International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 11 Issue 3 ǁ March 2023 ǁ PP. 571-580

Structure and performance analysis of a solar energy bed with thermal storage

XiaoHan-Lu[1*] , GuoQing-Yu[1]
School of Environment and Architecture, University of Shanghai for Science and Technology, China
Corresponding Author: XiaoHan-Lu

Abstract
This paper describes a kind of solar heating bed with both heat storage and heat dissipation. The bottom of the device is a heat storage tank to heat the bed, which obtains heat from the solar collector plate. This paper mainly studies the application of the heating system based on this bed in Beijing, and analyzes the heat dissipation on the upper surface of the bed plate and the temperature in the bed under different conditions. The results show that under the condition of all-day heat dissipation, the collector efficiency in the typical annual heating season is 37.7 %, the effective heat supply of the composite bed is 4390.2 MJ, and the solar energy guarantee rate is 80.7 %; under the condition of heat preservation during the day and heat dissipation at night, the collector efficiency is 33.1 %, the effective heat supply of the composite bed is 4441.1 MJ, and the solar energy guarantee rate is 81.8 %.

Keywords: *Storage-heating hybrid bed； Solar heating； Heat dissipation state； Heat preservation state； Solar fraction*

Date of Submission: 14-03-2023 Date of acceptance: 29-03-2023

I. INTRODUCTION

With the establishment of the dual carbon goal at the 75th United Nations General Assembly, the process of carbon reduction and decarbonization is gradually accelerating [1]. As an easily accessible and renewable clean energy, solar energy is more widely used in daily life, which is one of the powerful means of carbon reduction [2]. Solar heating, as one of the utilization methods, has been applied to a certain scale in buildings. However, some studies believe that existing solar heating systems are limited by uncontrollable solar radiation intensity, which is prone to the problem of matching supply and demand, which may lead to energy waste [3].

In order to adjust the contradiction between supply and demand when using solar energy for heating, many scholars have conducted relevant research. If the contradiction is adjusted from the perspective of system configuration and control, the selection of open loop and closed loop systems, and the layout of water system pipe networks have an important impact on the stable operation of solar hot water systems. Literature [4] introduces a make-up water heating tank to form a three-tank system based on traditional two-tank heating. When solar radiation is too strong or too weak, an additional tank is responsible for absorbing the heat that cannot be absorbed or cannot be absorbed by the heat storage tank and developing corresponding control strategies, thereby greatly improving the solar energy assurance rate of the system. Literature [5] comprehensively compares different configurations of solar water heating systems from the perspective of control methods and heat pipe connection methods. With the simulation and PID regulation, the designed closed-loop system can more effectively control its outlet temperature when solar radiation is variable, ensuring the stability of heating. It is found that the optimal configuration of solar water heating systems depends on the solar radiation intensity in the area where the system is installed.

In addition to adapting to changes in the intensity of solar radiation in terms of control strategy and system configuration, auxiliary heat sources can also be selected or heat storage modules can be added for peak shaving. Compared to pure electric assistance, increasing heat storage units to reduce the opening time of auxiliary heat sources has more energy-saving and environmental protection significance. From the perspective of optimizing heat storage modules, document [6] proposes an optimal design method for solar water heating systems based on real-time energy balance and adaptive matching, and uses this method to optimize and analyze the heating system of a civil building in Beijing, greatly reducing the energy mismatch on the supply and demand sides. In literature [7,8,9], phase change materials were added to typical solar water heating systems, and mathematical models were established and experimentally verified. The results showed that compared to traditional solar water heating systems, adding phase change materials can effectively reduce the power consumption caused by auxiliary heating.

Aiming at the contradiction between supply and demand of solar energy, this paper proposes a composite bed that integrates heat storage and heat dissipation from the perspective of heat storage, taking into account the control strategy of the system, and combining the use of solar energy with daily use beds. The heat dissipation and its influencing factors of the bed in different states are analyzed.

II. Model Introduction

2.1 Heat storage and heat dissipation composite bed model

The physical model of a heat storage and heat dissipation composite bed is mainly divided into two parts, as shown in Figure 1: the lower part is a water tank, and the part where the bottom of the water tank contacts the ground and the front and rear surfaces of the water tank are attached with thermal insulation materials with good performance; The upper part is the bed body, with four brackets standing at the four corners of the bed board. There is a horizontal air layer with a certain distance between the bed board and the upper surface of the water tank. The positive direction of the axis points to one side of the bed, and the positive direction of the axis points from the head of the bed board to the end of the bed.

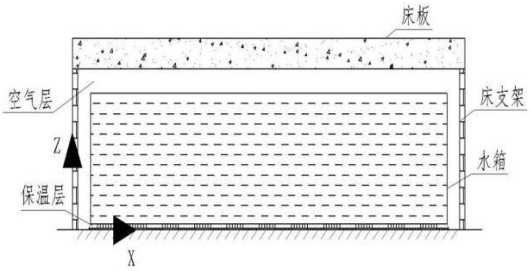

Fig.1 Model Diagram of Composite Bed

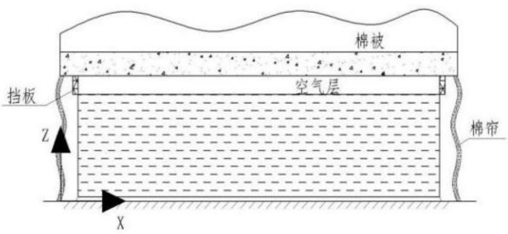

Fig.2 Model Diagram under Thermal Insulation

When the left and right sides and upper surfaces of the bed exchange heat with the surrounding air to transfer the heat in the bed to the interior, the state at this time is defined as the heat dissipation state of the bed; When the baffles around the horizontal air layer in the bed are closed, a closed air layer is formed between the upper surface of the water tank and the bed board. Bedding is placed on the upper surface of the bed board, and the left and right sides are covered with cotton curtains, as shown in Figure 2. At this time, the heat exchange between the bed and the indoor air decreases correspondingly, while the temperature of the bed board increases. This state is defined as the thermal insulation state of the bed.

The water tank in the bed can transfer heat indoors, and can bear the indoor heat load in the heat dissipation state, while the temperature in the bedding can be increased in the heat preservation state. The main difference between the heat dissipation state and the thermal insulation state of a sleeping bed is that in both states, the heat transfer effect on the upper surface of the water tank is different from that around it. When the sleeping bed is in a heat dissipation state, convection heat exchange is conducted between the upper surface of the water tank and the air on the left and right sides, radiation heat exchange is conducted between the upper surface of the water tank and the lower surface of the bed plate, and radiation heat exchange is conducted between the left and right sides of the water tank and the interior surface of the room; When the bed is in a thermal insulation state, the baffles around the horizontal air layer are closed, and a closed air layer is formed between the upper surface of the water tank and the bed plate. Bedding is placed on the upper surface of the bed plate, and the left and right sides are covered with cotton curtains. The upper surface of the water tank conducts convective and radiant heat exchange with the bed plate through the air layer, and the left and right sides conduct heat exchange with the indoor through the air layer and cotton curtains. At this time, the heat transfer effect of the heat dissipation surface of the bed will be reduced, resulting in less heat dissipation in the heat preservation state than in the heat dissipation state.

2.2 Introduction to solar heating system based on this bed

Based on the structure of a composite bed, a solar heating system (hereinafter referred to as a solar bed heating system) is established. When there is solar radiation, a solar collector is used to collect solar radiation energy, and then hot water is transferred to the heat storage and heat dissipation composite bed through a water pump to provide indoor heating. The solar heating system based on a composite bed is shown in Figure 3.

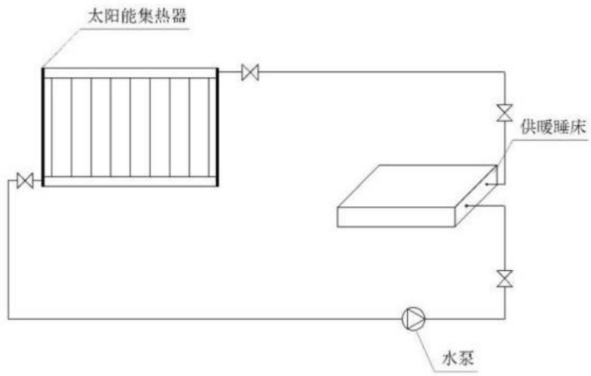

Fig. 3 Schematic Diagram of Solar Heating System Based on Composite Beds

The solar bed heating system uses a solar collector to convert the collected solar radiation energy into heat energy and transmit it to the working medium. Some of the energy is converted into the effective utilization energy of the collector, and some is converted into heat loss. The heat load of different heating rooms varies, so you can adapt to the needs of heating rooms by setting the properties of the bed: selecting appropriate bed size, surface emissivity, and horizontal air layer thickness. The heat dissipation of the bed can be adjusted by controlling the opening and closing of the horizontal air layer, the bedding on the bed board, and the left and right cotton curtains on the water tank to match the heating needs of the room at different times.

A heating room is a typical room facing south. The wall facing south is set as an exterior wall, the rest facing interior wall, and the upper and lower floors are set. The heat transfer coefficients of the south exterior window and the north interior door in the room enclosure structure are 3.5 $W \cdot K^{-1}$ and 2.5 $W \cdot K^{-1}$, respectively. Based on this, the heat load of the room under different conditions can be calculated.

2.3 Calculation of relevant parameters of solar collectors

In order to verify the reliability of the system, this paper selects three parameters, namely, the effective heat collection capacity of the collector, the collector efficiency, and the solar energy assurance rate, to evaluate the performance of the collector system.

(1)Effective heat collection of solar collectors:

$$Q_u = A_c F_R [S - U_L (T_{f,i} - T_a)] \quad (1)$$

where：

A_c——Collector area, m^2；

F_R——Heat transfer factor of heat collector；

S——Amount of solar radiation absorbed by the absorption surface, $W \cdot m^{-2}$, Calculated by hourly solar radiation；

$T_{f,i}$——Temperature of fluid entering the collector, ℃;

U_L——Heat loss coefficient of collector, $W \cdot m^{-2} \cdot K^{-1}$；

T_a——Ambient temperature, K;

(2)The temperature of the collector water tank and the effective heat collection balance equation of the collector:

$$Q_u = (m_T C_p)_s \frac{dT_S}{dt} + U_T A_S (T_S - T_a) \quad (2)$$

where：

m_T——Quality of water flowing into the collector tank, kg；

C_p——Specific heat capacity of fluid in a water tank, J/(kg·℃)；

U_T——Heat loss coefficient of water tank, W·m^{-2}·K^{-1}；

A_S——Surface area of water tank, m^2；

T_S——Temperature of the fluid in the water tank, K；

(3) Collector efficiency:

$$\eta = \frac{Q_u}{A_c I_T} \quad (3)$$

where：

I_T——Irradiation amount on the inclined surface of the collector, $W \cdot m^{-2}$；

(4) Solar energy guarantee rate:

$$f = \frac{Q_A}{Q_R} \quad (4)$$

where：

Q_A——Solar heating capacity, MJ；

Q_R——Actual heating capacity of the heating system, MJ。

III. Application analysis of the system

Beijing is a cold region, with carbon emissions caused by electricity consumption gradually increasing [10]. Introducing more solar energy into the energy consumption structure can help reduce carbon intensity [11,12]. Therefore, the application of solar energy bed heating systems in the heating season in Beijing is analyzed. The heating season in Beijing is from November 15th to March 15th of the next year. The average outdoor temperature during the typical annual heating season is 1.8℃. Calculate the heat load of the aforementioned typical heating room based on the meteorological parameters related to the heating season in Beijing, and select the basic applicable conditions for the bed and the area of the solar collector in the system based on the room heat load. Analyze the collector efficiency and solar energy assurance rate of this system in Beijing.

3.1 Analysis of Bed Design Conditions

The amount of heat storage water will affect the thermal performance of the system, which depends on the volume of the water tank. Without changing the height of the water tank, study the impact of water storage on the system, that is, study the impact of changing the width of the water tank on the heat dissipation. The surface temperature of the water tank is 35℃, the width of the water tank is 1.2 m, 1.5 m, 1.8 m, and the width of the bed plate is 1.3 m, 1.6 m, and 1.9 m. The remaining conditions for sleeping in the bed during the calculation are consistent with the above.

When the width of the water tank changes, the changes in the amount of heat transferred by convection and radiation on each surface with the width of the water tank are shown in Figure 4, and the changes in the total heat dissipation and total heat transfer coefficient with the width of the water tank are shown in Figure 5.

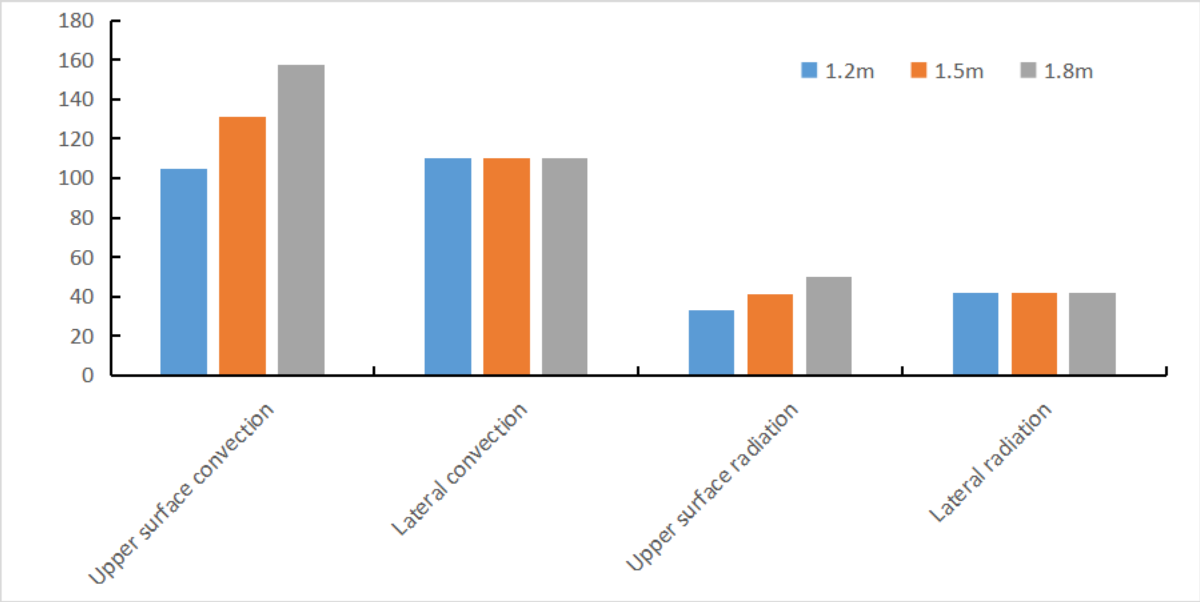

Fig.4 Comparison of heat transfer of each cooling surface under different water tank widths

The heat transfer by convection and radiation on the upper surface of the water tank increases as the width of the water tank increases, while the heat transfer by convection and radiation on the side remains unchanged. When the width of the water tank increases from 1.2 m to 1.8 m, the convective heat transfer on the upper surface of the water tank changes from 104.8 W to 157.2 W, increasing by 52.4 W; The radiant heat transfer on the upper surface changed from 33.1 W to 49.7 W, an increase of 16.6 W; Lateral convective heat transfer maintained at 109.9 W; The lateral radiant heat transfer remained at 41.9 W. This is mainly because as the width of the water tank increases, the heat dissipation area on the upper surface of the water tank increases, resulting in an increase in both convective and radiant heat transfer on the upper surface.

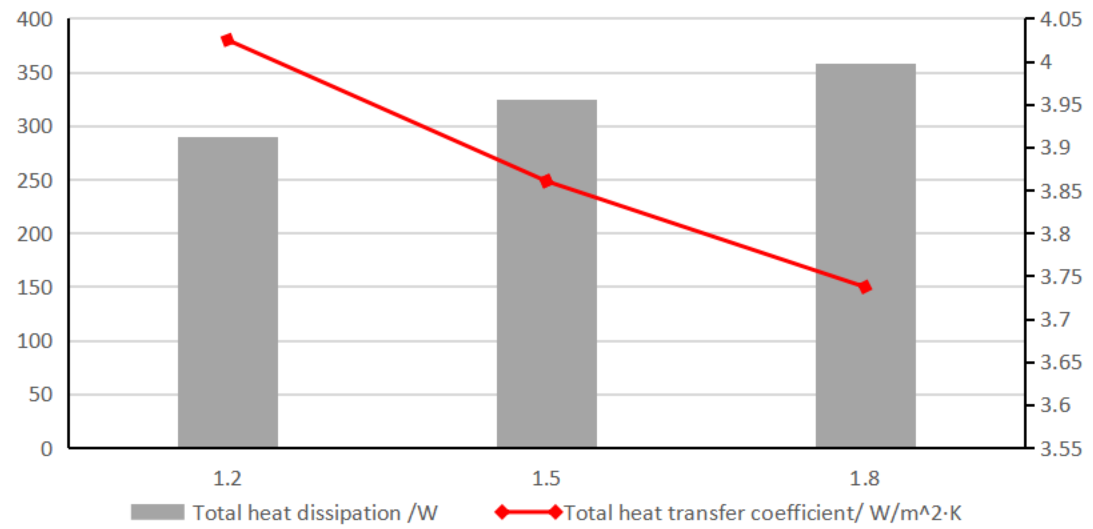

Fig.5 Comparison of total heat dissipation and total heat transfer coefficient under different water tank widths

The total heat dissipation increases as the width of the water tank increases, while the total heat transfer coefficient decreases as the width of the water tank increases. When the width of the water tank increases from 1.2 m to 1.8 m, the total heat dissipation changes from 289.8 W to 358.8 W, increasing by 69.0 W; The total heat transfer coefficient is 4.03 $W/m^2 \cdot K$ becomes 3.74 $W/m^2 \cdot K$. Reduced by 0.29 $W/m^2 \cdot K$. Therefore, increasing the width of the water tank (that is, increasing the maximum water storage capacity) will worsen the heat exchange effect of the bed, but increasing the heat transfer area can still effectively improve the heat dissipation capacity of the system.

As can be seen from the previous Equations 1 and 2, the temperature change of the water tank mainly depends on the local solar radiation intensity and temperature changes, that is, affected by the absorbed solar radiation intensity S and the outdoor temperature Tair. According to typical daily meteorological parameters in Beijing, heating bed conditions are designed to meet the thermal load of a typical heating room. The indoor temperature of the typical heating room is 15℃, and the room ventilation rate is taken as 0.5 times/hour. As shown in Figure 6, a typical room facing south is selected, with a length of 4.8 m, a width of 3.6 m, a height of 3 m, and a door size of 0.9 m×2 m, window size 1.5 m×1.8 m. The composition, relevant dimensions, and thermophysical parameters of the enclosure structure of the room are shown in Tables 1 and 2. The heat transfer coefficients of the south outer window and the north inner door in the enclosure structure are 3.5W/m²·K and 2.5W/m²·K, respectively. Based on this, the typical heating room in Beijing is designed with bed conditions, as shown in Table 3. The water tank can store 900 liters of water. According to the design conditions of the sleeping bed, the solar collector has an area of 8. When the heating capacity of the sleeping bed is insufficient, auxiliary heating is used to maintain a constant indoor temperature.

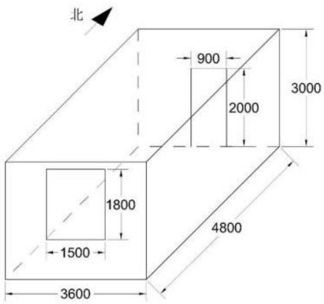

Fig.6 Schematic diagram of heating room

Tab.2 Thermal physical property parameters of components of exterior wall

	Thickness mm	Thermal conductivity W/(m·℃)	Specific heat kJ/(kg·℃)	Density kg/m³
Lime mortar	50	0.81	1.05	1600
Porous brick	240	0.58	1.05	1400
Lime mortar	20	0.81	1.05	1600

Tab.2 Thermal physical property parameters of components of exterior wall

	Thickness mm	Thermal conductivity W/(m·℃)	Specific heat kJ/(kg·℃)	Density kg/m³
Lime mortar	20	0.81	1.05	1600
Porous brick	240	0.58	1.05	1400
Lime mortar	20	0.81	1.05	1600

Tab.3 Conditions for bed selection

Name	Size	Surface emissivity
Upper surface of water tank	1.5m×2m	0.9
Left surface of water tank	0.3m×2m	0.9
Right surface of water tank	0.2m×2m	0.9
Air layer thickness	50mm	-
20mm thick bed board	1.6m×2m	0.9

3.2 Application in all-day cooling mode

When the bed is in a state of heat dissipation throughout the day, the horizontal air layer is opened, there is no bedding on the upper surface of the bed board, and there is no cotton curtain on the side of the water tank. The hourly variation diagram of typical daily bed heat dissipation and room heat load is shown in Figure 7, and the hourly variation diagram of water tank temperature and room heat load is shown in Figure 8. The typical daily outdoor average temperature is 5.5℃.

Under the condition of all day heat dissipation, the effective utilization energy per unit area of a typical daily heat collector is 12.5 MJm^2, the heat collected by the heat collector is 99.8 MJ, and the efficiency of the heat collector is 45.2%. The daily heat dissipation capacity of the bed is 60.6 MJ, the daily heat load of the room is 62.1 MJ, and the solar energy guarantee rate is 97.6%.

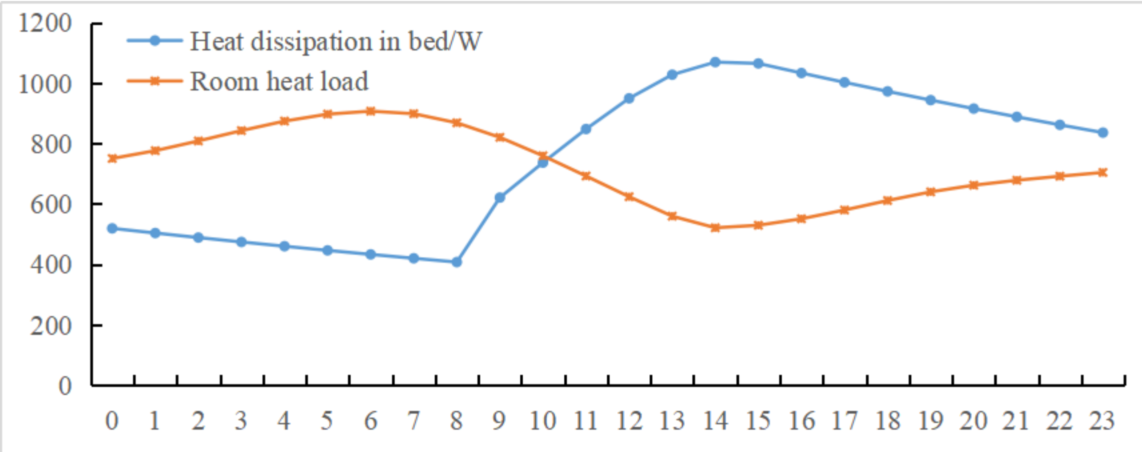

Fig. 7 Change of heat dissipation of bed and heat load of room during typical day heat dissipation

As can be seen from Figure 7, on a typical day, the heat dissipating capacity of the bed decreases from 0:00 to 7:00, the heat dissipating capacity of the bed increases rapidly from 8:00 to 15:00, and the heat dissipating capacity of the bed decreases again from 16:00 to 23:00. This is because after 8 o'clock, the temperature of the water tank rises after the solar collector collects solar radiation heat, resulting in a rapid increase in heat dissipation from the bed; After 16 o'clock, there is no solar radiation, and the water tank heats the room. The temperature of the water tank decreases, so the heat dissipation of the bed decreases.

The intensity of solar radiation can affect the water temperature in the water tank. After the amount of solar radiation collected by the heat collector is transferred to the bed water tank through the medium, the water temperature in the water tank increases, and the heat dissipated by the bed increases. When the solar radiation cannot be collected or is insufficient, the temperature in the water tank will decrease. The sunrise time of a typical day is 8:00, and the sunset time is 16:00. As can be seen from the graph, the temperature of the water tank and the upper surface of the bed plate decrease from 0:00 to 7:00 on a typical day, while the temperature of the water tank increases rapidly from 8:00 to 15:00, and the upper surface temperature of the bed plate increases, and the temperature of the water tank and the upper surface temperature of the bed plate decrease from 16:00 to 23:00. This is because after 8 o'clock, after the solar collector collects solar radiation heat, the temperature of the water tank can rise, so the temperature of the upper surface of the bed plate also increases; After 16 o'clock, there is no solar radiation, and the water tank heats the room. The temperature of the water tank decreases, so the temperature of the upper surface of the bed plate also decreases.

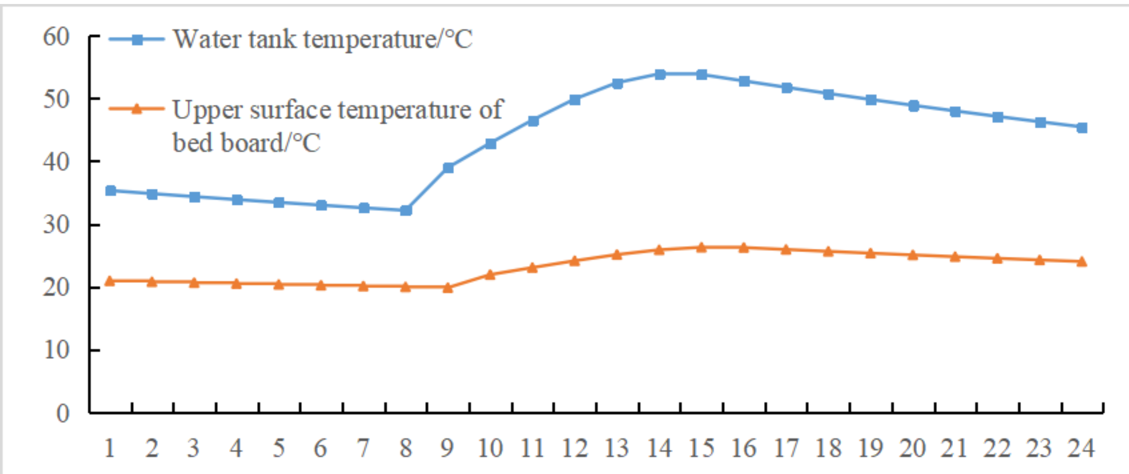

Fig. 8 Change of water tank temperature and upper surface temperature of bed plate during whole day heat dissipation

Taking the typical annual meteorological parameters of Beijing as the known conditions, when the bed is in the state of all-day heat dissipation, the effective utilization energy per unit area of the heat collector is 748.4 MJm^2, the total heat collected is 5990.4 MJ, and the efficiency of the heat collector is 37.7%. The amount of heat dissipated by the bed can vary greatly because when the solar radiation changes, the temperature of the water tank changes, and the amount of heat dissipated by the bed also changes. January 8th to 17th are overcast days, with low solar radiation, so the heat dissipation of the bed is at a low level. According to the data in Figure 9, the effective heating capacity of the composite bed in the heating season during the whole day's heat dissipation is 4390.2 MJ, with a solar energy guarantee rate of 80.7%. The days when the daily average temperature of the water tank is above 30℃ account for 82.6% of the total days in the heating season, and the days when the daily average temperature of the upper surface of the bed board is above 20℃ account for 72.7% of the total days in the heating season.

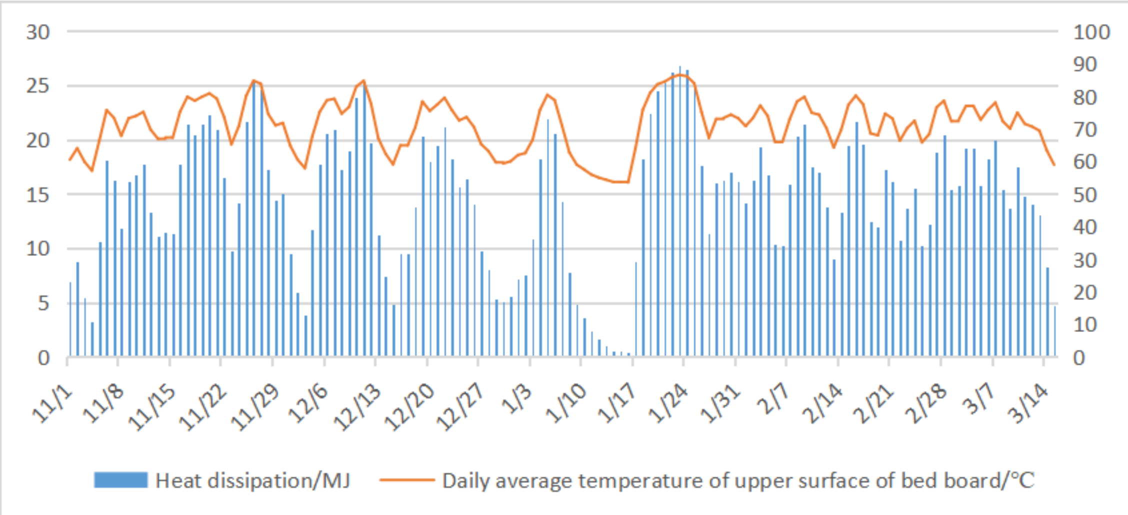

Fig. 9 The daily average temperature of the upper surface of the bed and the daily variation of the heat dissipation of the bed during the heating season

3.3 Application of thermal insulation during the daytime - heat dissipation at night

When the bed is running in this state, it is in a thermal insulation state from 8:00 to 19:00, with the horizontal air layer closed, bedding placed on the upper surface of the bed board, and cotton curtains on the side of the water tank; From 20:00 to 7:00 the next day, it is in the state of heat dissipation. At this time, the horizontal air layer is opened, there is no cotton curtain on the side of the water tank, and bedding is placed on the upper surface of the bed board.

As shown in Figure 10, on a typical day, the heat dissipation in bed decreases from 0:00 to 7:00, with a significant decrease from 7:00 to 8:00, an increase in heat dissipation in bed from 8:00 to 19:00, a significant increase from 19:00 to 20:00, and a decrease in heat dissipation in bed from 20:00 to 23:00. This is due to the fact that the heat dissipation amount in the heat preservation state is much smaller than that in the heat dissipation state when the bed is in the heat preservation state from 8:00 to 19:00, so the heat dissipation amount in the bed from 7:00 to 8:00 has significantly decreased; From 20:00 to 7:00 the next day, the heat dissipation state is in, so the heat dissipation from the bed from 19:00 to 20:00 significantly increases.

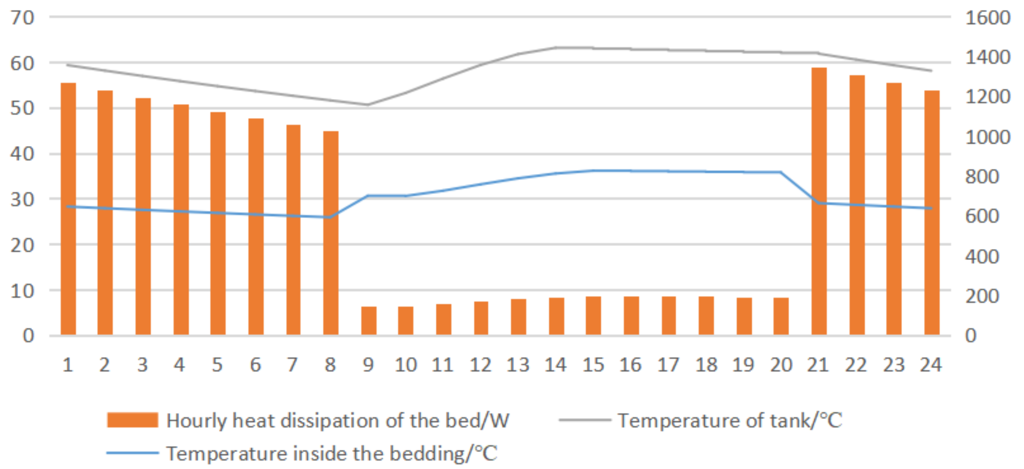

Fig. 10 Hourly variation of heat dissipation and temperature of the bed during daytime heat preservation and nighttime heat dissipation

From 0 to 7 o'clock, the temperature of the water tank and the temperature in the bedding decreased, while from 8 to 13 o'clock, the temperature in the water tank and the temperature in the bedding increased, and from 14 to 23 o'clock, the temperature in the water tank and the temperature in the bedding decreased. There was a significant mutation in the temperature in the bedding between 8 and 20 o'clock. This is because after 8 o'clock, after the solar collector collects solar radiation heat, the temperature of the water tank rises, so the temperature inside the bedding also rises; After 16 o'clock, there is no solar radiation, and the water tank heats the room. The temperature of the water tank decreases, so the temperature inside the bedding also decreases; The temperature drop in the bedding between 19:00 and 20:00 is due to the bed switching to the heat dissipation state at 20:00 and the horizontal air layer opening, resulting in a decrease in the temperature in the bedding. The temperature in the bedding will be at a high level between 8:00 and 18:00. If someone is inside the bedding at other times, the temperature in the bedding will be in a comfortable range. The effective utilization energy per unit area of a typical daily heat collector is 11.4 MJm^2, the total heat collected by the collector is 91.2 MJ, and the efficiency of the collector is 41.3%. The heat dissipation capacity of the sleeping bed is 44.8 MJ, the daily heat load of the room is 62.1 MJ, and the solar energy guarantee rate is 72.1%.

Taking the typical annual meteorological parameters of Beijing as known conditions, under the state of thermal insulation during the day and heat dissipation at night, the effective utilization energy per unit area of the heat collector in the heating season is 656.1 MJm^2, the total heat collected is 5248.8 MJ, and the efficiency of the heat collector is 33.1%.

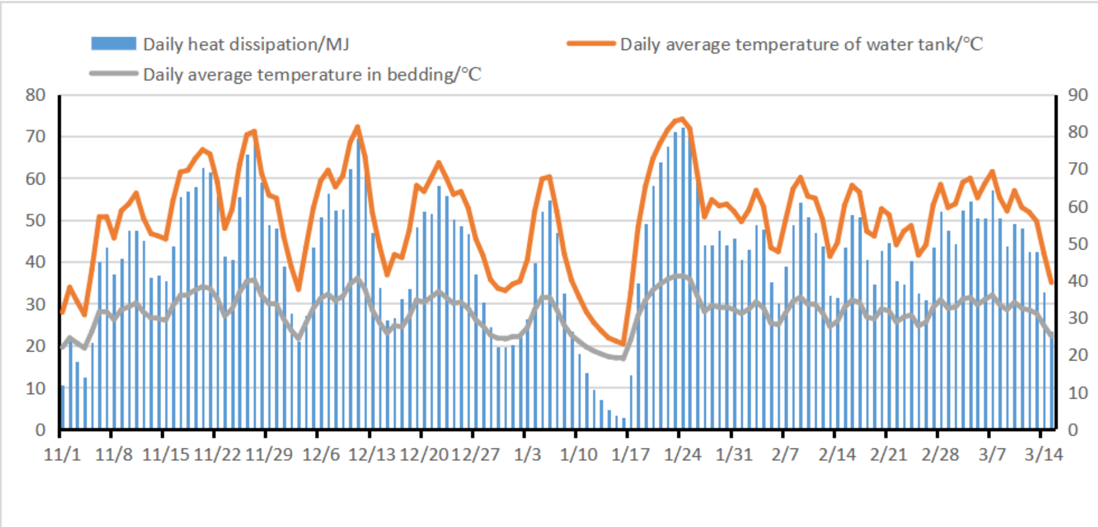

Fig.11 Daily variation of water tank heat dissipation and temperature during heat preservation in daytime and heat dissipation at night in heating season

By analyzing Figure 11, it can be seen that when the water tank is insulated during the day and dissipated heat at night, the amount of heat dissipated by the bed will also change. Since January 8th to 17th are overcast days and the amount of solar radiation is low, the amount of heat dissipated by the bed is at a low level. The effective heating capacity of the composite bed during daytime heat preservation and nighttime heat dissipation is 4441.1 MJ, and the solar energy guarantee rate is 81.8%. The days when the daily average temperature of the water tank is above 30℃ account for 95.0% of the total days in the heating season, and the days when the daily average temperature of the bedding is above 20℃ account for 95.0% of the total days in the heating season.

IV. Conclusion

This article designs a bed that integrates heat storage and dissipation: the bed can change the heat dissipation state and thermal insulation state by changing the relevant conditions. Taking Beijing as a representative of cold regions, after studying the application effect of solar energy bed heating systems in Beijing, the basic applicable conditions for the bed and the area of solar collectors in the system are selected based on the room heat load, and the heat dissipation amount, collector efficiency, and solar energy guarantee rate of the bed during the whole day heat dissipation and daytime heat preservation - night heat dissipation are analyzed. The following conclusions are drawn:

(1) Under the condition of all-day heat dissipation, the effective utilization energy per unit area of the heat collector in the typical annual heating season is 748.4 MJm^2, the total heat collected is 5990.4 MJ, and the efficiency of the heat collector is 37.7%. The effective heating capacity of the composite bed is 4390.2 MJ, and the solar energy guarantee rate is 80.7%. The days when the daily average temperature of the water tank is above 30℃ account for 82.6% of the total days in the heating season, and the days when the daily average temperature of the upper surface of the bed board is above 20℃ account for 72.7% of the total days in the heating season.

(2) In the typical annual heating season, the effective utilization energy per unit area of the collector is 656.1 MJm^2, the total heat collected is 5248.8 MJ, and the efficiency of the collector is 33.1%. The effective heating capacity of the composite bed is 4441.1 MJ, and the solar energy guarantee rate is 81.8%. The days when the daily average temperature of the water tank is above 30℃ account for 95.0% of the total days in the heating season, and the days when the daily average temperature of the bedding is above 20℃ account for 95.0% of the total days in the heating season.

REFERENCES

[1]. Jiang Yi, Hu Shan, et al. The Path to Carbon Neutralization in China's Construction Sector [J]. HVAC，2021,51(05)：1-13

[2]. Y. Elaouzy, A.El Fadar. Energy, economic and environmental benefits of integrating passive design strategies into buildings :A review[J]. Renewable and Sustainable Energy Reviews, 2020,167:112828

[3]. Datong Gao, Trevor Hocksun Kwan, Maobin Hu, et al. The energy, exergy, and techno-economic analysis of a solar seasonal residual energy utilization system[J]. Energy, 2022,248:123626

[4]. Yu Zhun, Liang Ke, Guo Zhiyong, et al. A novel three-tank solar hot water system and control strategy [J/OL]. Journal of Hunan University (Natural Science Edition):1-9[2023-02-16].

[5]. Mohammed Abu Mallouh, Hossam AbdelMeguid, Mohammad Salah. A comprehensive comparison and control for different solar water heating system configurations[J]. Engineering Science and Technology,an International Journal

[6]. Guangli Zhang, Kai Hu, Chengchu Yan, et al. Optimal design and integration of multiple-function solar water heating systems based on a co-adaptive matchmaking method[J]. Energy & Buildings, 2021,252:111492

[7]. Zhixiong Ding, Wei Wu,Youming Chen, et al. Dynamic simulation and parametric study of solar water heating system with phase change materials in different climate zones[J]. Solar Energy, 2020,205:399–408

[8]. Sun Hao. Research and Analysis on Staged Utilization of Residual Heat in University Baths by Phase Change Energy Storage Tanks].Shenyang: Shenyang Architectural University，2021

[9]. Wang Xi, Yuan Yanping, et al. Design and operation characteristics of phase change heat storage tanks[J]. Journal of Solar Energy，2014,35(04)：670-676

[10]. Xue Yuexin, Xie Jingchao, Huai Chaoping, Li Hang, Liu Jiaping. Decomposition analysis of factors affecting energy carbon emissions in Beijing[J]. Building energy efficiency，2022, 379(09)：128-132

[11]. Wang Shaohua, Zhang Wei. Analysis of carbon intensity factors in Beijing, Tianjin, and Hebei based on overall regional industrial decomposition[J]. soft science，2017,31(12)：96-100

[12]. Fan Decheng, Wang Shaohua. Construction and empirical analysis of low-carbon energy consumption structure optimization model[J]. Journal of Harbin Engineering University，2013,34(07)：939-944