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Experimental Study on Convection and Heat Conduction Heating of an Air-Conditioned Bed System under Winter Lunch Break Mode

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Abstract: In this paper, an experimental study of a system for heating an air-conditioned bed during a 2 h lunch was carried out. The results show that the power consumption of heat conduction heating was only 0.34 kW·h and that the average heat dissipation was 81.3 W, while the power consumption of convection heating was 1.43 kW·h, accompanied by an average heat dissipation of 748.7 W. Regardless of the power consumption or the heat dissipation, the convection heating was significantly higher than the heat conduction heating. As a result, the room air temperature increased from 12.3 °C to 17.3 °C under convection heating, but only increased from 14.4 °C to 15.2 °C under heat conduction heating. The study results indicate that when using heat conduction heating, water temperatures in the range of 38~40 °C could meet the thermal comfort needs of the human body; however, a higher temperature range was required when using convection heating. In contrast, the grade of the hot water required for heat conduction heating was lower. It was also found that the temperature under convection heating rises faster, but it tends to lead to a dry feeling after a long time, while the conductive heating showed a slower temperature rise. There was a cool feeling for 20 min when the heating started, and then the thermal comfort improved. The air-conditioning system in this paper was investigated in a heating experiment in the winter lunch break mode and compared with convection heating. The heat conduction heating resulted in better thermal comfort and higher energy efficiency. It is suggested to adopt the heat conduction heating mode in the winter heating operation of this system.

Keywords: air-conditioned bed system; heat conduction heating; convection heating; thermal comfort; energy conservation

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1. Introduction

With increasing energy demand in the world, energy conservation and reductions in carbon emissions have become important issues. In order to reduce the energy consumption of air conditioning and improve personal comfort, some scholars focus on the study of personal comfort system (PCS) [1]. A PCS relaxes the restriction on the temperature of inactive areas, and only adjusts the thermal comfort of the area where the individual is located, which is conducive to reducing the temperature difference between indoor and outdoor spaces and, thereby, reducing energy consumption. PCS, namely, task ambient conditioning or personal conditioning system, is a personal heating system that can ensure human thermal comfort under cold conditions by adopting low energy consumption. It is a good supplement to district heating systems in Northern China [2]. In the published review papers [3–6], researchers mainly discuss the thermal comfort and energy efficiency of various PCS, and focus more on cooling and ventilation than heating. There is currently limited research on PCS for heating during winter sleep. In this paper, a capillary convection and heat conduction air-conditioned bed system is proposed, which creates a local thermal comfort environment when people sleep and rest. It not only provides heating in winter, but also cooling in summer. There are three heat transfer modes: heat conduction, radiation, and convection. The energy-saving effect is obvious, and it can be used in homes, hotels, hospitals, and other places, which has certain research significance. This paper mainly focuses on the experimental study of heating in the noon break mode.

2. Literature Review

At present, the research related to personal comfort system is mainly based on personalized air supply in summer [7]. There are few studies on heating in winter, and they mainly apply to office spaces. In some cases, the airflow is directed toward the head and other parts of the human body by setting an outlet or placing a fan near the desk [8–10]. There are also heating or cooling seats designed to meet the requirements of human thermal comfort [11,12]. Other designs focus more directly on a certain part of the human body, such as a heating device placed on the feet, and operate through the form of heat conduction or radiation heating for the human body [13,14]. Foda et al. [15] proposed a strategy to maximize the energy efficiency using local floor heating and found that local floor heating can meet the comfort requirements at 18 °C. Zeiler et al. [16] studied the thermal comfort in school classrooms, and their results show that radiant heating is more comfortable than traditional heating methods. Deng et al. [17] found that the overall thermal sensation and comfort resulting from personalized heating at 16 °C were rated as neutral and comfortable, respectively, which were significantly higher than the ratings obtained without the personalized heating at 18 °C. In addition, there are some differences in the thermal sensation of different parts of the human body, and the influence on the overall thermal sensation is also different. Arens et al. found that in colder environments, the thermal sensation of certain parts of the human body, such as the back, chest, etc., is greater than that of the hands and feet [18]. Lv et al. conducted the relevant experimental research on human thermal sensation and found that in a specific hot and humid environment, local heating or cooling of indoor personnel can produce a sense of thermal comfort [19]. Schellen et al. studied the differences in the perception of thermal comfort between genders under non-uniform environmental conditions, and found that local thermal sensation and skin temperature have a more pronounced effect on the overall thermal sensation in women than in men [20].

In recent years, some experts and scholars have conducted much research work on personal comfort system in the sleep environment. Wang et al. [21] developed a water-heated bed, and Yu et al. [22] developed a solar phase-change heat-storage heating bed system. Both of these designs provide a thermal comfort environment during sleep through heat conduction. To provide a thermal comfort environment under sleeping conditions through convection, Pan et al. [23] designed a personal sleep comfort system with a flexible air duct and a static pressure box, but the structure is more complex. Mao et al. [24–27] designed a simplified system on this basis, removing the flexible air duct and the static pressure box, which is conducive to its development. Du et al. [28] added a radiation plate on the basis of the design by Mao et al., which assists in solving the discomfort caused by the tuyere blowing on to the human body. In addition, radiant air conditioning also has several advantages. Radiation heating or cooling has a small vertical temperature gradient and can maintain a high level of thermal comfort [29,30]. Xin et al. [31] designed a local space capillary radiation air-conditioning system for the sleeping environment. The capillary radiation plate was set above the horizontal human body and surrounded by a baffle and a bed curtain. The thermal comfort during heating was good, and the system was energy efficient. However, condensation tends to occur in radiant air-conditioning refrigeration, which is a key factor restricting its development. The air-conditioning bed system proposed in this article can provide both heating and cooling, and can avoid condensation during refrigeration. The system provides a high level of thermal comfort, has a simple structure, and results in obvious energy savings, which is conducive to its future development.

3. Experiment Introduction

3.1. Experimental Room and Equipment

The laboratory room is selected from the student dormitory building of Henan University of Urban Construction, where the walls are all made of 240 mm brick walls, the inside is painted with 20 mm white plaster, the outside is painted with 20 mm white plaster or cement mortar, the external windows are installed with 6 mm thick single-layer ordinary glass, and the room height is 3.1 m. During the lunch break heating experiment, none of the adjacent rooms (up and down, left and right) were heated. The size of the wooden bed in the room is 1860 × 1000 mm, a layer of 20 mm thick thermal insulation cotton is laid on the bed, a layer of capillary tube network is laid on top of the thermal insulation cotton, and a sponge-padded mattress is placed on the capillary tube. The capillary tube adopts the third-type of Polypropylene Pipe (PP-R), the main pipes for water supply and return are both 20 × 2.0 mm, the size of capillary diameter is 4.3 × 0.8 mm size, and the spacing is 40 mm. The relevant layout plan is shown in Figure 1.

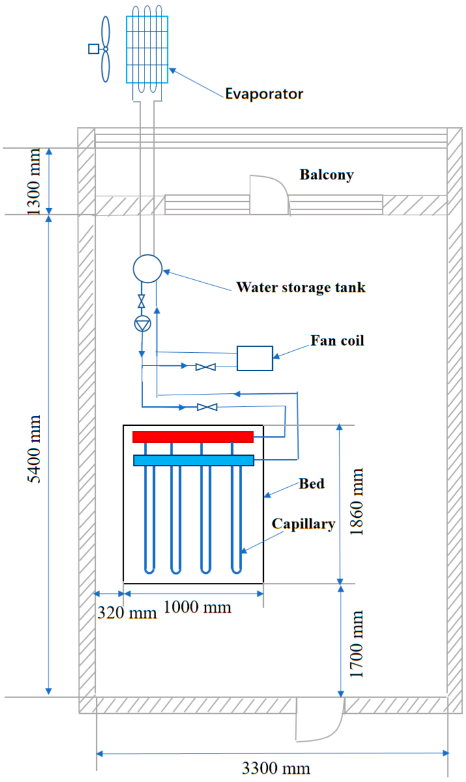


Figure 1. Layout of experimental room and air-conditioned bed system.

In the experiment, 1.8 kg of sponge-padded mattress and 1.9 kg of cotton silk quilt are selected. It adopts the FLIR T540 infrared thermal imager, the T-type thermocouple, the COS-04 temperature and humidity recorder, the GTLWGY10ALC2SSN turbine flowmeter, and the UNI-T anemometer, with the YP5000 multi-channel temperature recorder, to record data. The air duct adopts a telescopic PVC aluminum foil pipe with a diameter of 183 mm, and the heat source unit adopts a fixed frequency air source heat pump to provide the hot water for heating. A 280 W desktop computer is placed in the laboratory to collect data. As shown in Figures 2–5.

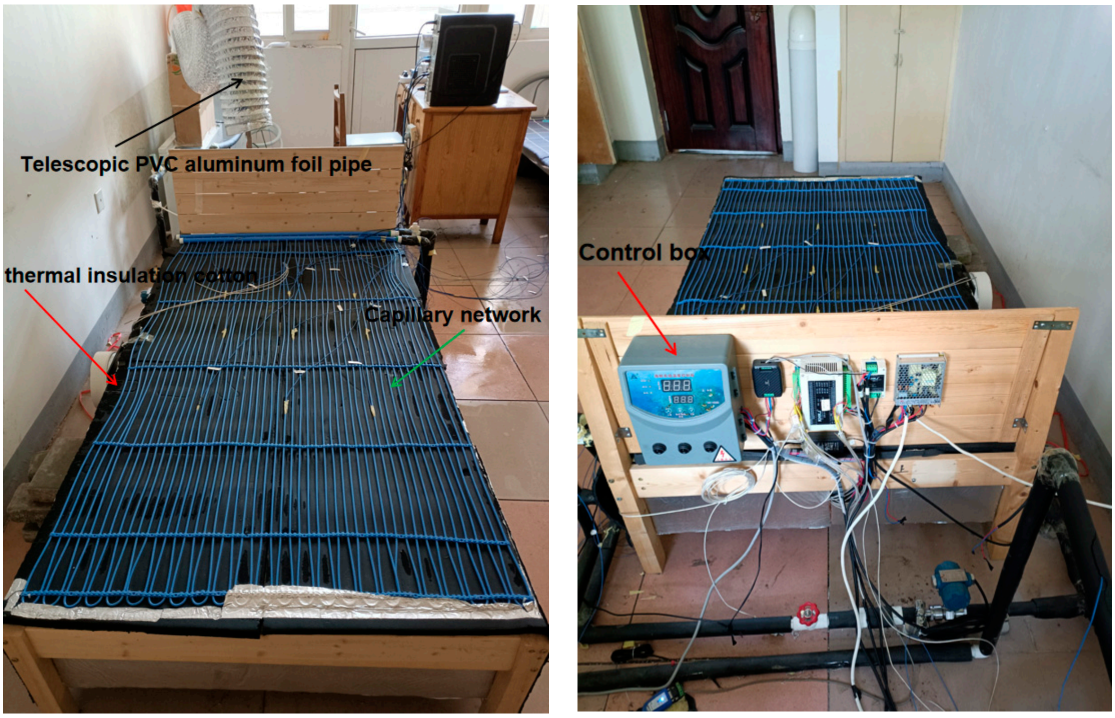


Figure 2. Physical diagram of capillary convection and heat conduction air-conditioned bed system.

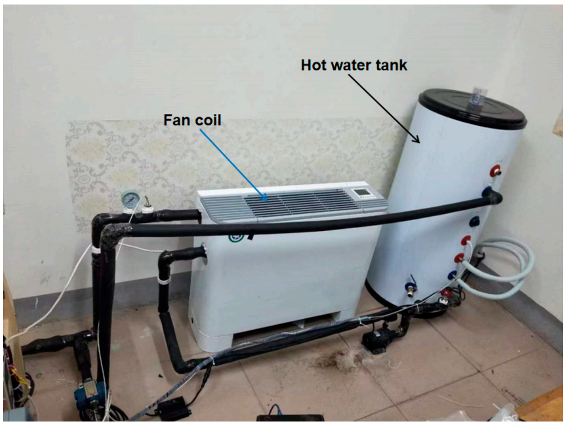


Figure 3. Fan coil and hot water tank.

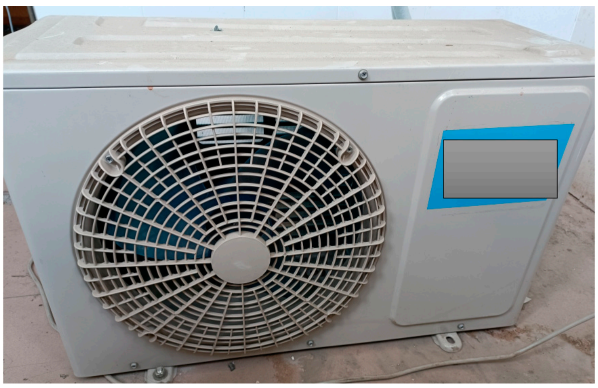


Figure 4. Air source heat pump.

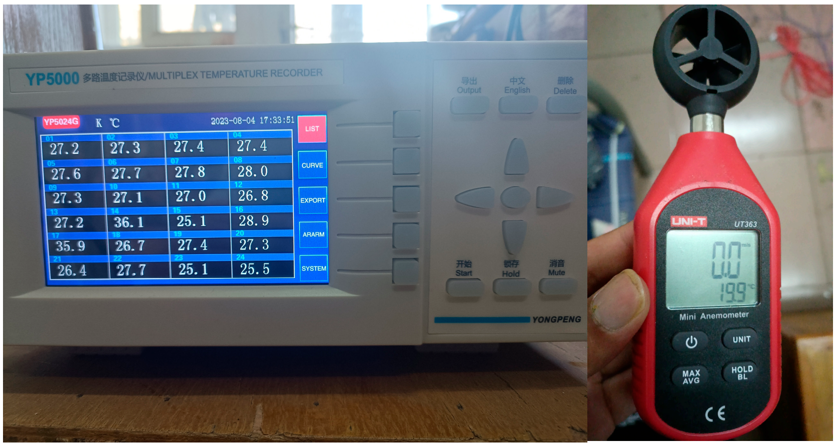


Figure 5. YP5000 multi-channel temperature recorder and anemometer.

3.2. Subjects and Measurement Point Arrangement

The subjects are four male college students and four female college students, aged 20–23 years, with a height of (1.70 ± 0.12) m, a body mass of (60 ± 14) kg, and a body mass index (BMI) of (20.4 ± 2.0) kg/m^2. In the experiment, everyone is required to wear thin long sleeves on top and thin pants on bottom, and the thermal resistance of the clothes is about 0.4 clo [32]. All subjects are in good physical condition, and do not exercise vigorously before the start of the experiment, and once the experiment begins, the subjects are required to lie flat and remain still throughout the entire process. During the experiment, we should know the subject's evaluation of thermal comfort at all times. Figure 6 shows the field photo of the subject during the experiment.

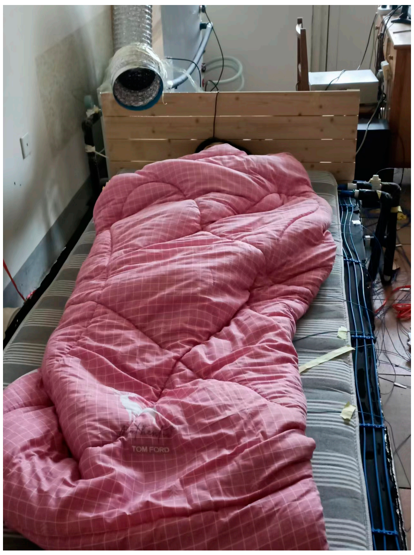


Figure 6. Field view of the subject during the experiment.

During the experiment, the inlet main pipe and outlet main pipe of the capillary network are arranged with T-type thermocouples, respectively, and the measured data is used as the supply water temperature (SWT) and return water temperature (RWT) for the experiment. The temperature of the thermocouple arranged on the surface of the mattress directly below the back of the human body is considered as the temperature of the contact surface between human body and bed (TSHB). Three thermocouples are arranged on the surface of the capillary water supply pipe, and six thermocouples are arranged on the surface of the return pipe, and the average value of their measurements is considered as the surface temperature of supply water capillary (STSWC) and the surface temperature of return water capillary (STRWC). The indoor and outdoor temperature and humidity changes are recorded with the temperature and humidity recorder.

3.3. Experimental Research Method

Choosing the time between 12:00–14:00 on 21 February 2023, and 26 February 2023, as the experimental time, the heating experiment mainly based on heat conduction and the heating experiment mainly based on convection were carried out. The external weather conditions during these times are relatively similar, which is conducive to comparing and analyzing the experimental results. During the experiment focused on heat conduction for heating purposes, the water pump will be running throughout the entire process, and while the heat pump unit will be started at 12:00 and stopped at 12:30, the supply water temperature will be controlled within a certain range using the control system, and the hot water will be sent into the capillary tube for the heat conduction experiments. During the experiment focused on convection, hot water will be also provided by the air source heat pump, the control system will maintain the supply water temperature within a certain range, the hot water will be sent into the fan coil unit, and the convective heat exchange will occur through the fan, and then the hot air will be directly delivered near the human body.

The Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) proposed by Fanger et al. [33] are commonly used to evaluate human thermal sensation, but this evaluation index is applicable for the evaluation of human thermal comfort in a steady-state thermal environment, not suitable for a dynamic environment. In addition, the other methods include ASHRAE 7-level scale method for thermal sensation voting in the form of questionnaire survey and the classification method of thermal comfort proposed by He et al. [34], but most of them are evaluated for a certain temperature rather than a certain temperature range. This paper adopts the subjective evaluation method to evaluate the thermal comfort of the human body, which is mainly based on the subjective feelings of the testers about the thermal environment, and it is also a voting method to find different temperature ranges of thermal comfort under the conditions of non-uniform environment and dynamic environment. The adopted method is based on the thermal comfort classification method proposed by He et al. [34] and makes appropriate adjustments on this basis, dividing thermal comfort into five grades: very uncomfortable, uncomfortable, unfeeling, comfortable, and very comfortable. In addition, during the experiment, the thermal comfort of eight subjects was tracked and investigated at all times, and the subjective voting method was used to find different thermal comfort temperature ranges according to the number of votes cast by subjects at different TSHB, and the thermal comfort temperature range with a turnout rate exceeding 75% was recognized.

4. Results and Analysis

4.1. Experimental Results of Thermally Conductive Heating

4.1.1. Analysis of Data Changes at Different Measurement Points

As shown in Figures 7 and 8, the indoor air temperature (IAT) and the indoor humidity are relatively stable, with the temperature ranging from 14.4 to 15.2 °C, with an average of 14.9 °C, and the relative humidity in the range of 39.7 to 41.2%, with an average of 40.6%. The outdoor air temperature (OAT) and the outdoor humidity also varied little, with the temperature ranging from 6.9 to 7.6 °C, with an average of 7.2 °C, and the relative humidity in the range of 47.5 to 56.2%, with an average of 51.4%.

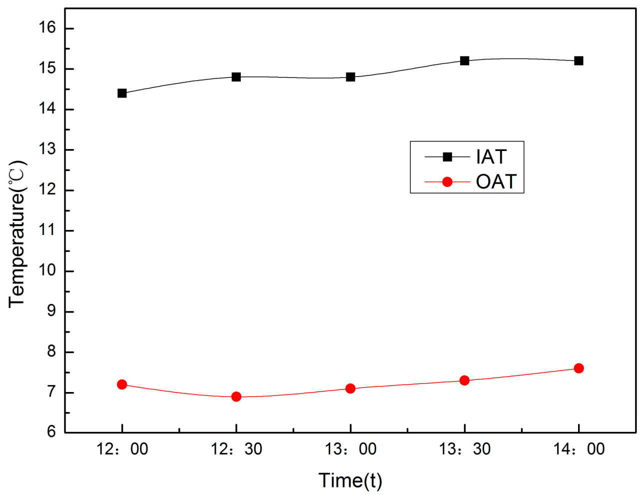


Figure 7. Change graph of indoor and outdoor air temperature.

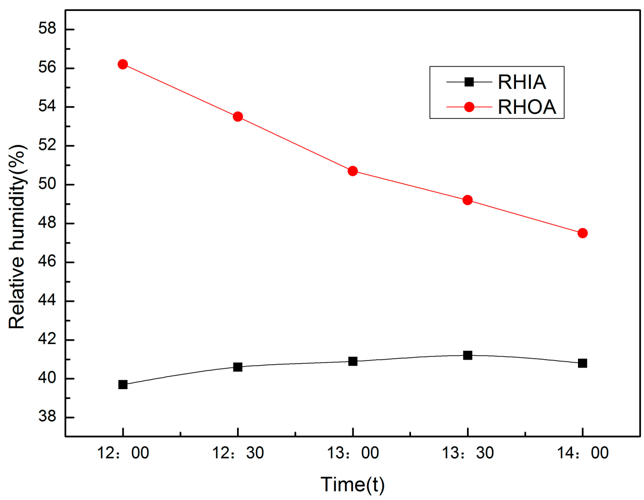
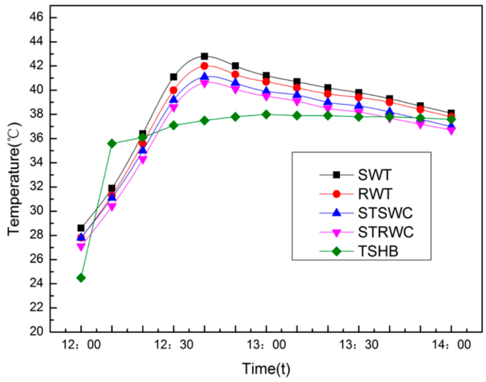


Figure 8. Variation curve of indoor and outdoor air relative humidity.

As shown in Figure 9, the unit is turned on at 12:00, the water supply temperature rises from 28.6 to 42.8 °C within 40 min, while the TSHB also rises rapidly from 24.5 to 37.5 °C. Referring to the ASHRAE seven-level scale method and making appropriate adjustments, the thermal sensation is divided into five levels. During the experiment, the thermal sensation of eight subjects is tracked and investigated at all times, and using subjective voting method, the temperature range of different thermal sensations is determined based on the number of votes cast by subjects at different TSHB. The specific results are shown in Table 1. When people lie on the bed, they feel obvious coldness at the beginning, then feel the surface temperature of the sponge-padded mattress is rising, and finally the cold feeling gradually disappears and a good warm feeling appears, which is consistent with the survey results in Table 1. Hot water enters into the capillary tube, first convection heat exchange with the inner wall of the capillary, then the heat is transferred to the outer surface of the capillary tube by heat conduction, and then to the outer surface of the sponge-padded mattress through thermal conduction. Part of the heat is transferred to the human body and quilt in contact with it through thermal conduction, while the remaining heat is mainly transferred to the quilt and room through heat radiation. During the period from 12:00 to 12:20, it is found that the temperature of the contact surface between human body and bed increased rapidly, and obviously exceeded the temperature of the supply and return water. It is obvious that it cannot be completely caused by the heat transfer from the heating hot water, and the main reason is that the human body is in contact with the surface of the mattress, and the heat of the human body is transferred to the contacted mattress, resulting in a significant increase in temperature at that area.



SWT-Supply water temperature
RWT-Return water temperature
STSWC-Surface temperature of supply water capillary
STRWC-Surface temperature of return water capillary
TSHB-Temperature of the contact surface between human body and bed

Figure 9. Temperature variation curve of different measuring points during thermal conduction heating.

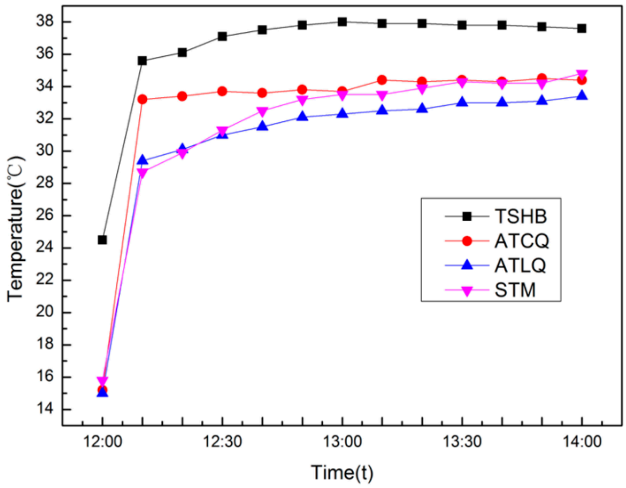
Table 1. Thermal sensation subjective voting questionnaire.

Temperature Range (°C)	Thermal Sensation (Number of Voters)				
	Cold	Cool	Neutral	Warm	Hot
(24.0–33.0)	8	0	0	0	0
(33.0–36.0)	2	6	0	0	0
(36.0–36.6)	0	1	7	0	0
(36.6–37.5)	0	0	1	7	0
(37.5–38.0)	0	0	0	5	3

As shown in Figure 10, after the unit has been running for 10 min, the temperature of the four positions increases significantly. Subsequently, the temperature of the contact surface between human body and bed tends to be stable, as does the air temperature near the chest in the quilt (ATCQ). While the air temperature near the legs in the quilt (ATLQ) and the surface temperature of the sponge-padded mattress in the middle of the legs (STM) show a slow increasing trend. The air temperature near the chest in the quilt is always higher than the air temperature near the legs in the quilt, with an average difference of 1.8 °C. On the one hand, this is related to the heat dissipation of the human body, as the chest area has greater heat dissipation, while the leg area has less. On the other hand, it is also because the quilt is covering the human body, sinking with gravity, and tightly adhering to the surface of the human body and the mattress, which hinders the circulation of the air inside the quilt. This tends to make the temperature of the legs rise slower, making people feel cold in their feet at first.

From the temperature curve change rule in Figure 9, it can be seen that after the unit is shut down, the supply water temperature still rises for about 10 min. The reason is that the temperature of the condenser will not decrease immediately, and the water in the hot water tank will still be heated until condenser achieves the same temperature as the water in the hot water tank. In addition, the temperature of the supply and return water and the surface temperature of the supply and return capillary, will gradually decrease after reaching the maximum value, and the water supply temperature will still remain at a high temperature of 38.1 °C at 14:00. In this process, the temperature of the contact surface between human body and bed reaches the maximum temperature of 38.0 °C, and then remains basically unchanged. Even at close to 14:00, it exceeds the surface temperature of the capillary for the supply and return water, and this is because as the supply and return water temperature decreases, the surface temperature of the capillary tube also decreases.

However, the sponge-padded mattress has a heat storage function, which greatly delays the attenuation of the temperature of the contact surface between human body and bed.



TSHB-Temperature of the contact surface between human body and bed
ATCQ-Air temperature near the chest in the quilt
ATLQ-Air temperature near the legs in the quilt
STM-Surface temperature of the sponge-padded mattress in the middle of the legs

Figure 10. Temperature change curve of measurement points in the quilt during thermal conduction heating.

4.1.2. Temperature Analysis of Infrared Thermal Imager

As shown in Figures 11–14, we have arranged measuring points at different locations on each graph, and from the temperature results shown at different measuring points, it can be seen that the surface temperature of the quilt is not high, and it changes very little over time, the average temperature in different time periods only changes within the range of 16.0 to 17.7 °C, which indicates that the quilt has a good heat insulation function. Additionally, it can be observed that the surface temperature of the quilt is lower at the edges compared to the central area. This is because the surface temperature of human body is higher, and the temperature of the quilt in contact with it is increased by heat conduction. It can also be seen that the outer surface temperature of the quilt at the foot position of the human body is slightly lower than that at other parts of the human body, resulting in a poor thermal comfort of the feet, which is also consistent with the above-mentioned law of air temperature distribution inside the quilt.

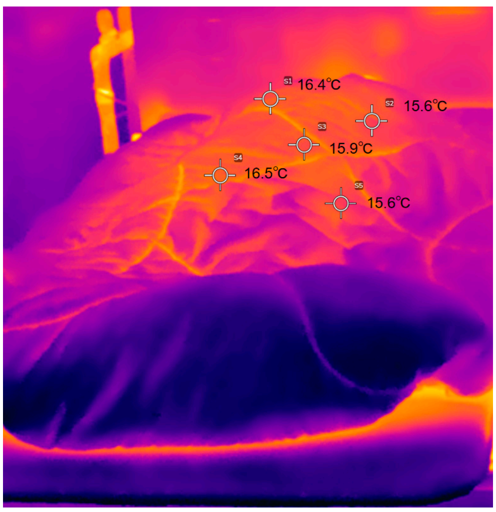


Figure 11. Temperature field distribution of infrared thermal imager at 12:30.

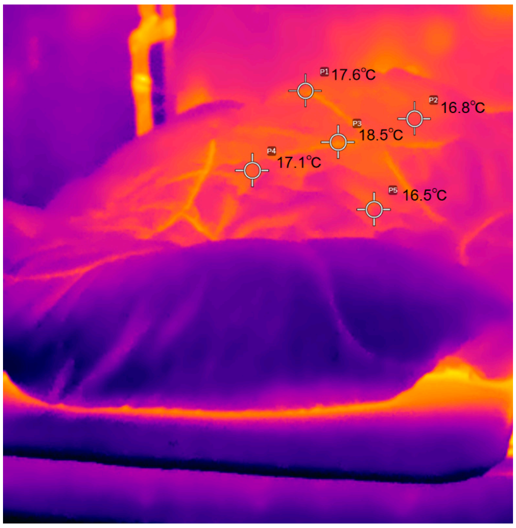


Figure 12. Temperature field distribution of infrared thermal imager at 13:00.

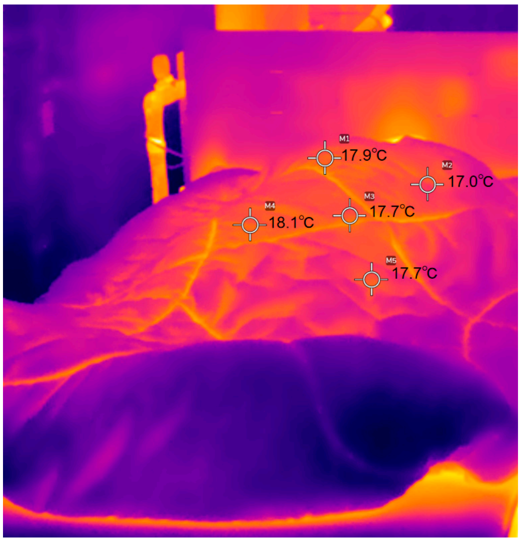


Figure 13. Temperature field distribution of infrared thermal imager at 13:30.

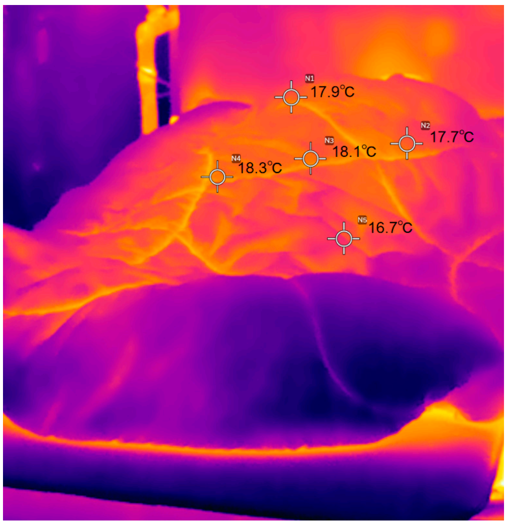


Figure 14. Temperature field distribution of infrared thermal imager at 14:00.

4.1.3. Analysis of Power and Heat Dissipation Data

As shown in Figure 15, the heat pump unit starts at 12:00 and stops at 12:30, operating for exactly half an hour. The average power of the unit during operation is 876.4 W, while the average power of the pump is 35.6 W. After the shutdown of heat pump unit, the pump continues to operate at an average power of 35.6 W, and the power consumption of the whole process is 0.52 kW·h. Through the experiment, it is found that if the lunch break mode experiment was conducted the day before and restarted the next day, the water supply temperature is often around 34 °C or even higher when the machine is turned on. The initial water supply temperature during the heat conduction heating experiment is only 28.6 °C, combining with the temperature change curve of supply and return water in Figure 9 and the power change curve in Figure 15, it can be seen that 0.18 kW·h energy consumption can be saved on this basis, that is to say, the heating in the lunch break mode only needs to consume 0.34 kW·h to meet the thermal comfort of the human body.

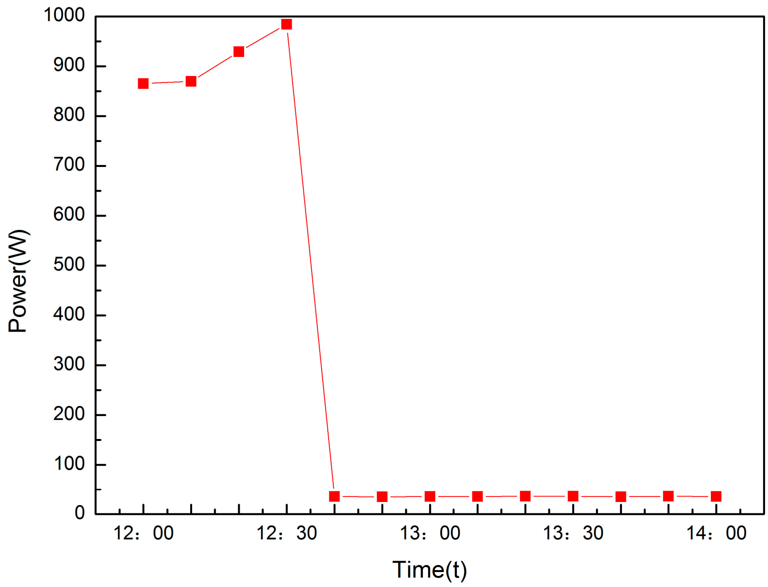


Figure 15. Power variation curve of heat conduction heating with time.

Through the water flow, the temperature difference between the supply and return water and the specific heat of the water, the heat dissipation of heat conduction heating can be calculated. During the whole experiment, the water flow rate changes slightly, and the average water flow rate is 2.0 L/min. As can be seen from Figure 16, the heat dissipation is large at the start, reaching 112.0 W, although the water supply temperature is only 28.6 °C. It is mainly because the ambient temperature of the room and the temperature of the mattress and quilt are relatively low when the unit is just started, which is easy to dissipate heat. With the increase in water supply temperature, the ambient temperature is also gradually increased, especially a sharp increase in the temperature of mattress and quilt, which reduces the temperature difference between them, but the heat dissipation is reduced, which reduces to 81.9 W at 12:10. With the further increase in the water supply temperature, it becomes more conducive to the surrounding heat dissipation, and its heat dissipation is also increased, especially reaching a maximum of 152.5 W at 12:30. And then as the temperature difference between the water supply and mattresses, quilt, etc., further decreases, the heat dissipation gradually decreases, and after 13:40, it tends to be flat. The average heat dissipation during the whole lunch break heating time is only 81.3 W, which is much lower than that of the conventional air conditioning system. In addition, it can also be seen that during the entire lunch break process, the time period of large heat dissipation is mainly concentrated in the period from the start of the unit to the 20 min after the unit stops.

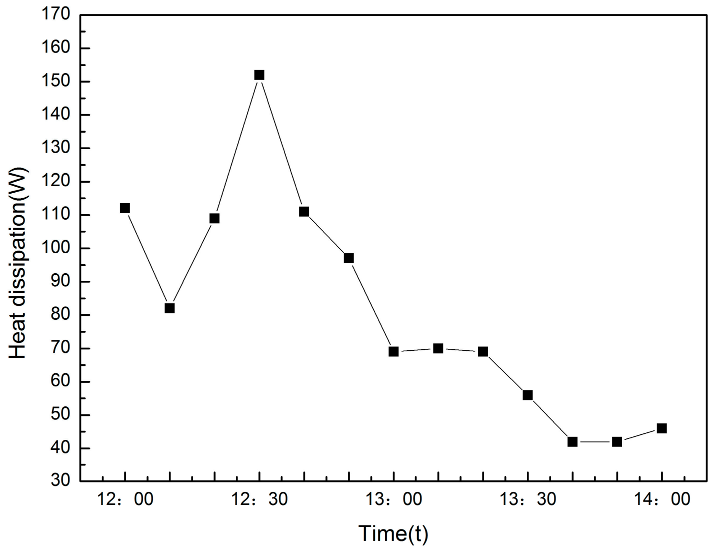


Figure 16. Curve of heat dissipation with time during heat conduction heating.

4.2. Experimental Results of Convective Heat Exchange Heating

4.2.1. Analysis of Data Changes at Different Measurement Points

From Figure 17, it can be seen that the indoor air temperature changes in the range of 12.3 to 17.3 °C, and the increase is more obvious. After half an hour, it tends to be stable, with an average of 16.2 °C. It can be seen that in the convective heating experiment, a large part of the heat is lost in the air, resulting in a significant increase in indoor air temperature. The outdoor air temperature ranges from 4.7 to 7.9 °C, and the average temperature is 6.4 °C, which is close to the weather conditions on the 21st.

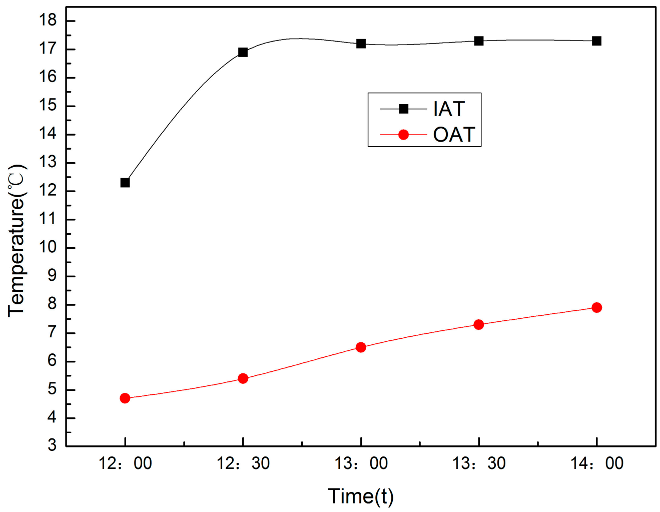


Figure 17. Change graph of indoor and outdoor air temperature.

From Figure 18, it can be seen that the indoor relative humidity ranges from 43.5 to 46.6%, with an average of 44.9%, which is also relatively stable. The outdoor relative humidity is relatively high, ranging from 60.3 to 80.6%, with an average of 71.8%, showing a downward trend.

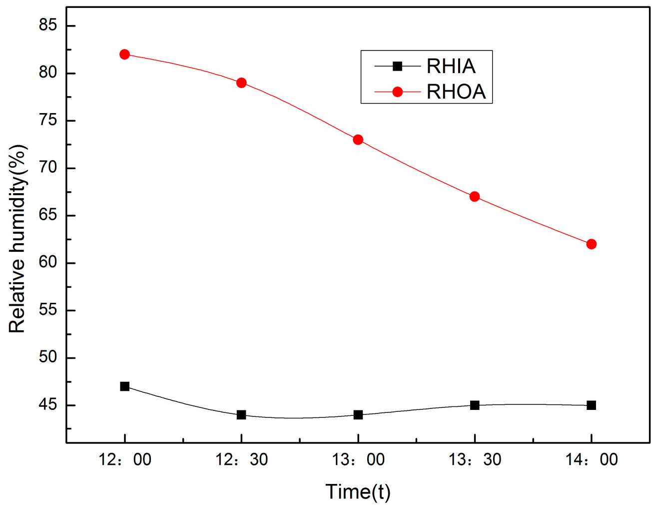


Figure 18. Variation curve of indoor and outdoor air relative humidity.

From Figure 19, it can be seen that when doing the convective heating experiment, the water supply temperature changes in the range of 39.9 to 48.8 °C, and the average temperature difference between the supply and return water is 6.7 °C, However, the average temperature difference between water supply and return in the heat conduction heating mode is only 0.6 °C. In addition, the air temperature near the legs in the quilt is still significantly lower than the air temperature near the chest in the quilt, and the average difference between the two is 1.6 °C. This is due to the greater heat dissipation of the chest than the legs, and the main reason is that the air outlet blows near the head of the person, and the temperature near the chest is obviously higher than the temperature in other parts. Throughout the experiment, it is found that the wind speed at the tuyere and the wind speed near the human face is uneven, and the maximum value and the minimum value are very different. In this paper, the maximum value is expressed. During the experiment, the wind speed in the air outlet and near the person's face has been stable over time, and the maximum wind speed of air outlet has been maintained at about 2.0 m/s, while the temperature of air outlet changes with the change in water supply temperature, and remains in the range of 29.6 to 33.3 °C. The maximum wind speed near human face has been maintained at about 0.8 m/s, and the temperature varies between 24.2 °C and 27.1 °C, which gives people a weak sense of blowing. The temperature is relatively comfortable, but there is a slight sense of dryness.

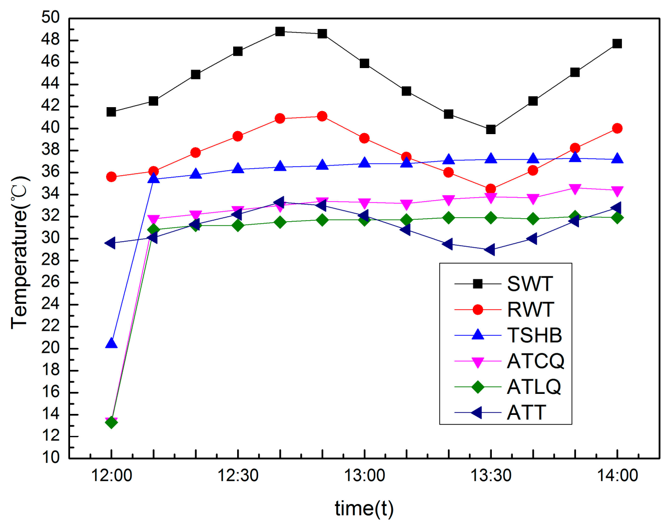


Figure 19. Temperature variation curves at different measuring points during convective heating.

4.2.2. Temperature Analysis of Infrared Thermal Imager

From Figures 20–24, we have also arranged measuring points at different locations on each graph, and from the temperature results shown at different measuring points, it can be seen that at the beginning of the experiment, the outer surface temperature of the quilt is significantly lower, with an average temperature of 15.3 °C. Subsequently, the temperature rises significantly and remains stable thereafter, with an average temperature ranging from 21.0 to 22.7 °C. The surface temperature of the quilt is significantly higher than that of the heat conduction heating experiment, resulting in a large amount of heat being lost into the air, which is also the fundamental reason why the room temperature is significantly higher than that of the heat conduction heating mode. The temperature is obviously higher in the area near the air outlet, while the temperature is lower in the farther place, especially near the human foot, which is also an important reason why the air temperature near the chest in the quilt is higher than the air temperature near the legs in the quilt. Therefore, at the beginning of lying on the bed, there will be a phenomenon of cold feet, until the phenomenon of cold feet gradually disappears and warm feet appears.

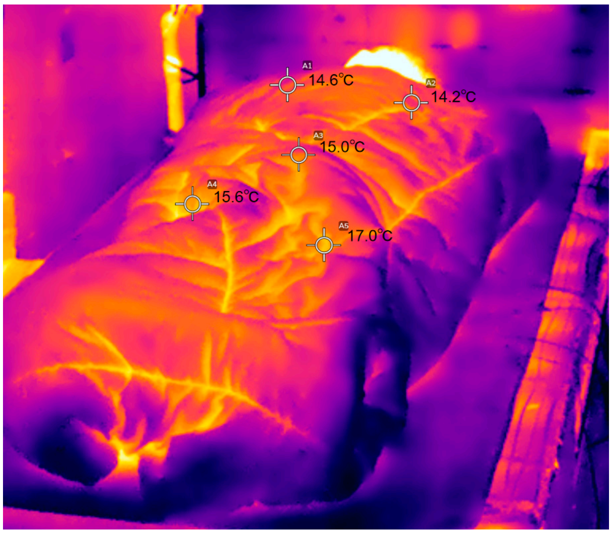


Figure 20. Temperature field distribution of infrared thermal imager at 12:00.

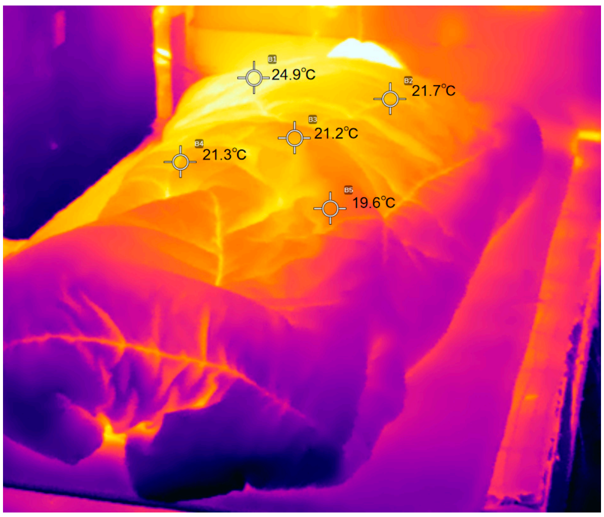


Figure 21. Temperature field distribution of infrared thermal imager at 12:30.

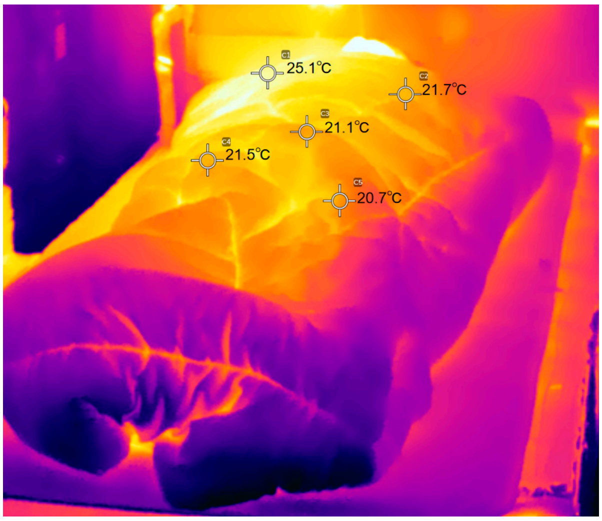


Figure 22. Temperature field distribution of infrared thermal imager at 13:00.

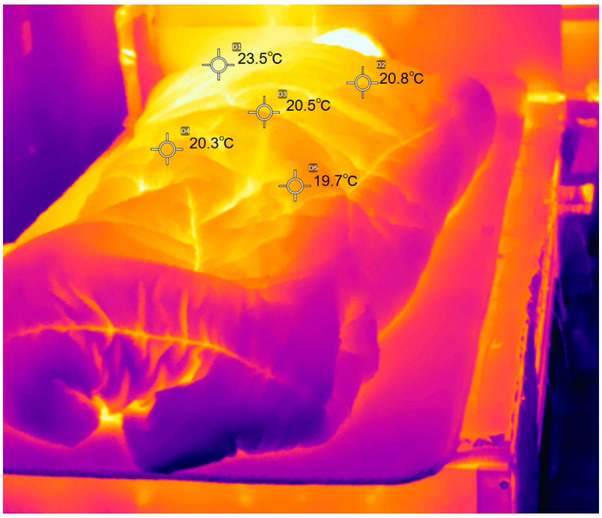


Figure 23. Temperature field distribution of infrared thermal imager at 13:30.

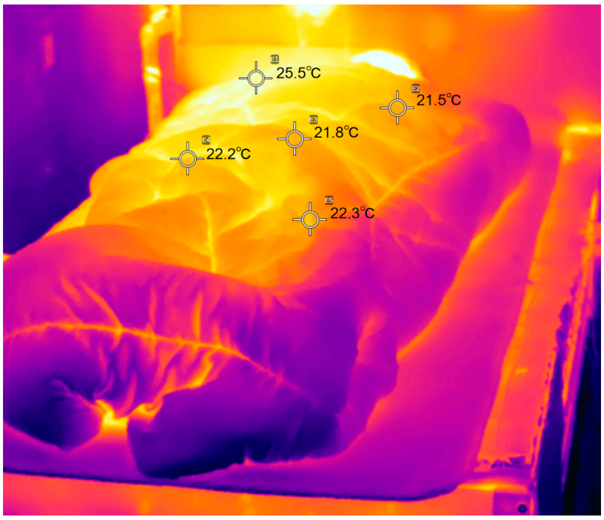


Figure 24. Temperature field distribution of infrared thermal imager at 14:00.

4.2.3. Analysis of Power and Heat Dissipation Data

As shown in Figure 25, the pump heat unit starts at 12:00 for convection heating. The initial water supply temperature is 41.5 °C. When the water supply temperature is close to 50 °C, the unit stops and reopens when it is reduced to close to 40 °C, so it changes periodically during operation. The heat pump unit has been running for two periods of time, with an average power of 928.5 W and a total of 76 min of operation, while the average power of the pump and fan is 105.9 W. The power consumption during the whole lunch break is 1.43 kW·h, which is significantly higher than that of heat conduction heating mode.

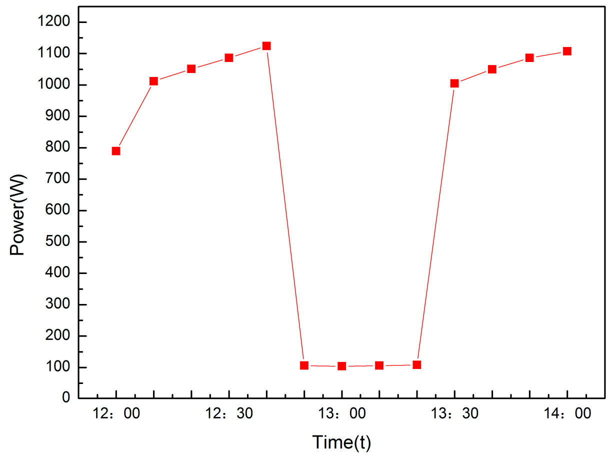


Figure 25. Power variation curve of convection heating with time.

As shown in Figure 26, the amount of heat dissipation varies with the operation law of the heat pump unit. The amount of heat dissipation increases when the heat pump unit is running, and begins to decrease when the unit stops. The average heat dissipation of the whole process is 748.7 W, which is much larger than the average heat dissipation of 81.3 W in the conductive heating mode, and the former is more than nine times the latter.

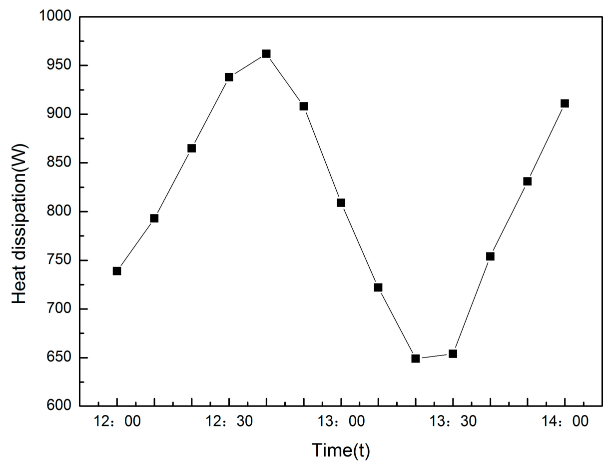


Figure 26. Curve of heat dissipation with time during convection heating.

5. Discussion

5.1. Thermal Comfort Analysis

In the study, it is found that in the heat conduction heating experiment, the human body basically reached a state of no cold feeling after 20 min of operation, and the discomfort basically disappeared. After that, the human body feels slightly warm and gradually warmer, and the sense of comfort gradually strengthens. Different individuals may have different levels of thermal comfort. This article adopts a subjective voting method to evaluate human thermal comfort. For the evaluation of thermal comfort in non-uniform and dynamic environmental conditions with direct contact, it is divided into five grades: very uncomfortable, uncomfortable, unfeeling, comfortable, and very comfortable. During the experiment, the subjects were continuously asked about their thermal comfort and were asked to vote, similar to the survey form in Table 1. By adopting the identification method with a voter turnout of more than 75%, finding different thermal comfort temperature ranges. Finally, it is concluded that the temperature of the contact surface between human body and bed is comfortable in the range of 36.7 to 37.2 °C and very comfortable in the range of 37.2 to 37.8 °C.

In the convection heating experiment, if the air velocity at the air outlet is too high, people will feel the obvious sense of blowing, thus feeling uncomfortable. When the air velocity is too low, the temperature of the blown air declines too quickly. When it reaches the head of human body, the air temperature is already low, which will also affect the thermal comfort. Therefore, during the experiment, the air velocity at the air outlet was adjusted to around 2.0 m/s, and the temperature near the human face could be maintained in the range of 24.2 to 27.1 °C. The blowing feeling was weak, and the overall thermal comfort was good, but for a long time, there would be a slight sense of dryness. The overall thermal comfort is not as good as the heat conduction heating.

5.2. Energy Saving Analysis

In the heat conduction heating experiment, the supply water temperature varied within the range of 28.6 to 42.8 °C, and the average heat dissipation during the whole lunch break heating time is only 81.3 W. If we exclude the heat loss caused by the exposed capillary tubes, this value would be even lower. If the initial water supply temperature is set at 34 °C according to the experimental experience, the power consumption during the lunch break is 0.34 kW·h, and a large part of the power consumption is used for heating the water in hot water tank and storing energy in the water. We choose a day with similar outdoor weather conditions, using a KFR-35GW air conditioner to perform heating experiments in the experimental room, also 2 h at noon, and found that when the indoor temperature is maintained around 20.3 °C, the power consumption is 2.21 kW·h. In comparison, the energy-saving effect of the air-conditioned bed system is very obvious, and its power consumption is only 15.4% of the ordinary air conditioner. In addition, it is found that the heat conduction heating water temperature is roughly in the range of 38 to 40 °C, which can makes people more comfortable. Compared with radiators, floor heating, etc., the required water temperature is lower, which is more conducive to energy saving. And the heat pump unit only needs to run for 30 min to meet the heating needs of the two hours of lunch break.

In the convective heating experiment, the water supply temperature varied within the range of 39.9 to 48.8 °C, and the heating effect is relatively rapid. However, the average heat dissipation during the lunch break is 748.7 W, which is more than nine times that of the heat conduction heating experiment. During the whole lunch break heating period, the power consumption is 1.43 kW·h, which is 64.7% of the ordinary air conditioner, and more than four times that of the heat conduction heating experiment. In addition, compared with the heat conduction heating experiment, the water supply temperature of the convection heating experiment is significantly higher, which is not conducive to energy saving. The air-conditioned bed system, especially the heat conduction heating mode, has an obvious energy-saving effect and strong thermal comfort, and its prospect for future application is good. However, the factors that constrain its development include the requirement for people to believe that it has obvious advantages along with its cost, installation, and other issues, especially the cooling effect. These will be solved in future research, so as to promote the possibility of widespread use of the air-conditioned system in the future.

6. Conclusions

In this paper, the heat conduction heating experiment and convection heating experiment of the capillary convection and heat conduction air-conditioned bed system are carried out, respectively. The experimental results show that during a 2 h lunch break, the heat conduction heating only consumes 0.34 kW·h of electrical energy, with an average heat dissipation of only 81.3 W, and the power consumption is 15.4% of the ordinary air conditioner. The convection heating needs to consume 1.43 kW·h of electric energy, with an average heat dissipation of 748.7 W, and the power consumption is 64.7% of the ordinary air conditioner. These two heating modes are both relatively energy-saving, especially the heat conduction heating mode, which has a more obvious effect.

From the images captured by the infrared thermal imager, it can be seen that compared to thermal conduction heating, the outer surface temperature of the quilt is significantly higher during convective heating, resulting in a higher heat dissipation of the quilt. In addition, there is a continuous flow of hot air from the air outlet, resulting in the room air temperature rising from 12.3 to 17.3 °C, while the air temperature of the heat conduction heating room only rises from 14.4 to 15.2 °C.

Compared to heat conduction heating, convective heating is effective in heating quickly, but it is prone to dryness for a long time, while heat conduction heating heats up slowly and may even feel cool in the first 20 min. But its thermal comfort has been better, making the overall thermal comfort of convective heating inferior to heat conduction heating. In addition, heat conduction heating requires a lower range of water temperature and has lower requirements for the quality of hot water, which is advantageous for energy saving.

Regardless of heat conduction heating or convective heating, the air temperature near the chest in the quilt is significantly higher than that near the legs in the quilt, causing the upper body to feel hotter than the lower body. This is also the reason why cold feet often occur at the beginning of the experiment. After comparison, it is found that the heat conduction heating provides better overall thermal comfort and is more energy efficient, but there is a phenomenon of cold feeling in the first 20 min of heating. It is suggested that when heating in winter, the system should use two heating modes simultaneously for the first 20 min, and then only heat conduction heating mode should be used, or the heat conduction heating mode should be started 20 min before the lunch break.

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Nomenclature

IAT	Indoor air temperature (°C)
OAT	Outdoor air temperature (°C)
RHIA	Relative humidity of indoor air (%)
RHOA	Relative humidity of outdoor air (%)
SWT	Supply water temperature (°C)
RWT	Return water temperature (°C)
STSWC	Surface temperature of supply water capillary (°C)
STRWC	Surface temperature of return water capillary (°C)
TSHB	Temperature of the contact surface between human body and bed (°C)
ATCQ	Air temperature near the chest in the quilt (°C)
ATLQ	Air temperature near the legs in the quilt (°C)
STM	Surface temperature of the sponge-padded mattress in the middle of the legs (°C)
ATT	Air temperature of tuyere (°C)

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