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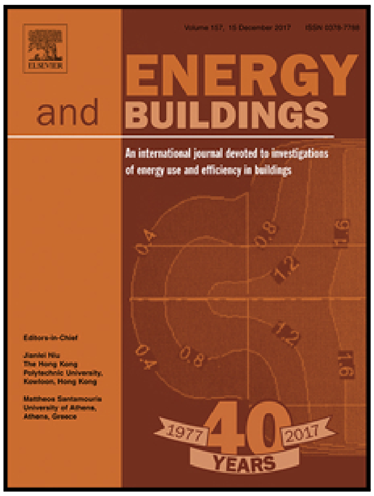

A study on thermal characteristic and sleeping comfort of a hybrid solar heating system applied in cold rural areas

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Highlights

- Mathematic model of hybrid solar heating system is built and verified by a rural building in Qinghai province.
- Factors such as collector area and insulation layer of wall are discussed to find out the heating characteristic of the system
- Operation of the system can keep indoor air temperature about 6℃ when ambient temperature is just -7.8℃.
- Thermal load of sleeping people can be hold in acceptable level when the beddings insulation value is kept at the value of 4.0clo during night time.

A study on thermal characteristic and sleeping comfort of a hybrid solar heating system applied in cold rural areas

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Abstract

A hybrid solar heating system combining a solar kang subsystem and a solar air heating subsystem for keeping indoor space within thermal comfort level has been investigated in this article for the climatic conditions of Qinghai Province (35°N 96°E)- China. The main aim of the current research is to study the hybrid heating system's thermal characteristic and the sleeping comfort for occupants of rural buildings. A mathematical model to study the hybrid heating system has been developed and the results have been validated by conducting an experimental study at a building located in Qinghai province. The influence of the different solar thermal collector areas, insulation levels of wall, thermal sensation of the system and different operation strategies have been investigated. It has been observed that the indoor temperature can be improved by up to 6℃ when the ambient temperature is -7.8℃ (average). By changing the solar collector area from 4m^2 to 8m^2, kang surface average temperature can be improved from 22℃ to 31℃. Thermal load of sleeping can also be held steady within acceptable levels when the beddings insulation value is

maintained at 4.0clo during night time. It has been observed that without auxiliary power, making the kang system work only at night would be more suitable in the experimental condition.

keywords:

Solar Chinese kang; Solar air collector; Heating characteristic

Sleeping comfort; Operation strategy

1. Introduction

Residential buildings account for 27% of the global energy consumption and 17% of CO_2 emissions[1]. Reducing building energy consumption is of great importance to sustainable development and the environment. Applying solar heating/cooling systems can help solve the problem and improve the indoor environment simultaneously. Among the various solar heating systems, Trombe walls (solar heating walls) are widely used because of high thermal efficiency and low running cost[2]. Many studies have been performed to improve the heating effect and increase the utilization of solar energy, including changing the structure[3], adding PV modules /forced convection[4] and coupling with phase change materials[5]. These facilities can provide enormous heat when there sunshine is sufficient and are suitable for commercial and office buildings.

In rural areas of China, indoor heating is essential in for most of the months. As indicated by the field survey by Yanfeng Liu[6] , the Chinese kang is the most used heating method in winter in Northwest China. A traditional Chinese kang[7] is composed of a stove, a kang body and a chimney for the flue gasses. It uses the residual heat of fuels for cooking. Many authors have studied the thermal performance of the Chinese kang [8, 9] to enhance its thermal efficiency. Gao et al.[10]analyzed a simplified dynamic model of a room with a Chinese kang and proved its correctness with experimental results. Wang et al.[11]modified the kang system with forced convection and adopted water as the heat transfer medium. Although this system can raise the utilization of fuels, smoke from the burning fuels may cause various health-related issues.

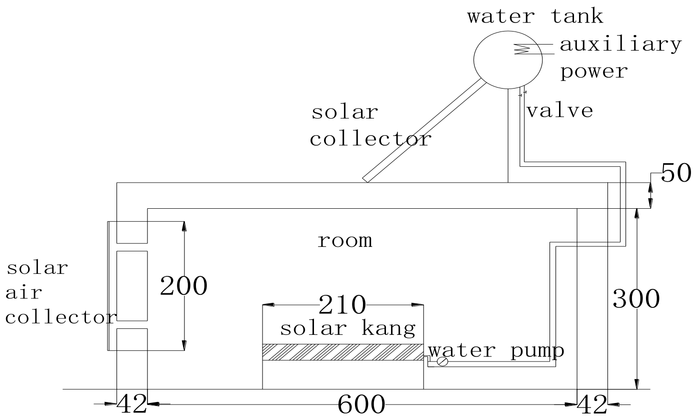
Solar power is clean, free and excellent for use in combination with the kang system. Chen et al.[12]conducted a field survey of a building with a coupled kang and solar wall heating system. It can reduce by half the fuel cost compared with traditional residences. Yang et al.[13, 14] developed a kang system that integrates a solar air collector into the Chinese kang and built a dynamic model to analyze its heating performance. Thermal physical parameters of the air vent greatly affect the thermal process of the system. He et al.[15]studied the thermal comfort of a kang system on the premise of fixed inlet water temperature. The kang system used solar heated water to represent fuels. Wei et al.[16]proposed a novel system combining the solar kang and the solar air collector and studied its alternative operating modes. The daily mean indoor temperature reached 18.5℃ while the temperature in the reference room was 8.9℃.

The systems mentioned above not only reduce the indoor air pollution but also solve the non-uniform and overheating problems of the traditional kang. However, most studies are concentrated on the indoor environment and the temperature distribution of the room, few studies have focused on the system's capacity to create a bed climate. In the rural areas of northern China, indoor air temperature is quite low during winter, and it is a waste of energy using indoor air heating during the whole night.[17, 18]. So if a good thermal feeling in low air temperature is desired, bed warming may be more effective and suitable [6, 17].

In this paper, a thermal model of a hybrid heating system is built, it contains a solar kang subsystem and a solar air heating subsystem. A night-time sleeping model is built to determine the thermal sleeping condition of the system. Modifications and simulations are based on experimental data conducted in a rural building in Qinghai Province. With experimental data and simulation results, influence factors and the thermal comfort at night of the system are presented.

2. Mathematical model

As shown in Fig. 1, the system consists of a solar kang subsystem, a solar air heating subsystem and the building envelope. The solar kang subsystem consists of a solar water collector, a water tank (with auxiliary power), a water pipe, a water pump, and a solar kang in the room. Two pieces of solar air collectors constitute the solar air subsystem. The basic model is already mentioned in the author's previous work[19].



(a)

(b)

Fig. 1 Description of (a) the solar heating system (/cm) and (b) the test rural building

2.1 Solar air heating system

The solar air collector is composed of a glass cover, an aluminum absorption plate and a back insulation plate. The absorption plate with selective coatings can absorb sunlight and heat the flow channel air. Then air in the air flow channel transports the heat into the room. At night, air vents are closed to prevent heat loss. For the absorption plate:

$$\rho_{ab}c_{ab}V_{ab}\frac{\partial T_{ab}}{\partial t}=h_{aa}(T_{air}-T_{ab})+h_{mid}(T_{mid}-T_{ab})+h_{a,g}\left(T_g-T_{ab}\right)+h_{a,b}(T_b-T_{ab})+W_{ab} \quad (1)$$

where $h_{a,g}/h_{a,b}$ are the heat transfer coefficient of radiation between the glass cover/back insulation board and absorption plate and W_{ab} is the radiation gained by absorption plate.

Methods of numerical calculation of the back insulation and glass cover layers are the same as the absorption plate. For the air in air duct:

$$\dot{m}c_{air}\frac{dT_{air}}{dx}=h_{ab}w(T_{ab}-T_{air})+h_b w(T_b-T_{air}) \quad (2)$$

where w means the width of the collector and $h_{ab}/\,h_b$ are coefficients of the convection heat transfer between the absorption plate/back insulation board and the flow channel air. The following formula can be used to compute them:

$$h=Nu\frac{k}{D_{duct}} \quad (3)$$

For the velocity of the air in flow channel:

$$v_{air} = \sqrt{\frac{2\beta g H(\overline{T_{al}} - \overline{T_{air}})}{C_1\left(\frac{A_{duct}}{A_v}\right)^2 + C_2}} \quad (4)$$

where C_1 and C_2 are constants. A_{duct} is the cross-sectional area of air vent and A_v is the area of air inlet(outlet).

2.2 Solar kang system

The operation of the solar kang system can be divided into two parts: solar power is gathered by the solar air collector and stored in a water tank; heated water flows through the kang body. For the solar water collector:

$$c_{tank} M_{tank} \frac{dT_{tank}}{dt} = Q_s - Q_{kang} - Q_l \quad (5)$$

where Q_{kang} is the heat supply of the solar kang system, Q_l is the heat loss of the water collector and the water tank and Q_s means the total gain in solar radiation.

For the kang body, all the calculation of kang body's compute nodes follow the equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho C_p \frac{\partial T}{\partial t} \quad (6)$$

When the solar kang system works, the water tube can be set as the internal heating source of the compute nodes ($\dot{q}$) of the kang body. For the water flow process in the water tube:

$$c_p \rho V_i \frac{\partial T}{\partial t} = \dot{m} c_p \frac{\partial T}{\partial x} + \left(H_f A_f\right)_i (T_n - T_i) \quad (7)$$

where V_i is volume, T_i is the average temperature of the compute water node and T_n is the temperature of the kang body node which contains the water node. The two terms after the equals sign indicate heat exchange by water flow and heat conduction between water and water tube, respectively.

2.3 Building and indoor environment

The ambient and indoor air temperature are supposed to be uniform in the simulation model. The model of each wall and roof can be considered as a one-dimensional system[15],:

$$\rho_{wall,i} c_{wall,i} \frac{\partial T_{wall,i}}{\partial t} = \frac{\partial}{\partial x}\left(k_{wall,i} \frac{\partial T_{wall,i}}{\partial x}\right) \quad (8)$$

The heat convection coefficient of indoor surfaces and outdoor surfaces can be calculated as follows[20]::

$$h_{in} = 2.03 \Delta T^{0.14} \quad (9)$$

$$h_{out} = 5.6 + 3.8v \quad (10)$$

Indoor air exchanges heat with the surfaces of walls and the kang and gain heat from solar air collector:

$$\rho_a V_{room} c_a \frac{\partial T_{indoor}}{\partial t} = \sum h_{in,i} A_i \left(T_{wall,i} - T_{indoor}\right) + \rho_a v_{air} A_v (T_{air} - T_{indoor}) \quad (11)$$

It is supposed that solar radiation through the window is absorbed by the floor in the simulation model.

2.4 Sleeping thermal comfort model of the kang system

Several environmental factors may affect a person's comfort, such as temperature, humidity, air velocity. Most research concentrates on the thermal balance of waking people. Fanger suggested a predicted mean vote(PMV) index and related it to the imbalance between actual heat flow from body and optimum comfort heat flow[21]:

$$PMV = [0.303 \exp(-0.036M) + 0.028]L = \alpha L \quad (12)$$

where M is the metabolic rate of the body produced by the person's activity and shivering and L is the thermal load on the human body, defined as the difference between internal heat production and heat loss to the environment. When PMV value is between -0.5 and 0.5, the thermal environment should be comfortable. However, the metabolic rate of sleeping people is reduced to 0.7 met, so the assessment method may not be applicable. Referring to[22], the thermal load is used to appraise the comfort of the heating system. The thermal load of the sleeping situation is reduced to 20% of waking people in sedentary positions (1.2 met). Then, the thermal load of sleeping people can be calculated. According to [22], the normal level of an acceptable thermal load for sleeping condition is between -3.3 W to 3.3 W and the acceptable level is between -4.6 W to 4.6 W.

According to a previous study[23], the human body's thermal balance is based on the metabolic rate and the thermal exchange between body and environment：

$$M - W = q_{sk} + q_{res} + S = (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr}) \quad (13)$$

where $C + R$ means the total sensible heat loss from skin. According to [23], it can be assumed that the resident is immobile during the sleeping time, and the parameters can be decided by:

$$M = 40\ W/m^2, W = 0\ W/m^2 \quad (14)$$

$$C_{res} = 0.0014M(34 - t_a) \quad E_{res} = 0.0173M(5.87 - p_a) \quad (15)$$

$$E_{sk} = \frac{i_m L_R w(p_{k,s} - p_a)}{R_t} \quad (16)$$

where W means the energy production of the external work performed by muscles, C_{res} and E_{res} means the sensible loss and latent loss due to respiration, and E_{sk} is the evaporative heat loss of skin. Mean skin temperature can be assumed as a constant due to the thermoregulatory feature of the bedding system. It can also be assumed that over a long period of time, a heat balance will exist for the whole body so that no energy is stored in the body, which means $S_{cr} = 0$ and $S_{sk} = 0$.

People seldom cover their entire bodies when sleeping. In the simulation, it is supposed that people only expose their head to the indoor air and the total coverage is 94.1%. When calculating the heat exchange, it should be divided into two parts, one is between the kang and the body, and the other part is between body and the indoor air/building envelope:

$$C + R = a\frac{\overline{t_{sk}} - t_o}{R_{t1}} + b\frac{\overline{t_{sk}} - t_{kang}}{R_{t2}} \text{ , a+b=1} \quad (17)$$

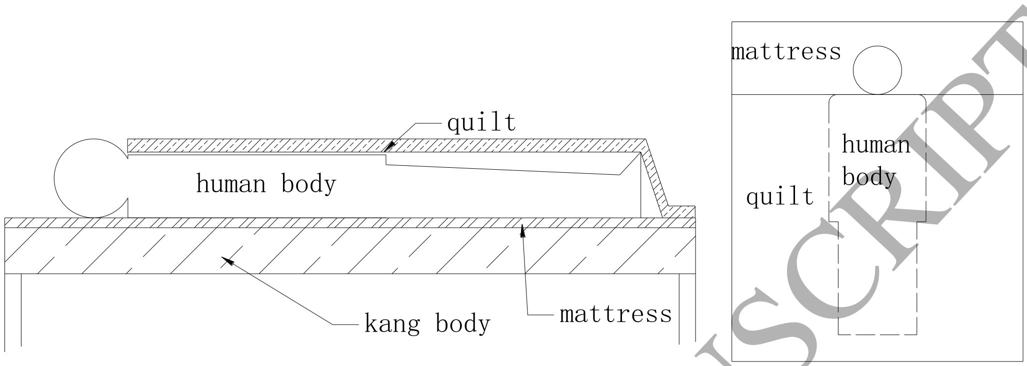
where a/b are the percentage of the heat exchange between the human body and indoor environment/kang. According to[23] ,the requirement on mean skin temperature can be set to 34.6℃. Therefore, the comfort equation should be:

$$40 = a\frac{34.6 - t_o}{R_{t1}} + b\frac{34.6 - t_{kang}}{R_{t2}} + \frac{0.06 i_m L_R (p_{sk,\ s} - p_a)}{R_{t3}} + 0.056(34 - t_a) + 0.692(5.87 - p_a) \quad (18)$$

In the daytime, the kang surface is exposed to the indoor environment to heat the room. In the sleeping simulation model, a mattress and a quilt are placed on the kang surface, as shown in Fig. 2(a) and 2(b). It is assumed that the mattress and quilt are made of cotton (0.049 $\mathrm{W/(m \cdot K)}$). When people sleep on the kang (from 9:00 p.m. to 8:00 a.m. the next day), the mattress is put on the kang and covers the entire kang surface, and the quilt covers the area below the person's head. The person lies in the middle of the kang and covers an area of 1.8 m*0.6 m. The mathematical model of the mattress and quilt is similar to the layers of the kang body as in equation (6). Their model is divided into small calculation nodes, and some of the calculation nodes are in contact with the human body. The total thermal resistance of mattress and quilt can be calculated as follows[24]:

$$R_t = \frac{\sum(a_i t_{sk,i}) - t_0}{\sum(a_i H_i)} \quad (19)$$

$$I_T = K R_t,\ \mathrm{K} = 6.45\mathrm{clo} \cdot \mathrm{W}/(m^2 \cdot ℃) \quad (20)$$



(a) (b)

Fig. 2 (a) side view and(b)vertical view of the simulation model of the sleeping condition

3. Description and model validation

To verify the thermal performance and the practicability of the system, real demonstration buildings with the hybrid solar heating system were built in Qinghai. One of the 75 demonstration buildings is chosen to test, which the situation has already mentioned in author's previous study[19]. The whole building has an area of 142.6 m^2 and the solar heating system is applied in the east room. The parameters of the room and material properties are shown in Table 1. Fig. 3 shows the structure and size of the test room.

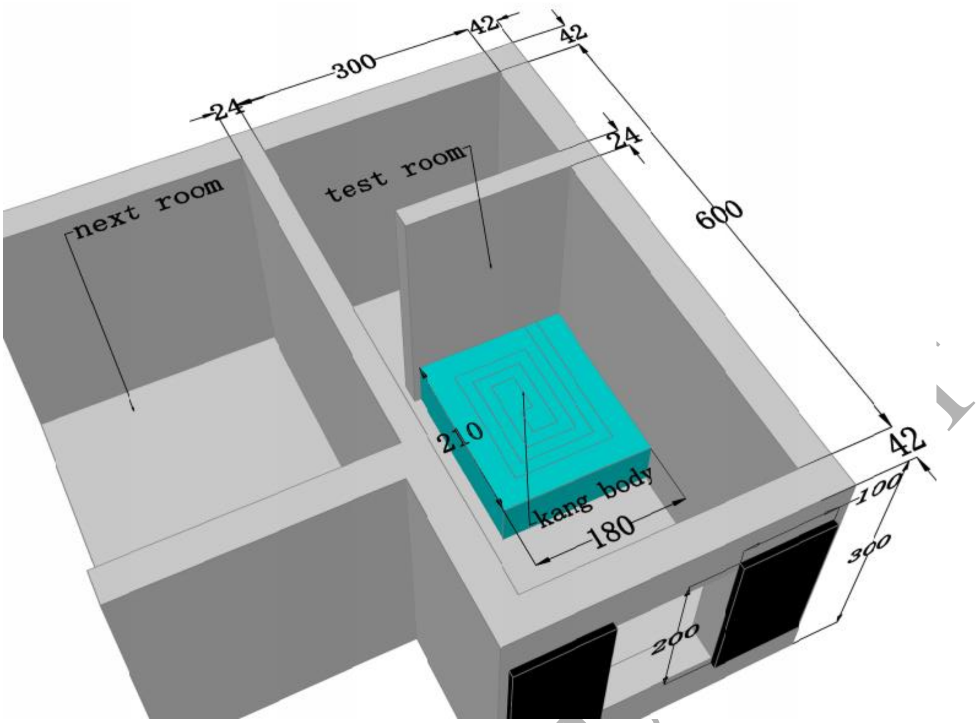


Fig. 3 The structure of the test room (/cm)

Table 1: Material parameters of the combined solar heating system used in the simulation[19]

Solar air collector	
Height×width of collector	2.0 m×1.0 m
Height×width of upper/lower vent	0.12 m×0.4 m
Width of air duct	0.05 m
k, ρ, c value of glass cover	1.005 W/m · K,2500 kg/m^3,750 J/kg · K
k, ρ, c value of aluminum absorption plate	237 W/m · K,2702 kg/m^3,903 J/kg · K
Solar kang system	
Length×width of kang body	2.1 m×1.8 m
k,ρ,c value of main kang body(clay)	1.4 W/m · K,1925 kg/m^3,872 J/kg · K
k,ρ,c value of support part of kang(concrete)	0.93 W/m · K,1800 kg/m^3,1050 J/kg · K
Area of solar water collector	4 m^2
Volume of water tank	360 L
Test room and building envelope	
Length×width×height of room	3 m×6 m× 3 m
Thickness of east/south/north wall	0.36 m brick+0.06 m insulation layer
Thickness of west wall	0.24 m brick
Thickness of roof	0.4 m brick+ 0.1 m insulation layer
k,ρ,c value of insulation layer	0.027 W/m · K,16 kg/m^3,1210 J/kg · K
k,ρ,c value of brick	1.2 W/m · K,1920 kg/m^3,835 J/kg · K
Height×width of window on south wall	1.8 m×1.5 m

The solar collectors on the rooftop are glass evacuated tube collectors placed at a 45-degree angle to the ground, head to the south. The auxiliary power of the system in case of less sunlight is 3kW. The kang is elevated 0.5 m above the floor, and the kang body is divided into four layers: concrete support layer (10 cm), thermal insulation layer (4 cm), water pipe layer (4 cm) and the surface layer (2 cm). The kang body is supported by bricks around the edge, and the space below the kang body is empty. A water pipe with an inside diameter of 12 mm is buried in the kang in the shape of a snake, as shown in Fig. 3. The distribution of pipes is uniform to make the kang surface temperature comfortable.

In the experiment, the temperatures of the walls' inner surface, the kang surface and the air vent of the solar air collector are measured by T-type thermocouples (accuracy 0.1 ℃). Nine thermocouples are set uniformly on the kang surface, and the surface has no coverings. The water temperature in the tank and the inlet/out let of the kang are also measured. The incident global solar radiation of collectors is monitored by solarimeters (accuracy 0.1 W/m^2) individually. The interval of recorded data is 5 min.

The operation of the hybrid heating system was tested from January 23rd 2016 to January 29th 2016. The operation strategy of the system is such that the solar air heating system worked during the daytime, and the solar kang system works all day for heating. Extra power is supplied to heat the water from 11:00 to 24:00. Fig. 4 shows the ambient temperature and solar radiation of January 27th measured in the experiment. Daily mean air temperature was as low as -7.8℃, but the maximum radiation gained by the air collector could reach 700 W/m^2.

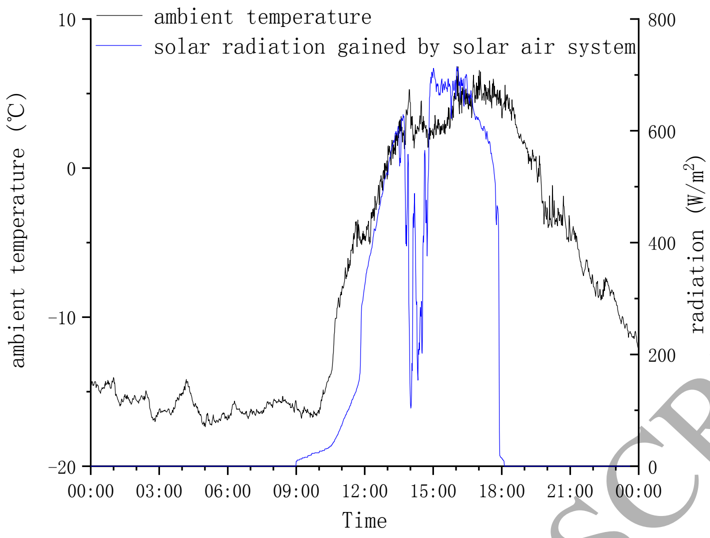
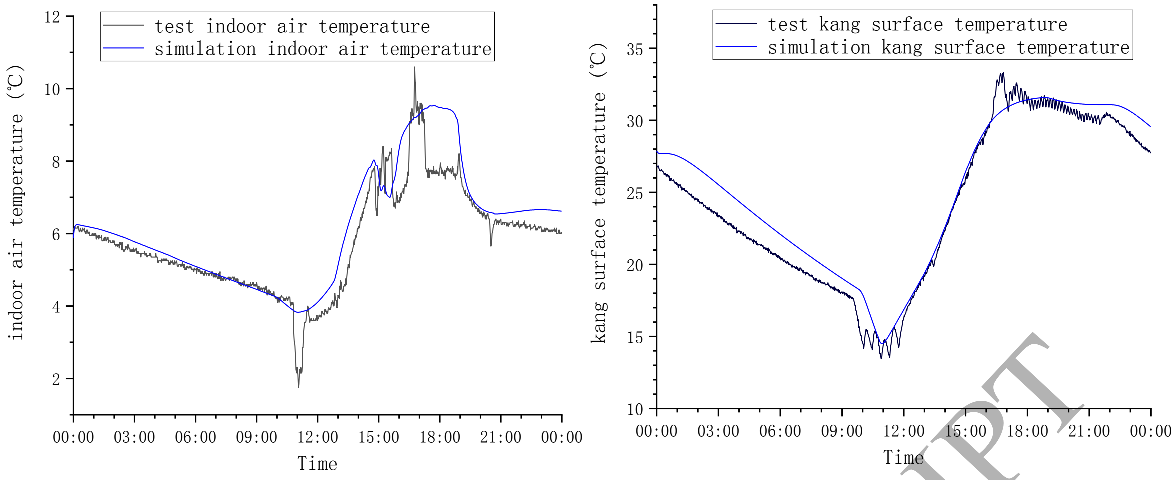


Fig. 4 The thermal condition of January 27th

Experiment situations are used as simulation conditions and indoor air temperature/kang surface temperature is used to compare the results. As shown in Fig. 5, although the ambient air temperature is as low as -7.8℃ during the day, the whole heating system can maintain an indoor environment temperature of approximately 6℃. The kang surface temperature can reach 30℃ by 16:00 and stay above 25℃ during the night. The simulation results are basically consistent with the experimental data. The initial temperature of the building is set as the test surface temperature, and practical situations may differ. The cold air infiltration is complicated to measure, and in the simulation, it is set as a constant, which is the main reason for the air temperature difference in the simulation and the experiment between 14:00 and 19:00. The differences between the simulation results and experiment may also be caused by the simplified mathematical model and the fluctuation in the real environment, such as the flux of the solar kang system and the fluctuation of solar radiation.



(a) (b)

Fig. 5 Simulation and experiment result of (a)indoor air temperature and (b)kang surface temperature

4. Performance analysis and discussion

The mathematical model of the hybrid solar heating system has been compared and verified with the experimental data measured in Qinghai, thus, the simulation can be expanded to study the thermal characteristic of the hybrid heating system.

Increasing the collector area and improving the thermal resistance of the building envelope may be efficient for improving heating performance. With a limited solar source, the operation strategy can be changed to increase the heating effect. Meanwhile, the solar kang system should focus on providing a good sleeping environment for energy saving. Analysis and discussions are as follows.

4.1 Variation of collector area and insulating layer of walls

A greater solar collector area for the system implies more heating energy for the indoor environment, conditions of different solar collector areas are set as follows: the area of solar water collectors varied from 4 m^2 to 8 m^2, and water volume and other conditions remain unchanged. Experimental weather data are used in the calculation, and no auxiliary power exists for heating during the day. Fig. 6(a) and 6(b) shows the changes in the mean indoor air temperature and the kang surface temperature. Since the collector area changes from 4 m^2 to 8 m^2, energy gained from the solar water collector is doubled, and the indoor air temperature rises by approximately 1℃. Indoor air velocity is supposed to be slow, so that the heat exchange between the kang and the indoor air is quite slow too. The kang system is designed for resident's rest and it is not so good at air heating, so its surface temperature is more worthy of attention.

A larger collector area increases the kang surface temperature significantly. The maximum kang surface temperature changes from 22℃ to 31℃. If the kang surface is covered with beddings, the temperature could be too high for resting with a larger collector area. The water supply of the solar water collector should be controlled in case of overheating.

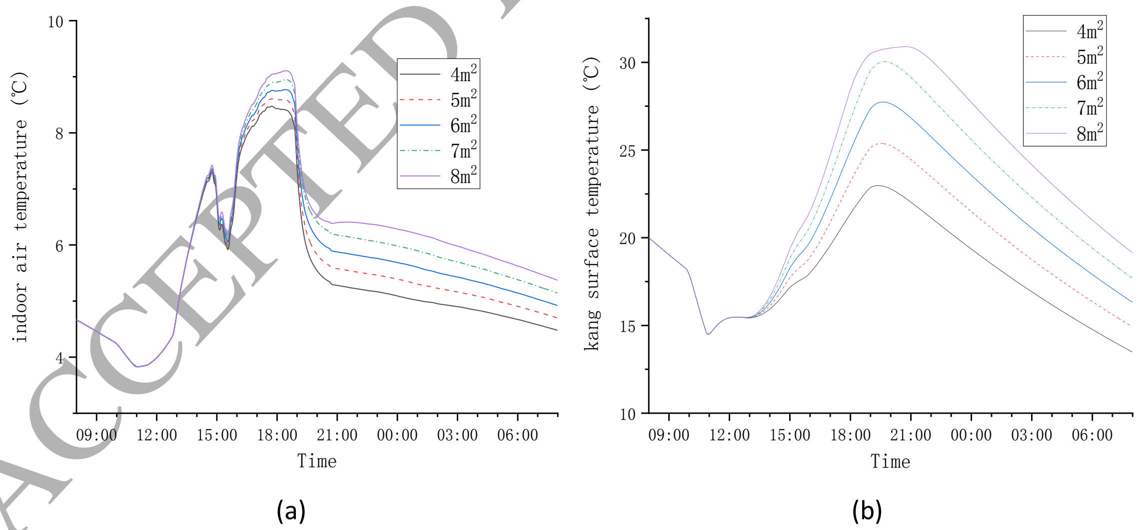


Fig. 6 (a)Indoor air temperature and (b)kang surface temperature of different solar water collector areas

Solar air collectors can provide much heat for indoor air when solar radiation is sufficient. Given the limit of the area of the south wall and window for daylight, we suppose each collector can be extended to 3 m^2 (3 m tall and 1 m wide each.) Fig. 7

shows the indoor mean air temperature of different situation of solar air collectors. Average indoor air temperature of the three conditions are 5.5℃, 5.9℃ and 6.5℃. Each additional collector area (2 m^2) can raise the maximum air temperature approximately 2℃. At nightfall when the collector is closed, air temperature declined rapidly because the heat source was lost. Additional collector area can increase the temperature at night within a small range.

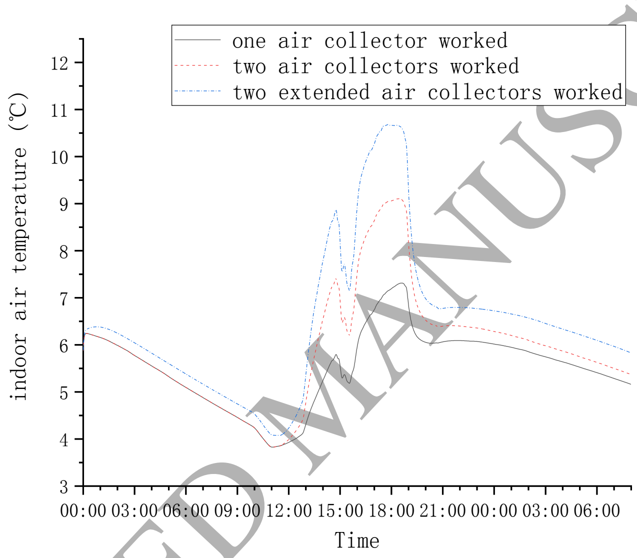


Fig. 7 Mean indoor air temperature of different situation of solar air collector

As an experimental situation, the west wall of test room is connected to another room. All the walls are covered with insulation layers except the west wall. The discussion is about how the west wall's heat-insulating property may influence the thermal performance of the room. Condition 2 means the insulation layer is added to the west wall and Condition 3 means the test room is set as a separate building with insulation layer on the west wall. The difference between Condition 3 and Condition 4 is that the latter has no insulation layer on west wall. Fig. 8 shows the result of the simulation for the next room and insulation layer. As an experimental condition, air temperature in the next room is sufficiently high that the insulation layer does not have much of an effect on thermal condition. However, if the next room is removed, it is essential to add an insulation layer. Nightly average temperature (0:00 to 8:00) would decrease from 4.9℃ to 4.1℃ without the west wall's insulation, comparing Condition 3 with Condition 4. Considering the long term operation of the system, the room's heat-insulating capability is quite necessary against a limited heat source and cold weather.

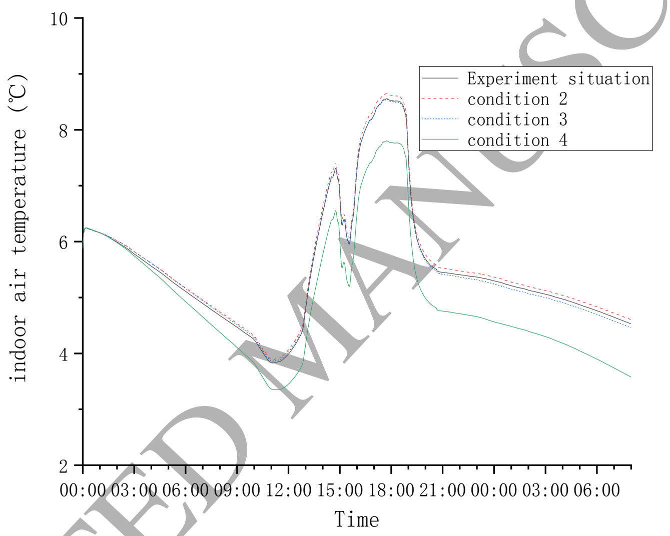
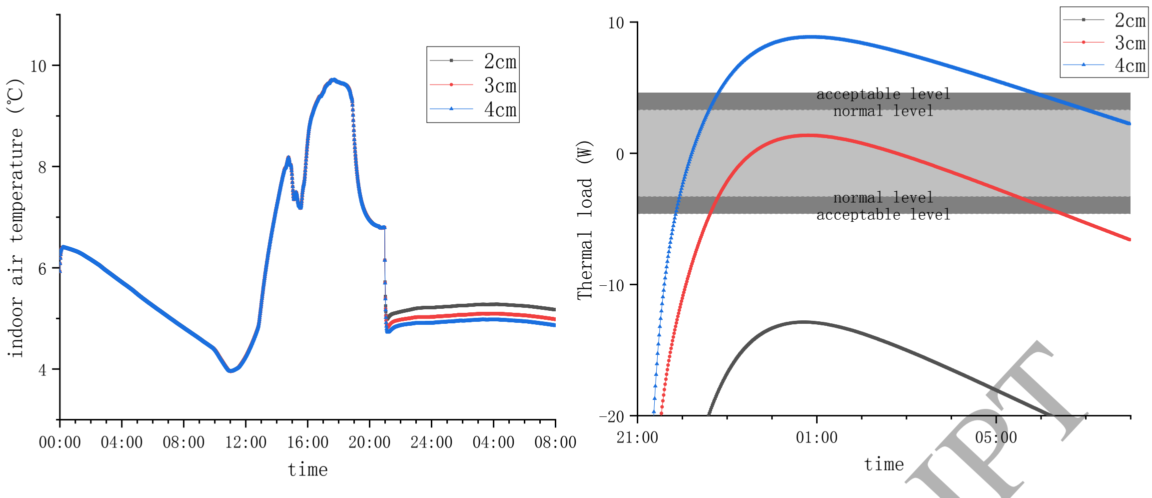


Fig. 8 Mean indoor air temperature of different west wall conditions

4.2 Sleeping thermal comfort estimation

After proving the correctness of the model, the simulation model of the system is coupled with the beddings' model and used to analyze the sleeping performance. A mattress and quilt should be on the kang surface when sleeping. The kang can provide heat for rest, so the mattress is used for comfort instead of staying warm. The quilt should provide sufficient thermal insulation qualities since the indoor air temperature is quite low. It is assumed that the mattress is 2 cm thick. Thickness of the quilt varies from 2 cm to 4 cm. When people sleep on the kang (from 9:00 p.m. to 8:00 a.m. next day), the mattress and quilt are put on the kang to cover the entire kang surface. When calculating the heat exchange of the sleeping human body, heat exchange between person and quilt, the mattress and indoor environment are considered. Experimental data are chosen to be the simulation initial data. The simulation results can be seen as Fig. 9(a), 9(b) and 10.When placing the mattress and quilt on the kang surface, the indoor air temperature decreased rapidly because of the loss of the heat source, and people would feel cold because the heat has not transferred to the body. Increasing the thickness of the quilt can improve sleeping comfort significantly. The total thermal resistance of beddings increases from 3.88clo to 4.46clo since the quilt thickness varies from 2 cm to 4 cm. People would feel cold with a 2 cm thick the quilt against low air temperature. The thermal load can be controlled at an acceptable level (-4.6 W to 4.6 W as ref[22]) if quilt is 3 cm thick. With 4 cm thick quilt, people would feel somewhat hot during the night. As shown in Fig.10, mattress average temperature can maintain at approximately 35℃ during night time, which is close to body temperature. The human sleeping metabolic rate is lower than in daytime, so the kang system can reduce the heat loss and provide a stable thermal environment, which is essential for rest.



(a) (b)

Fig. 9 Simulation result of (a)indoor air temperature and (b)PMV value in sleeping condition with different thickness of quilt

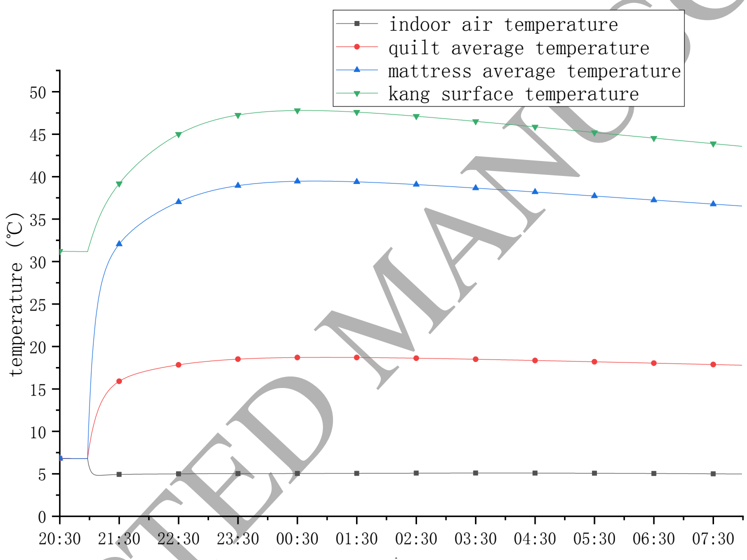


Fig. 10 temperature of different parts of sleeping environment (quilt 3cm thick)

Fig. 11 shows the line of thermal neutral with different indoor air temperatures, different thermal resistances and indoor air temperatures. The thermal resistance is the total resistance of quilt and mattress, and their thickness in this part is supposed to be the same. When beddings cover the kang surface, its temperature could reach 40℃. When lighter beddings are used, people need higher air temperature to gain thermal balance. As in the simulation mentioned above, the equivalent thermal resistance is approximately 4.0clo. Three ways exist to achieve a good sleeping thermal environment: increasing the air temperature, increasing the kang surface temperature and increasing the beddings thickness. When beddings are selected, a suitable kang temperature can provide a good sleeping environment in low air temperature.

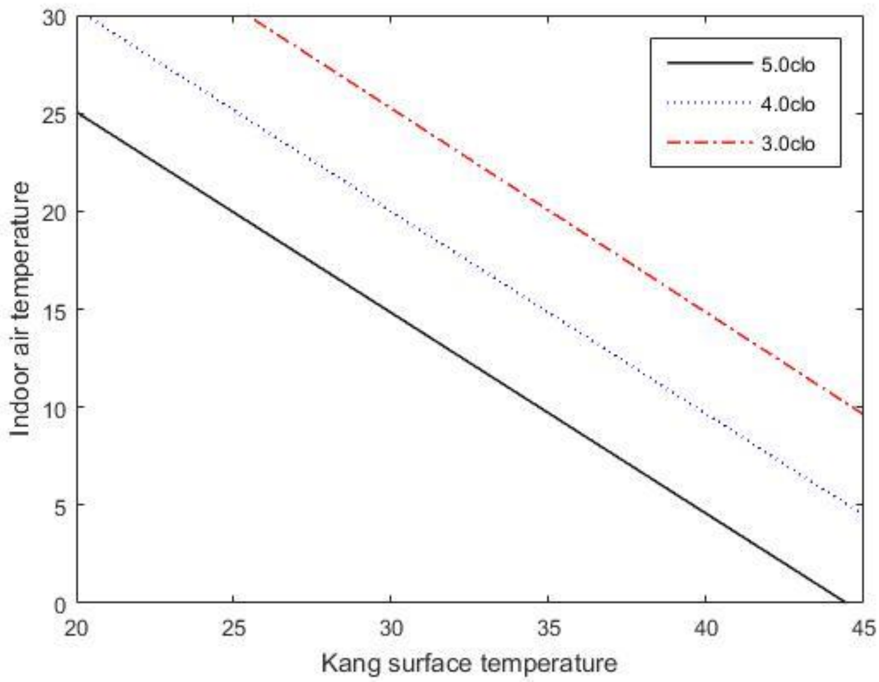
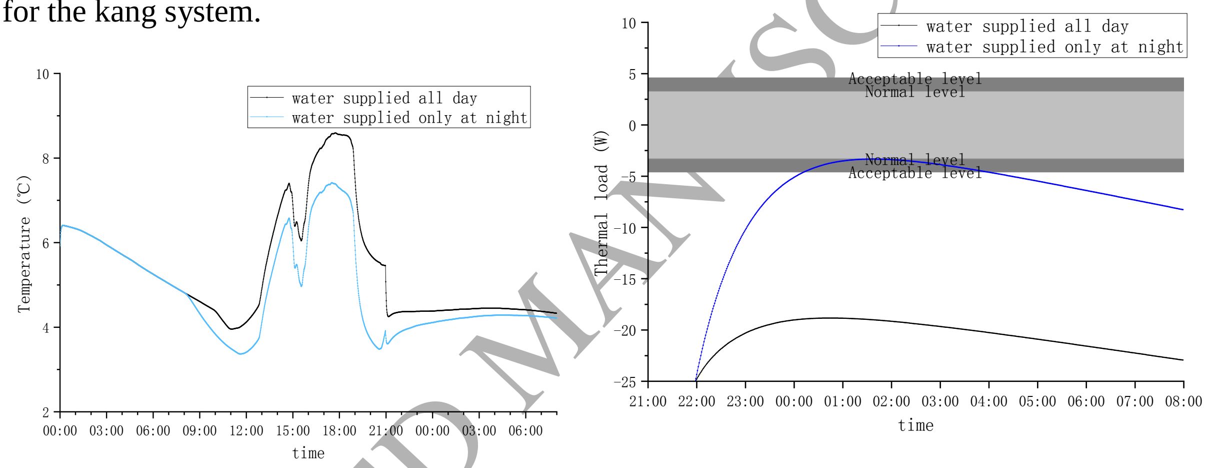


Fig. 11 Contour line of different sleep thermal resistances, air temperatures and kang surface temperatures when people are thermal neutral

4.3 Optimization of operation strategy on the system

To increase the heating efficiency of the system and decrease the usage of auxiliary power, some operation strategies can be changed to test the system's heating performance. Fig. 12(a) and (b) shows the two situations of different system operations. Water supplied all day means the strategy is similar to the experimental condition expect for the usage of the auxiliary power of solar water collector. Another scheme is that the collector only provides water at night (beginning at 8:30 p.m, some time before the beddings are put down).The thickness of the quilt is set as 4 cm. Although the later situation's temperature is lower during the day, sleeping at night is much more comfortable than in the case of the former one. If the solar kang system works in daytime, the water in the tank gives too much energy to the room and cannot afford the heat load of night, resulting in the thermal load being below an acceptable level at night. People would feel cold if the kang is not sufficiently warm. On the other hand, changing the operation strategy did not completely satisfy night sleeping needs. The whole system is insufficient for daily indoor air heating in this environment situation, so some extra power should be added. Considering the rural residents' winter clothes and daily routine, only working at night should be suitable for the kang system.



(a) (b)

Fig.12 (a)Indoor mean air temperature and (b)Thermal load at night of different operation modes without auxiliary power

4.4 Discussion

The kang system can maintain the thermal neutral balance of the body in low indoor air temperature. However, people may still feel uncomfortable if one or more parts of the body are too warm or too cold. Referring to [25], young men were significantly dissatisfied with 3°C indoor temperature in sleep quality evaluation. The ambient temperature should be maintained at a level higher than 10°C in the bedroom. Although the thermal load with a 3 cm thick quilt in section 4.2 is between the acceptable levels, low air temperature may cause some feelings of discomfort.

Another point is that a kang surface temperature that is too high is uncomfortable as well. Because the heating performance of the kang system is like that of an electric blanket, the comfort range calculated by Song [26]according to experiment results[6] can provide references. The bed temperature is in the range of 31.1-35.7℃ with whole percent dissatisfied model of 85%. Therefore, when considering the operation of the kang system, the temperature of supplied water and the flow velocity of water should be controlled to avoid overheating.

Some other hybrid heating systems[27] are proposed by other authors and can improve the overall heating effect while showing complementary advantages. For example, Li[28] studied a combined floor and kang heating terminal to find a proper operation condition that can satisfy the differentiated thermal demands at daytime or night. However, for the hybrid solar heating system, the total heating energy from solar power is limited and cannot completely afford the heating load under the experimental situation. The system did not work well under extreme cold weather, and the thermal sensation would be more comfortable in warmer months (February, November, etc.) so the optimization of the operation strategy under that condition should be studied in the future.

5. Conclusion

To explore the practicability of a hybrid solar heating system, and make full use of solar power, the mathematical model of the solar kang subsystem, the solar air subsystem and the building envelope was built and examined. This model is verified with experimental data from a Qinghai rural building which the hybrid solar heating system is applied. Based on the mathematical model and the measured data, some simulations are conducted to determine the thermal performance and sleeping environment of the combined heating system:

The area of collectors is an important factor affecting the heating performance. As solar water collector area changes from 4 m^2 to 8 m^2, the maximum kang surface temperature varies from 22℃ to 31℃. Each additional 2 m^2 air collector area can raise the maximum indoor air temperature approximately 2℃. With regard to the limited heating source of solar energy, thermal insulation material is essential to each wall exposed to the ambient air to prevent heat loss.

When the beddings insulation value is approximately 4.0clo, the solar kang system can maintain the thermal load of people in an acceptable range during the night. Warm kang surfaces and good heat-insulating beddings can create good sleeping conditions in low indoor air temperatures. A solar kang system provides a bed environment instead of an indoor air environment at night, due to the energy saving potential.

An appropriate operation strategy can make full use of the system. Although it may decrease thermal performance in the daytime, making the solar kang system only work during sleeping hours should be more suitable with limited heating power. The system cannot afford the heating load under extreme cold weather so some extra heating methods can be added, and further studies about the heating effect and complementary advantages should be performed in the future.

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Nomenclature

A: area, m^2
c: specific heat $\mathrm{J}/(kg \cdot K)$
H: height, m
h: heat transfer coefficient, $\mathrm{W}/(m^2 \cdot K)$
I:bedding thermal resistance,clo
k: heat conduction coefficient,$\mathrm{W}/(m \cdot K)$
L:thermal load of human body,W
M: weight ,kg
Nu: Nusselt number,-
p: air pressure,kPa
T: temperature,℃
Q: energy ,J
R: thermal resistance,K/W
t: time,s

v: velocity, m/s
V: volume,m^3
w: width, m
W: radiation, W/m^2
Greek
β: volume expansion coeffcient,1/K
ρ: density kg/m^3
Subscripts
a: air
air: air in the air duct
ab: aluminum absorption plate
b: back insulation layer
cl: clothes
duct: air duct
g: glass cover
indoor: indoor air
mid: middle air duct
res: respiratory heat loss
sk : skin
tank: water in water tank
v: air vent