back, thigh, and calf. Especially 80% of the subjects felt uncomfortable in the back. However, when the supply water temperature was 28 or 30 °C, more than 85% of the subjects felt comfortable in the shoulder, abdomen, back, buttock, thigh, and calf, and the proportion of overall thermal comfort votes reached 85–90%. The results indicate that the thermal-conductive bed with the supply water temperature at 28 or 30 °C satisfied the requirements of subjects' thermal comfort during sleep.

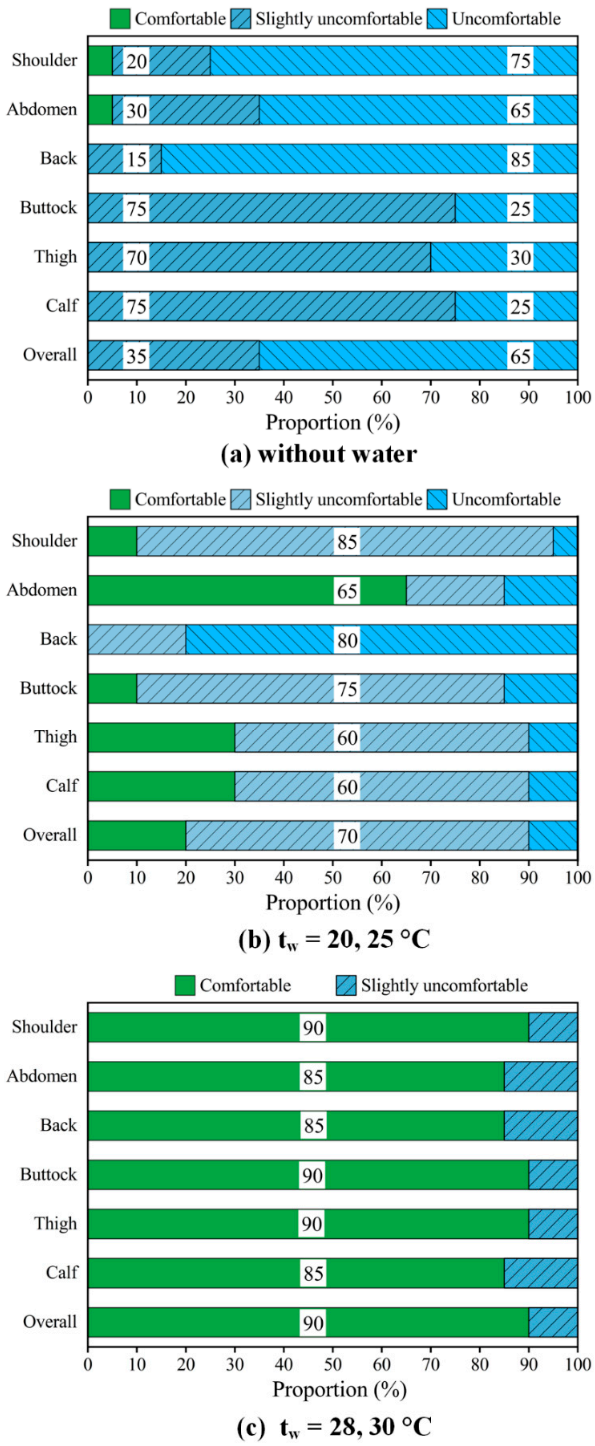

Figure 9. The proportion of thermal comfort votes with different supply water temperatures.

4. Discussion

The results in Section 3.4 indicate that the thermal-conductive bed helps improve subjects' thermal comfort during sleep in summer. Furthermore, the thermal-conductive bed also exerted great energy-saving potential. Firstly, the thermal-conductive bed maintains human thermal comfort with a background temperature of 32 °C during sleep. The upper limit of the set-point temperature of air conditioners in actual buildings at night in summer could be increased. It was reported by Zhang et al. [22] that approximately 10% energy of an air-conditioning system can be reduced when the indoor set temperature in summer increases by 1 °C. In order to obtain a comfortable zone proposed by ASHRAE Standard [48], the indoor temperature of air-conditioning buildings during summer is generally below 26 °C [41,51,52]. When occupants use this type of thermal-conductive bed for sleep, the indoor temperature could be improved to 32 °C, and the energy consumption of the air conditioning system could be reduced by over 60%. In addition, the supply water temperature of the thermal-conductive bed was high (>25 °C), which makes it possible to directly use natural cooling sources in summer and to achieve a super high COP value if any chiller is needed.

Despite the effects of the thermal-conductive bed in terms of thermal comfort and energy-saving during sleep in hot summer, some problems remain unsolved:

(1) This study only recruited male subjects aged 22.5 ± 2.5 years old for testing. Females were probably more sensitive to the thermal environment [53,54]. Moreover, subjects of other age groups may have different reactions to the thermal-conductive bed. It would be better to explore this issue in the future experimental environment;
(2) This study only investigated subjects' thermal comfort with the thermal-conductive bed when the indoor temperature was 32 °C. If the bed is effective in maintaining thermal comfort in extreme conditions, it is reasonable to believe that it is also effective in less extreme conditions, although the findings with other indoor temperatures may be different. While more experiments are needed to demonstrate the thermal comfort of people with the thermal-conductive bed in different indoor temperatures;
(3) Psychological parameters, such as electroencephalogram, electrooculogram, and electroencephalogram, were not measured to evaluate human sleep quality. The measurements of these parameters can provide basic information for examining the sleep process [55] and can be investigated in the future;
(4) It must be noted that the thermal-conductive bed was still crudely made. Future research should focus on retrofits of design, structure, and appearance to better meet the requirements of sleeping people;
(5) The optimal operating strategy of the thermal-conductive bed and the air conditioners was not discussed.

5. Conclusions

In this study, a series of experiments on human thermal comfort with a thermal-conductive bed during sleep were conducted in the summer. The main conclusions are summarized as follows:

(1) The bed surface temperature was 0–1.5 °C higher than the indoor temperature when there was no water supply in the pipes of the thermal-conductive bed. When the supply water temperature was 20 °C, the bed surface temperature was lower than 26 °C. When the supply water temperature varied between 25 to 30 °C, the bed surface temperature was relatively stable (29–31 °C);
(2) The mean skin temperature on the back of the human body was more sensitive to the supply water temperature than the upper and the side areas of the human body. When the supply water temperature varied between 28 to 30 °C, the mean skin temperature on the back and the side of the human body was consistent.
(3) Subjects perceived a slightly warm feeling when there was no water supply in the pipes of the thermal-conductive bed. When the supply water temperature was 28 or 30 °C, subjects felt thermally comfortable. Under such conditions, the mean skin

temperature of the upper, the back, and the side of the human body varied from 34 to 35 °C.

The thermal-conductive bed could be used for people who have no air conditioning systems in summer or as an alternative bed for sleep by extending the indoor set-point temperature range. It can also help save a lot of energy in buildings. However, the limitations of this study should not be ignored; for example, only male subjects aged 22.5 ± 2.5 years old participated in the experiment, while the findings of male subjects at other ages or female subjects may be different. Therefore, the experiment conditions and target subjects must be improved in future studies to verify the thermal comfort of the thermal-conductive bed for improving night sleep quality in summer. In addition, the design of the bed is required to be improved before applying it to actual buildings.

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