Improving the indoor thermal environment in lightweight buildings in winter by passive solar heating: An experimental study

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Abstract
Traditional lightweight building envelopes with constant thermal properties are of small heat capacity and large thermal resistance. Lightweight building envelopes with variable thermal conductivity and variable equivalent specific heat capacity can promote passive solar heat gain for clean heating and improve the indoor thermal environment in winter. In this paper, a real-scale lightweight solar house integrated with flat gravity-assisted heat pipes and PCM (phase change material) was built up, and the indoor heating effects of four forms of the solar house were experimentally studied. The results showed that (1) the heat pipes efficiently transferred solar heat absorbed by the exterior surface of the south envelope into the indoor environment during the day and increased the average daytime indoor air temperature by 3.8°C, but this benefit was not proportional to the area of heat pipes. (2) The PCM effectively stored solar energy during the day and released heat to the indoor environment at night, and the daily range of indoor air temperature was reduced by 8.7°C, with only 81% mass and 33% volume of concrete block, respectively. (3) The solar house increased the effective proportion of solar energy for indoor heating from 8.7% to 57.5% in the form of DHP + PCM house.

Keywords
Solar house, heat pipe, phase change material, thermal diode, building envelope

Introduction
More than 30% of the total primary energy in the world is consumed in buildings. In China, the energy consumption of building operations accounts for 23% of the total energy consumption, and the CO₂ emission related to building operations accounts for 22% of the total CO₂ emissions. Indoor heating accounts for a large part of building energy consumption. In 2019, the urban heating energy consumption in northern China was 213 million tons of standard coal equivalents, accounting for 20% of the total building energy consumption, and the urban heating CO₂ emission in northern China was 550 million tons, accounting for 26% of the total CO₂ emissions related to building operations. The reduction of heating energy consumption is significant to realize building energy savings and emission reductions. The utilization of renewable energy through appropriate design has been receiving impressive considerations to replace fossil energy, as a feasible source of building energy supply in the renewable energy dominated regions.

Solar energy resources are abundant in China, and as clean and renewable energy, solar energy could serve as an important energy supply for building indoor heating to replace the fossil energy. The passive solar house makes

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use of solar radiation to meet indoor thermal comfort needs, with low energy consumption and zero environmental pollution. The most mature applications of the passive solar house are mainly three forms: direct-gain room, Trombe wall and attached sunspace. Solar radiation is a time-dependent energy source with intermittent and variable characteristics. These conventional solar houses are usually made of heavy materials so that the envelope can supply sufficient thermal inertia to dampen indoor temperature fluctuation.

Building envelopes with a unit mass of less than 100 kg/m² are usually referred to as lightweight building envelopes. Compared with heavyweight buildings, the advantages of lightweight buildings include wide application range, short construction time, high construction quality, small impact on the environment, low construction cost and relatively safe construction process. However, the heat capacity of the lightweight building envelope is often lower than that of the traditional heavyweight building envelope, and the indoor air temperature is greatly affected by the external environment due to poor thermal inertia, leading to an uncomfortable indoor thermal environment. Thermal insulation is generally adopted to improve the total thermal resistance of the building wall. However, due to the limitation of the wall thickness and the lack of sufficient heat capacity of the wall material, the desired natural indoor air temperature may not be achieved. From the perspective of the thermal performance of a lightweight building envelope, on one hand, it is difficult to transfer absorbed solar energy at the exterior surface of the opaque envelope indoors by heat conduction because of its large and immutable thermal resistance. On the other hand, due to the small heat capacity and poor thermal inertia of the lightweight building envelope, the solar energy by the transparent envelope into the room could not be effectively used. Conventional lightweight buildings with constant small heat capacity and large thermal resistance are difficult to achieve thermal comfort without additional fossil energy. Therefore, a new idea is needed for the effective utilization of solar energy for indoor heating of lightweight buildings.

Building envelopes with variable thermal conductivity and heat storage are listed as two grand thermal energy utilization challenges for energy saving and decarbonization. Improving the thermal performance of the building envelope is an important way to shorten building energy consumption. Building envelopes with variable thermal properties can improve the passive use of natural resources to save fossil energy and achieve indoor thermal comfort.

For the building envelope with variable thermal conductivity, Zhang et al. theoretically studied the ideal thermal conductivity of wall material in the form of the square wave function, and the overall indoor discomfort was reduced by 64.3% after optimization compared with traditional exterior walls. Kishore et al. proposed dynamic insulation material and system with changeable thermal resistance based on the indoor and outdoor conditions, and the simulation results showed it could provide 15–72% reduction in annual heat gain and 7–38% reduction in annual heat loss, but the material had not been widely used in practice yet. In terms of practical research, Si et al. proposed a novel double-layer transparent building envelope with variable thermal conductivity by step control strategy, and the average indoor air temperature was 2°C higher than that of the traditional passive solar house. Concerning the building envelope component, the heat pipe has attracted increasing considerations. The heat pipe is a passive thermal transfer device based on the gas-liquid phase change principle and is one of the most efficient heat transfer elements. After being properly set, a gravity-assisted heat pipe can act as a thermal diode with variable thermal conductivity, transferring heat efficiently in the bottom-top direction and acting as a thermal insulator in the opposite. Sun et al. studied a heating terminal device combined with flat heat pipes, which can provide a quick thermal response speed and high thermal uniformity. Gong et al. proposed a novel passive solar house with variable thermal properties based on L-shaped flat gravity-assisted heat pipes, and the simulation results showed that the average indoor operative temperature of the novel heavy-weight house was 6.8°C higher than that of a reference house. Liu et al. reported the performance of a wall implanted with heat pipes connected with an intelligent control valve and showed a 0.5°C increase in the average temperature of the inside surface of the wall. However, the above research focused on heavyweight envelope structures but lack further consideration on the implementation of variable thermal conductivity for lightweight buildings, especially on how to reasonably store and distribute the heat conducted by the variable thermal conductivity envelope structure.

For the heat storage in the building envelope with variable equivalent specific heat capacity, Zeng et al. theoretically studied the ideal specific heat capacity of thermal mass in buildings in the form of δ function by using the inverse problem method and provided the theoretical basis for application of the phase change material (PCM) in buildings. The PCM absorbs or releases a large amount of heat in the phase change process and has a high energy density over a narrow temperature range, which is of great value to maintain a stable indoor thermal environment. Xiao et al. analysed the benefits of adding PCM to the interior surface of light passive solar house envelopes, and the results showed the indoor air temperature fluctuation was affected by the surface heat transfer coefficient and the area of PCM, but the average temperature did not change. Jiang et al. concluded that in different building climate regions in China, the optimal phase change temperature of
PCM for passive solar houses was 1.1–3.3°C higher than the lower limit of the thermal comfort zone. Wang et al.\textsuperscript{35} conducted parametric analyses of energy saving by PCM in lightweight buildings and proposed the 20–26°C as the optimal melting temperature range of PCM and the melting temperature range was seasonal. Bai et al.\textsuperscript{36} developed a mathematical model for passive buildings, and the factors affecting the heat storage process of PCM envelopes were analysed to determine an efficient method to control the temperature of the room with PCM. The above studies focused on how to use PCM to delay and weaken the impact of outdoor environment fluctuations and improve indoor thermal stability and comfort. However, without a strong heat source input, the PCM is of limited practical use because the indoor air temperature tends to fall below the thermal comfort zone. Therefore, it is not enough to consider only enhancing the heat capacity as a measure to reduce the indoor air temperature fluctuation.\textsuperscript{37} It is also necessary to improve the characteristic of large thermal resistance of the envelope and increase the amount of heat transmitted into the room during the daytime.

To sum up, the traditional lightweight building envelope has the characteristics of constant small heat capacity and large thermal resistance, and these defects would limit the utilization of solar energy for indoor heating and restrict the usage scenarios of lightweight buildings. In this research, a novel real-scale lightweight solar house integrated with flat gravity-assisted heat pipes and PCM was built up. This paper aims to study its practical application effect through field comparison experiments based on indoor air temperature and energy utilization analyses. After comprehensive consideration of variable thermal conductivity and variable equivalent specific heat capacity, the solar energy transferred into the building through envelopes is greatly

\textbf{Figure 1.} Schematic diagram of the structure of (a) the lightweight HP house and (b) the reference house.
increased. It provides a new possible path to improve the indoor thermal environment in lightweight buildings in winter by passive solar heating.

**Experimental methodology**

This paper reported a study of a novel lightweight passive solar house (HP house) fitted with L-shaped flat gravity-assisted heat pipes and PCM, as shown in Figure 1(a). The structure of a typical lightweight HP house includes a glazing cover, lightweight insulation external walls, an internal wall, flat gravity-assisted heat pipes and PCM plates. The southern wall is a lightweight thermal insulation wall, with a glazing cover on the outside, forming a cavity of an air layer between them. The L-shaped flat gravity-assisted heat pipes are bent into two parts, namely the evaporator section and the condenser section. The heat pipes are arranged at an inclined angle, and the evaporator section is lower than the condenser section, creating a height difference for liquid flow by gravity. The surface of the evaporator section is evenly sprayed with black paint and laid on the exterior surface of the southern wall. The condenser section clings to the interior surface of the internal wall, and the PCM plate covers all surfaces of the condenser section. For comparison, a reference house (RF house) without heat pipes and PCM is shown in Figure 1(b).

The working principle of the lightweight HP house is as follows. During the daytime, the evaporator section of the heat pipes sprayed with black paint is irradiated by sunlight, absorbing radiation heat and heating up rapidly. The inside liquid working medium located at the evaporator section due to the height difference evaporates into the gaseous state after heat absorption and flows to the condenser section. Then, the gaseous working medium at the condenser section releases heat to the PCM plate and becomes liquid again and flows back to the evaporator section by gravity to complete a flow cycle. Therefore, the heat pipes work automatically, and a large amount of heat is transferred from the evaporator section to the condenser section and then stored in the PCM. During the nighttime, the condensed liquid working medium stays in the evaporator section and the heat transfer process does not take place, without solar radiation as the heat source. Because of the heat diode characteristic of the flat gravity-assisted heat pipes, the heat loss from the indoor to the outdoor environment can be avoided. The effective thermal conductivity of the heat pipe can reach up to $1.78 \times 10^4$ W/(m·K) when working normally, and it could be neglected when not working. As a result, in a typical day, the trend of effective thermal conductivity of the heat pipe is in the form of an approximate square-wave function, as Figure 2 shows. The glazing cover allows sunlight in, and the air layer in the cavity reduces the southward heat loss. The lightweight HP house takes advantage of the ultrahigh thermal conductivity and the thermal diode characteristic of heat pipes, and the large equivalent heat capacity of PCM to transfer and store the solar energy that was absorbed on the exterior surface of the southern envelope during the daytime and release it indoors at night. The variable thermal conductivity and variable equivalent specific heat capacity effectively improve the utilization efficiency of solar energy for indoor heating.
Based on the above structure, two houses (an HP house and an RF house) were built in Beijing for the experimental study, as shown in Figure 3. The overall dimensions of these two houses were both $2.40 \text{ m} \times 2.40 \text{ m} \times 2.40 \text{ m}$. The roof, ceiling and walls of each house were made of 150 mm rock wool board, with a thermal resistance of 5 K/W. There was no window to avoid the effect of direct solar radiation on the indoor environment. A door was set on the eastern wall with the same material as the wall. The size of the glazing cover was $2.10 \text{ m} \times 1.50 \text{ m} \times 0.02 \text{ m}$, with a heat transfer coefficient of $3.3 \text{ W/(m}^2\cdot \text{K})$. The thickness of the air layer between the glazing cover and the south wall was 0.08 m. The width of a heat pipe was 0.10 m, and the lengths of the evaporator section and condenser section were 0.75 m and 1.05 m, respectively. In the experiment, 14 heat pipes were installed close to each other in the vertical direction, and they were called a set of heat pipes. The heat pipes were located at the location of the internal wall, and the total areas of the evaporator section and condenser section of one set of heat pipes were 0.84 m$^2$ and 1.18 m$^2$, respectively. The surface of the evaporator section of heat pipes was sprayed with black paint evenly. Solid concrete block of 0.27 m$^3$ (189 kg) and calcium chloride hexahydrate of 0.09 m$^3$ (153 kg) were chosen as heat storage materials in the experiment, and the thermal properties are listed in Table 1. Calcium chloride hexahydrate was encapsulated in boxes with the size of $0.20 \text{ m} \times 0.15 \text{ m} \times 0.02 \text{ m}$. There was no indoor heat disturbance in the room. Air changes per hour (ACH) was 0.1 h$^{-1}$, which was obtained by the tracer-gas technique with CO$_2$. Due to the limited area of the field space, the eastern and western walls of both houses were external walls, so the direction of the heat pipe was extended to the middle of the room to make the heat release indoors.

According to the area of the heat pipe and whether there is heat storage material, four forms of HP house were experimentally studied. The structural layout of the four forms of HP house is shown in Figure 4. The experiments were conducted from 13th April to 21st May, and the test periods and features of these four forms are listed in Table 2. For the HP house with a single set of heat pipes (SHP house), the area of the heat pipe was half that of the HP house with double sets of heat pipes (DHP house). The condenser section of heat pipes was exposed to indoor air for these two forms. For the two forms with heat storage materials, the condenser section of heat pipes was fully covered by concrete block (DHP + CB house) or phase change material.
To be clear, the experimental study conducted in spring did not focus on the absolute values of indoor air temperature and whether in the comfort zone, but analysed the effects of different measures on the improvement of indoor thermal environment, providing a further guidance for the application of HP house in winter.

The experiment instruments information is listed in Table 3. Figure 5 shows the layout of temperature measuring points, including the temperatures of the evaporator and the condenser sections of the heat pipes, the temperatures of the interior and exterior surfaces of the southern wall, the southern cavity air temperature and the indoor and outdoor air temperatures. The indoor air temperature was obtained

**Table 2.** Test period and features of the four forms of HP house in the experiment.

<table>
<thead>
<tr>
<th>Form</th>
<th>Test period</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHP house</td>
<td>13th April–20th April</td>
<td>One set of heat pipes</td>
</tr>
<tr>
<td>DHP house</td>
<td>23rd April–2nd May</td>
<td>The total area of the heat pipe was twice that of SHP</td>
</tr>
<tr>
<td>DHP + CB house</td>
<td>2nd May–11th May</td>
<td>Concrete blocks were placed close to both sides of the heat pipe and covered all areas of the condenser section</td>
</tr>
<tr>
<td>DHP + PCM house</td>
<td>11th May–21st May</td>
<td>Boxed phase change materials were placed close to both sides of the heat pipe and covered all areas of the condenser section</td>
</tr>
</tbody>
</table>

**Table 3.** Information of the experimental instruments.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Test parameter</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic recording thermometer</td>
<td>Temperature</td>
<td>±0.3°C</td>
</tr>
<tr>
<td>Automatic recording solar energy metre</td>
<td>Solar radiation intensity</td>
<td>±10 W/m²</td>
</tr>
<tr>
<td>CO₂ automatic recorder</td>
<td>Carbon dioxide concentration (for the measurement of ACH)</td>
<td>±75 ppm</td>
</tr>
</tbody>
</table>

**Figure 5.** Layout of the temperature measuring points in the experiment: (a) HP house without heat storage material, (b) HP house with heat storage material and (c) RF house.

(DHP + PCM house), respectively. To be clear, the experimental study conducted in spring did not focus on the absolute values of indoor air temperature and whether in the comfort zone, but analysed the effects of different measures on the improvement of indoor thermal environment, providing a further guidance for the application of HP house in winter.
by the mean value of three measuring points arranged at the height of 0.5 m, 1.0 m and 1.5 m at the centre location of the room. The temperature test interval was 1 min. The automatic recording solar energy metre was set on the southern facade behind the glazing cover to record the solar radiation intensity received by the evaporator section of the heat pipes.

**Evaluation indexes**

To simplify the analysis processing of experimental data, the following assumptions were made:

1. Building envelopes are composed as homogeneous isotropic materials.
2. The lumped parameter model was applied for the temperatures of the evaporator and condenser sections of the heat pipes.
3. The air in the southern cavity was fully mixed. Likewise, the air in the room was regarded as a homogeneous mixture.
4. The long-wave mutual radiation among components was not considered.

As shown in Figure 3, for the HP house in the experiment, the southern envelope could be divided into upper and lower parts according to whether covered by the evaporator section of the heat pipe. The lower part was not covered by the heat pipe, the same as the RF house. To focus on the different upper parts, the southern envelope in the following analysis only refers to the upper part of the southern wall, and its area is equal to the area of the evaporator section of the heat pipe, namely the area of glazing cover. The energy analysis considers the glazing cover, the heat pipe and the southern wall as a research unit, as shown in Figure 6. The solar radiation through the glazing cover during the day, $q_{sol}$ is the heat input from the outside environment to the unit, which is the most important heat source for indoor heating of the solar house. During the experiment, the southern cavity air temperature was always higher than the outdoor temperature in the daytime, so the outdoor environment was a heat sink for the research unit. The convective heat was transferred at the exterior surface of the glazing cover and is called heat loss $q_{gc,out}$. The heat transfer processes inside the unit include the heat conduction of the southern wall, the heat convection of the air layer in the cavity and the heat transfer due to the liquid-gas phase change caused by the heat pipes $q_{hp}$. $q_{sw,in}$ is the heat released indoors by the interior surface of the southern wall. When the heat pipes are exposed to indoor air, $q_{hp,in}$ is the heat released indoors by the condenser section of the heat pipes and equals $q_{hp}$. When the heat pipes are covered by heat storage material, $q_{hsm,sto}$ is the heat stored in the heat storage material and $q_{hsm,in}$ is the heat released indoors by the surface of the heat storage material.

From sunrise to sunset, the cumulative amount of heat on each surface is the cumulative daytime solar radiation through the glazing cover, the cumulative daytime heat loss by the glazing cover, the cumulative daytime heat transferred indoors by the interior surface of the southern wall and the cumulative daytime heat transferred indoors by the heat pipes in the interior wall.

a. The cumulative daytime solar radiation through the glazing cover is defined by equation (1)

$$ Q_{sol} = \int_{\text{sunset}}^{\text{sunrise}} q_{sol}(\tau)A_{gc} d\tau \tag{1} $$

where $Q_{sol}$ is the cumulative daytime solar radiation through the glazing cover, J; $q_{sol}$ is the instantaneous solar radiation...
at the southern facade behind the glazing cover, W/m²; and $A_{gc}$ is the area of the glazing cover, m².

b. The cumulative daytime heat loss by the glazing cover is defined by equation (2)

$$Q_{gc, out} = \int_{\text{sunset}}^{\text{sunrise}} g_{ge, out}(\tau) A_{gc} d\tau = \int_{\text{sunset}}^{\text{sunrise}} K_{gc}(T_{gap}(\tau) - T_{out}(\tau)) A_{gc} d\tau$$

where $Q_{gc, out}$ is the cumulative daytime heat loss by the glazing cover, W/(m²·K); $K_{gc}$ is the heat transfer coefficient of the glazing cover, W/(m²·K); $T_{gap}$ is the air temperature in the cavity, °C; and $T_{out}$ is the outdoor air temperature, °C.

c. The cumulative daytime heat transferred indoors by the interior surface of the southern wall is defined by equation (3)

$$Q_{sw, in} = \int_{\text{sunset}}^{\text{sunrise}} q_{sw, in}(\tau) A_{gc} d\tau = \int_{\text{sunset}}^{\text{sunrise}} h_{sw, in}(T_{sw, in}(\tau) - T_{in}(\tau)) A_{gc} d\tau$$

where $Q_{sw, in}$ is the cumulative daytime heat transferred indoors by the interior surface of the southern wall, W/(m²·K); $T_{sw, in}$ is the interior surface temperature of the southern wall, °C; $T_{in}$ is the indoor air temperature, °C; and $h_{sw, in}$ is the surface convective heat transfer coefficient on the interior surface of the southern wall, calculated by equation (4), W/(m²·K)

$$h_{sw, in} = Nu \frac{\lambda_{air}}{H_{sw}}$$

where $Nu$ is the Nusselt number; $\lambda_{air}$ is the coefficient of thermal conductivity of air, W/(m·K); and $H_{sw}$ is the height of the south wall, m.

d. The cumulative daytime heat transferred indoors by the heat pipes in the interior wall is defined by equation (5):

$$Q_{hp} = \int_{\text{sunset}}^{\text{sunrise}} q_{hp, in}(\tau) A_{hp, c} d\tau = \int_{\text{sunset}}^{\text{sunrise}} h_{hp, c}(T_{hp, c}(\tau) - T_{in}(\tau)) A_{hp, c} d\tau$$

where $Q_{hp}$ is the cumulative daytime heat transferred indoors by the heat pipes in the interior wall, W/(m²·K); $h_{hp, c}$ is the surface convective heat transfer coefficient at the condenser section of heat pipes, W/(m²·K); $T_{hp, c}$ is the surface temperature of the condenser section of heat pipes, °C; and $A_{hp, c}$ is the surface area of the condenser section of heat pipes, m².

When the heat pipes are covered by heat storage material, calculation periods were chosen after the temperature of the research unit returned to the starting point on a typical day, therefore equation (6) describes the cumulative daytime heat transferred indoors by the heat pipes in the interior wall

$$Q_{hp} = Q_{sol} - Q_{gc, out} - Q_{sw, in}$$

To quantify the proportion of each energy item to the energy source and characterize the effective utilization degree of solar radiation resources, the following evaluation indexes are defined.

1. The ratio, $\eta_1$, of the daytime heat transferred indoors by the southern wall to the solar radiation, is defined by equation (7) to evaluate the proportion of solar radiation heat supplied by the southern wall for indoor heating

$$\eta_1 = \frac{Q_{sw, in}}{Q_{sol}}$$

2. The ratio, $\eta_2$, of the daytime heat transferred indoors by the heat pipes in the interior wall to the solar radiation is defined by equation (8) to evaluate the proportion of the solar radiation heat supplied by the heat pipes in the interior wall for indoor heating

$$\eta_2 = \frac{Q_{hp}}{Q_{sol}}$$

3. The ratio, $\eta_3$, of the cumulative daytime heat loss by the glazing cover to the solar radiation is defined by equation (9) to evaluate the proportion of the solar radiation heat received through the glazing cover and lost to the outdoor environment

$$\eta_3 = \frac{Q_{gc, out}}{Q_{sol}}$$

Results and discussion

Heat pipes

The average temperatures of the evaporator section and condenser section of heat pipes and their temperature difference in four forms of the HP house in four typical days are shown in Figure 6. The working and non-working phases of heat pipes were divided according to sunrise and sunset. The daytime period was from 6:00 to 18:00, while the solar radiation existed and the heat pipes worked normally. The nighttime period was from 18:00 to 6:00 the next day, with no solar radiation and the heat pipes not working. The heat pipes used in the experiment had a very small mass and the heat capacity was ignored. Two
important characteristics of the heat pipes can be seen from Figure 7.

1. Temperature uniformity at daytime:

From 6:00 to 18:00, the flow circulation of working fluid inside the heat pipes worked normally, and the temperatures of each measuring point at the evaporator section and condenser section of the heat pipes were basically the same, with the temperature difference between two sections was less than 0.5°C most of the time. This is the embodiment of the ultrahigh thermal conductivity of the heat pipes, which means the heat pipes are able to transfer plenty of heat under a small temperature difference between the evaporator section and the condenser section.

2. Thermal diode effect at nighttime:

From 18:00 to 6:00 the next day, the heat pipes did not work, and the temperatures of the evaporator section and condenser section were mainly affected by outdoor and indoor environments, respectively. The temperature of the evaporator section was always lower than that of the condenser section, and the largest temperature difference was from 1.4°C to 7.5°C for the various forms. The heat pipes have a thermal diode effect when not working, and the temperature of the condenser section does not change with the evaporator section.

Southern envelope

In a typical day, temperature differences of the southern envelope between the HP house and the RF house are

Figure 7. Temperatures of the evaporator section and the condenser section of the heat pipes in four typical days: (a) SHP house, (b) DHP house, (c) DHP + CB house and (d) DHP + PCM house.

Figure 8. Temperature differences in the southern envelope between the DHP house and the RF house in a typical day.
shown in Figure 8, including the temperature difference of the air in the cavity $\Delta T_{\text{air,gc}}$, and the interior and exterior surface temperature differences in the southern wall, which are $\Delta T_{\text{in,sw}}$ and $\Delta T_{\text{out,sw}}$ respectively. All differences are values of the HP house minus those of the RF house. During the day, the surface temperature of the southern wall exterior and the air temperature in the cavity of the HP house were much lower than those of the RF house, and the maximum temperature difference was more than 13.4°C. However, the interior surface temperature of the southern wall of the HP house was higher than that of the RF house all the time, and the largest temperature difference reached 7.1°C, indicating that the heat pipes had a more significant role than the southern wall in heat supply to the indoor environment. This showed that an ordinary envelope is not an efficient component to introduce solar energy indoors, especially with a wall with a large thermal resistance due to insulation requirements.

**Indoor air temperature**

Through the comparison of indoor air temperature between the HP house and the RF house, the improvement effect of different measures on the natural indoor air temperature in the lightweight solar house was analyzed. The individual and comparative analyses of these four forms of HP house in typical days were made.

**Analysis of individual four forms of HP houses**

a. SHP house

On a typical day, the curves of the indoor air temperature of the SHP house and RF house and outdoor air temperature are shown in Figure 9(a), and the maximum and minimum and the all-day average temperatures are shown in Figure 9(b). The red and blue curves are the indoor air temperatures of the HP house and the RF house, respectively, and the grey curve is the outdoor air temperature. The daytime and nighttime average indoor air temperatures are marked. The yellow shadow represents the solar radiation intensity through the glazing cover.

During the day, the average indoor air temperatures of the HP house and the RF house were 27.9°C and 25.2°C, respectively, and the average outdoor air temperature was 24.3°C. As a high-efficient heat transfer component, the heat pipe can introduce much solar radiation heat through the glazing cover indoors and thus significantly improve the indoor air temperature level of the HP house during the day. The highest temperatures and their emergence moments of the HP house and the RF house were 39.1°C (15:15) and 35.0°C (15:30), respectively, and the highest outdoor air temperature was 31.0°C (15:00). The RF house could only use the envelopes to conduct heat indoors, and the envelopes had a certain thermal inertia, so the process of temperature rising had a time lag. The temperature rising of the HP house was earlier because the increase of indoor air temperature depended not only on the heat transfer of envelope structure but also on the heat introduced indoors by heat pipes in the previous period. The solar radiation diminished rapidly after 16:00, and the outdoor air temperature began to decline, so the indoor air temperatures of two houses also decreased immediately.

At night, the average indoor air temperatures of the HP house and RF house were 22.3°C and 20.8°C, respectively, and the average outdoor air temperature was 20.1°C. There was no significant difference between the indoor air temperature of the RF house and the outdoor air temperature, especially the follow-up effect of daytime heating disappeared completely after 22:00. The lowest temperatures of the HP house and RF house were 12.7°C (7:00) and 11.9°C (6:45), respectively, and the lowest outdoor air temperature was 11.9°C (6:00). As the next sunrise approached, the indoor air temperatures had declined to the outdoor air temperature level. This showed that the heat pipes alone could not benefit much from the nighttime indoor thermal environment, as the heat pipes stopped...
working after sunset. Besides, although the average indoor air temperature was improved, the daily range of the indoor air temperature was also increased.

b. DHP house

Experimental results of the DHP house in a typical day are shown in Figure 10.

During the day, the average indoor air temperatures of the HP house and RF house were 27.5°C and 23.7°C, respectively, and the average outdoor air temperature was 21.7°C. The highest temperatures of the HP house and the RF house were 39.2°C (14:15) and 32.1°C (14:45), respectively, and the highest outdoor air temperature was 26.4°C (14:00). The average and peak indoor air temperatures increased significantly, which means that the increase in the heat pipe area did improve the indoor heat supply. The highest indoor air temperature of the HP house was 12.8°C higher than the outdoor air temperature, indicating that excessive daytime indoor heating may occur in the practical application of the HP house; thus, reasonable optimization of the heat supply and demand matching is required.

At night, the average indoor air temperatures of the HP house and RF house were 19.0°C and 18.1°C, respectively, and the average outdoor air temperature was 16.9°C. The lowest temperatures of the HP house and RF house were 12.9°C (6:30) and 12.3°C (6:30), respectively, and the lowest outdoor air temperature was 12.3°C (5:30). Similar to the SHP type, due to a lack of heat capacity, the temperature advantage brought by solar radiation during the day decreased and disappeared quickly for the DHP house.

c. DHP + CB house

Indoor heat storage materials are required to store heat transferred by heat pipes during the day to prevent indoor air temperature from rising too high and to release heat indoors at night to delay the decline of indoor air temperature. The concrete block was selected as the heat storage material with constant thermal properties (see Table 1). Experimental results of the DHP + CB house in a typical day are shown in Figure 11.

During the day, the average indoor air temperatures of the HP house and RF house were 28.9°C and 27.7°C, respectively, and the average outdoor air temperature was 24.9°C. The highest temperatures of the HP house and the RF house were 35.4°C (16:00) and 34.3°C (14:45), respectively, and the highest outdoor air temperature was
30.1°C (14:00). Compared to the SHP house and DHP house without heat storage material, the concrete block provided a large heat capacity as a heat buffer between the heat pipes and the indoor environment, absorbing the heat released by the condenser section during the daytime. Therefore, there was a significant time delay in the temperature rise, and the range of temperature rise was reduced, which was helpful to improve the excessive heating problem during the daytime.

At night, the average indoor air temperatures of the HP house and the RF house were 23.5°C and 20.3°C, respectively, and the average outdoor air temperature was 19.8°C. The lowest temperatures of the HP house and the RF house were 17.9°C (6:45) and 15.5°C (6:00), respectively, and the lowest outdoor air temperature was 15.1°C (5:00). When the heat pipes stopped working after sunset, the concrete block no longer absorbed heat. At night, the concrete block released heat into the room and narrowed the amplitude of the indoor air temperature decrease.

d. DHP + PCM house

In this form, calcium chloride hexahydrate was selected as the heat storage material with variable thermal properties (see Table 1). Experimental results of the DHP + PCM house on a typical day are shown in Figure 12.

During the day, the average indoor air temperatures of the HP house and the RF house were 23.7°C and 23.9°C, respectively, and the average outdoor air temperature was 23.6°C. The average daytime indoor air temperature of the HP house was even lower than that of the RF house, indicating that the amount of PCM was sufficient, and its heat storage capacity was more significant compared with that of the concrete block. The highest temperatures of the HP house and the RF house were 29.2°C (16:30) and 33.2°C (15:15), respectively, and the highest outdoor air temperature was 30.3°C (14:45). The maximum indoor air temperature of the HP house was even lower than the outdoor air temperature, which was close to the phase change temperature of the PCM (27°C). During the daytime, the temperature of the condenser section of the heat pipes was higher than that of the PCM, so the PCM was heated up by the heat pipes, and the phase change process occurred near the phase change temperature, storing a large amount of heat. This shows that through reasonable selection, PCM can well solve the problem of high temperature rise of the HP house during the daytime, and the effect is more significant than normal heat storage materials with constant thermal properties.

At night, the average indoor air temperatures of the HP house and the RF house were 23.6°C and 20.3°C, respectively, and the average outdoor air temperature was 19.2°C. The lowest temperatures of the HP house and the RF house were 19.0°C (7:15) and 14.3°C (6:15), respectively, and the lowest outdoor air temperature was 13.9°C (5:30). The heat pipes stopped working after sunset and the PCM no longer absorbed heat. As the indoor air temperature declined below the phase change temperature of the PCM, the phase change process took place and the heat stored during the day was released indoors. Thus, the indoor air temperature was kept at a relatively high level. The lowest temperature of the HP house was nearly 6°C higher than the outdoor air temperature. The effect of the PCM was better than concrete blocks, although the mass and volume of PCM only accounted for 81% and 33% of concrete block, respectively.

Comparative analysis of four forms of HP house

The average all-day indoor air temperature differences and daily range of indoor air temperatures are shown in Figure 13. For the SHP house and DHP house, the heat pipes improved the average all-day indoor air temperatures by 2.1°C and 2.3°C, respectively, but also increased the daily range at the same time. According to the above individual analyses of the SHP house and DHP house, as there was overheating during the daytime and the indoor air temperature was still low at night, thus a large daily...
temperature difference and obvious indoor discomfort may occur. However, after the incorporation of the heat storage material, with concrete block and PCM, the daily temperature difference was reduced to 17.5°C and 10.2°C, respectively, and indoor thermal comfort was greatly improved. At the same time, the average all-day indoor air temperature did not decrease and was still 1.6°C higher than the RF house. This shows that the PCM can greatly reduce the daily range of indoor air temperature and effectively improve the indoor thermal comfort, without reducing the average temperature.

The temperature difference and time lag of the maximum and minimum indoor air temperature \( T_{\text{in,max}} \), \( T_{\text{in,min}} \) compared to outdoor air temperature \( T_{\text{out}} \) are shown in Figure 14. The maximum and minimum indoor air temperatures of all houses appeared later than outdoor air temperature due to the thermal inertia of the envelope structure. For the SHP house and DHP house, on one hand, the maximum temperatures of the indoor air appeared earlier than that of the RF house, and the temperature differences in the SHP house and DHP house compared to \( T_{\text{out}} \) were much higher than that of the RF house. The reason was due to the indoor air temperature of the HP house was largely related to solar radiation, which reached a high level earlier than the outdoor air temperature during the experiment. On the other hand, the occurrence times of the lowest temperature and the temperature difference were close to the RF house, indicating that without heat storage, the influence of the heat pipes on the indoor air temperature almost disappeared after a night. For the DHP + CB house and DHP + PCM house, on one hand, the maximum indoor air temperature appeared 1.25 h later than that of the RF house and at least 1.75 h later than \( T_{\text{out}} \), and the maximum indoor air temperature of the DHP + PCM house was even 1.1°C lower than outdoor air temperature. This indicated that the PCM can greatly reduce the daily range of indoor air temperature and effectively improve the indoor thermal comfort, without reducing the average temperature.

Figure 13. Temperature difference of \( T_{\text{ave,ad}} \) and daily range of \( T_{\text{in}} \) of the four types of HP house and RF house.

Figure 14. Temperature differences and time lags of \( T_{\text{in,max}} \) and \( T_{\text{in,min}} \) compared to \( T_{\text{out}} \).
release area became smaller, and there was an air interlayer of about 0.20 m between the surfaces of two sets of heat pipes, which affected the effective heat release on both surfaces of heat pipes to a certain extent.

**Energy analysis**

Figure 16 shows the results of $\eta_1$, $\eta_2$ and $\eta_3$ of the four forms of HP house in typical days of each experiment.

For the RF house, the cumulative daytime heat transferred indoors by the interior surface of the southern wall $Q_{sw,in}$ accounted for 5%–9% of the cumulative daytime solar radiation through the glazing cover $Q_{sol}$ in four typical days, and this difference was caused by different weather conditions in the 4 days. At least 91% of $Q_{sol}$ was lost to the outdoor environment through the glazing cover. The southern wall of the RF house had a large thermal resistance, so the transfer of solar heat to indoors by heat conduction of the southern wall would be difficult. In addition, the temperature of the air layer inside the glazing cover was high and the heat loss to the outside was large.

For the DHP house, 2.6% of the cumulative daytime solar radiation through the glazing cover $Q_{sol}$ entered the room through the southern wall, which was smaller than the RF house, because the exterior surface of the southern wall was shielded by the evaporator section of heat pipes and the surface temperature was much lower than that of the RF house. 22.8% of $Q_{sol}$ entered the room via the heat pipes incorporated in the interior wall, and 25.4% of $Q_{sol}$ entered the room altogether considering the southern wall and heat pipes installed in the interior wall, which was four times that of the RF house. The heat loss to the outdoor environment was reduced from 93.7% to 74.6%, as more solar heat was transferred to indoors, and the temperature of the air in the cavity was lowered.

For the DHP + CB house and DHP + PCM house, the proportion of daytime heat transferred to indoors via the

![Figure 15. Temperature differences for the SHP house and the DHP house.](image)

![Figure 16. Energy performance ratios of the four forms of HP house and RF house: (a) SHP house, (b) DHP house, (c) DHP + CB house and (d) DHP + PCM house.](image)
interior wall incorporated with heat pipes was increased to 32.2% and 55.1%, respectively, and the total proportion of heat considering both the southern wall and interior wall incorporated with heat pipes was increased to 34.4% and 57.5%, respectively. The proportion of heat entering the room via heat storage materials with large thermal capacities was increased through the interior wall incorporated with heat pipes, and it benefitted more with the PCM than with the concrete block. This is due to constant thermal properties, and the concrete block temperature was increased by the heat absorption, so the temperature difference between the concrete block and the condenser section of the heat pipes as the driving force in the heat transfer process gradually becomes smaller. However, PCM can absorb much heat and keep its temperature fluctuation within a narrow range during the phase change process, and the heat transfer is basically not hindered.

Conclusions
In this paper, an experimental study was carried out on the application benefits of a lightweight solar house with variable thermal properties using flat gravity-assisted heat pipes and PCM. The heat pipes with ultrahigh effective thermal conductivity and the thermal diode effect can efficiently introduce the solar radiation absorbed by the exterior surface of the southern envelope and transfer the heat to indoors without heat loss to the outdoors at night. The large heat capacity of PCM can effectively store heat during daytime and release it indoors at night. These characteristics are helpful to improve the indoor thermal environment and enhance the utilization efficiency of solar energy. The main results are presented below:

1. The heat pipes alone can raise the average daytime indoor air temperature, but cannot significantly improve the average nighttime indoor air temperature, and the daily range of indoor air temperature becomes larger. In the experiment, the average daytime indoor air temperature of the DHP house was 3.8°C higher than that of the RF house, but the daily range of indoor air temperature was 6.5°C higher.
2. The thermal storage materials, especially PCM, effectively reduce the rise of indoor air temperature in the daytime and keep indoor air temperature at a relatively high level at night, so as to narrow the daily range of indoor air temperature. In the experiment, the average nighttime indoor air temperature of the DHP + PCM house was 3.3°C higher than that of the RF house, and the daily range of indoor air temperature was reduced by 8.7°C.
3. The lightweight solar house with variable thermal properties effectively improves the proportion of solar radiation heat for indoor heating. In the experiment, this proportion was increased from less than 9–57.5% for the DHP + PCM house.

This experimental study proves that due to better use of solar energy absorbed on the exterior surface of the southern envelope, the lightweight solar house integrated with flat gravity-assisted heat pipes and PCM can effectively improve the indoor thermal environment in winter, which would significantly expand the usage scenarios of lightweight buildings. Building envelopes of other orientations are also worth considering in practical use. In addition, the solar house can be integrated with a heat pump or other auxiliary heating systems to reduce the fossil energy consumption for indoor heating. The novel solar house provides a new direction for the clean heating of lightweight buildings and will contribute toward the realization of near-zero energy buildings.

Authors’ contributions
Fangcheng Kou: methodology, experimental research, data analysis, visualization, writing – original draft and writing – review and editing. Shaohang Shi: experimental research, data curation and writing – original draft. Ning Zhu: supervision and resources. Yehao Song: supervision and resources. Yu Zou: supervision and resources. Jinhan Mo: supervision and resources. Xin Wang: conceptualization, writing – review and editing, project administration, funding acquisition and supervision.

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