Solar application potential and thermal property optimization of a novel zero-carbon heating building

Fangcheng Kou \textsuperscript{a,b}, Qipeng Gong \textsuperscript{a}, Yu Zou \textsuperscript{b}, Jinhan Mo \textsuperscript{a,c}, Xin Wang \textsuperscript{a,c,*}

\textsuperscript{a} Department of Building Science, Tsinghua University, Beijing 100084, China
\textsuperscript{b} Institute of Building Environment and Energy, China Academy of Building Research, Beijing 100013, China
\textsuperscript{c} Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Beijing 100084, China

\textbf{A R T I C L E   I N F O}

Article history:
Received 3 August 2022
Revised 10 November 2022
Accepted 20 November 2022
Available online 24 November 2022

Keywords:
Zero-carbon heating
Building envelope
Variable thermal property
Particle swarm optimization
Thermal diode

\textbf{A B S T R A C T}

Building Integrated Heat Pipes (BIHP), specifically a novel passive solar house integrated with gravity heat pipes, realizes envelopes with variable thermal properties and makes effective and efficient use of solar energy to reach zero-carbon heating, and can greatly improve the indoor thermal environment in winter. In this paper, an efficient method based on particle swarm optimization for the optimization of thermal properties of the BIHP interior envelope is proposed. The key thermal properties of the heat pipe and the exterior and interior envelopes are optimized, and the solar application potential of improving indoor thermal comfort by BIHP in five representative cities of northern China is obtained. The results show that the equivalent thermal conductivity of the heat pipe is suggested to be greater than 2 \times 10^4 W/(m K). The optimal BIHP should have exterior envelopes with high thermal resistance and interior envelopes with large thermal capacity. In the selected areas, the optimal BIHP improves indoor thermal comfort by 36\%–100\% and increases the minimum indoor operative temperature by 5.1–10.5 °C compared to the reference building. BIHP is recommended in areas with the ratio of radiation to temperature difference greater than 5 W/(m\(^2\) K) and can reach zero-carbon heating in Lhasa and Yinchuan. This research provides a global matching and optimization method for the effective and efficient utilization of solar energy to reach zero-carbon heating and evaluates the application potential of BIHP.

© 2022 Elsevier B.V. All rights reserved.

1. Introduction

In China, the energy consumption of building operations accounts for 23\% of the total energy consumption, and the CO\(_2\) emission related to building operations accounts for 22\% of the total CO\(_2\) emissions [1]. The energy used for space heating accounts for 27.0\% of the total operational energy of buildings in urban areas, and 41.5\% in rural areas [2]. Reducing energy consumption for building heating is significant to achieve the goal of carbon peaking and carbon neutrality. The building envelope with variable thermal properties, such as variable thermal conductivity and variable equivalent specific heat, can greatly improve the passive use of natural resources for indoor heating [3], and it is an important means to reduce building energy consumption and create a comfortable indoor thermal environment [4,5]. Thus, building envelopes with variable thermal conductivity and heat storage are listed as two grand thermal energy utilization challenges for building energy saving and decarbonization [6].

The building envelope, as a vital component for heat storage and release, plays an important role in building thermal performance. Thermal properties of the building envelope greatly affect its heat transfer characteristics and building energy consumption [7]. Many studies have been conducted on the optimization of the thermal properties of opaque building envelopes for energy conservation, mainly focusing on optimizing the thermal resistance and thermal capacitance, which are widely recognized as two effective measures to improve the thermal performance of building envelopes [8]. The optimization of the thermal performance of building envelopes involves many influencing factors, such as meteorological parameters, indoor demands, and thermal properties of envelope materials. The influences of each factor on the heat transfer process are coupled, so the algorithm is required to be strong in global optimization. The particle swarm optimization (PSO) algorithm is a heuristic optimization algorithm based on information shared within the group and is often used in the optimization of the thermal properties of the building envelope [9].

The exterior envelope is the separation between indoor and outdoor environments, and optimizing the thermal properties is of great significance for reducing building energy consumption and improving indoor thermal comfort. Cheng et al. [10] used var-
ious optimization methods including the PSO method to determine the optimized specific heat distribution of the exterior brick wall with nonlinear thermal properties. Yang et al. [11] used an inverse optimization method based on PSO for determining the optimal thermal resistance and capacitance allocation of the exterior wall that minimizes the heat flux through. Himmetoglu et al. [12] proposed a model based on PSO and ant colony optimization to find the optimal exterior envelope combinations that provide minimum thermal energy consumption. Bamdad et al. [13] considered four optimization algorithms, including the PSO, the ant colony optimization, the Nelder-Mead algorithm, and the hybrid particle swarm optimization and Hooke-Jeeves algorithm to optimize a commercial building, and they found that optimization could achieve an additional energy savings of more than 11.4% for a typical commercial building. Lu et al. [14] utilized the classical PSO to optimize various factors that affect building energy consumption including exterior envelope parameters and showed that the energy-saving rate of an optimized rural residence was about 26%–30%. Delgarm et al. [15] used a multi-objective PSO algorithm coupled to a building energy simulation program to enhance the energy performance of a typical room in different climatic regions, and the optimum design led to a 1.6%–11.3% diminution of the total annual building electricity demand. Alvaro [16] optimized a dynamic building envelope for cooling purposes using a PSO algorithm and obtained that the system with optimum design and optimum control achieved a cooling load reduction of 379% in comparison to an ordinary system. These studies showed that the PSO algorithm can search for the optimal variable parameters according to different targets, and is well adapted for optimizing the thermal properties of building exterior envelopes. However, most studies focused on the optimization of the thermal properties of the exterior envelope, while few were on the interior envelope of the building. The interior envelope with appropriate thermal properties is essential and should not be ignored to create a comfortable indoor thermal environment.

The effect of local climate is crucial in the optimization of the thermal properties of building envelopes. Climatic conditions including outdoor air temperature and solar radiation have great impacts on the local application effect of a thermal design of buildings [17]. The optimal combination of thermal properties of building envelopes and the maximum application effect are different in various climate zones, because of the significant differences in natural resources among them. Zhang et al. [18] obtained the ideal thermophysical properties of the building envelope material in seven climatic regions of China, and the corresponding characteristic temperatures of the ideal thermal mass fell in the temperature ranges of about 18.3–19.3 °C in winter and about 26.5–26.7 °C in summer. Zou et al. [19] conducted a sensitivity analysis to explore the impact of the passive design of envelope construction on the life cycle energy demand in different climate zones of China and found that the building envelope with good thermal performance is conducive to energy saving in areas where heating energy dominates building energy demand. Naji et al. [20] quantified the effects of building envelope parameters on the energy use, thermal comfort, and daylighting levels of a prefabricated house in six climate zones of Australia, and carried out a hierarchical cluster analysis to find similar patterns of sensitivity in different climate zones. Rosti et al. [21] determined the optimal thickness of insulation, energy saving, and payback period for various classic and modern exterior wall structures in eight cities representing all climate regions, and the optimum design led to a 1.6%–11.3% diminution of the total annual building electricity demand.
zones of Iran, and the energy saving was obtained between 12.8 % and 69 %. Sabapathy and Gedupudi [22] proposed recommendations for envelope configuration based on energy and cost savings for five different climatic zones in India, and energy savings in the range of 67 %–96 % are achievable across different climatic zones. Sassine et al. [23] assessed the thermal impact of using lightweight concrete in Lebanese traditional detached building constructions in the four different Lebanese climate zones and demonstrated that the use of lightweight concrete in the vertical walls can reduce the heating needs by up to 9 %. Dervishi et al. [24] applied and examined seven improvement scenarios of the building envelope of traditional residential buildings built in Albania in different climatic zones, and the combination of all the retrofitting measures reduced the energy performance by up to 52.9 %. In these studies, the influence of climatic conditions in different countries and regions on the optimization of thermal properties of building envelopes is taken into consideration. However, there is a lack of a simple evaluation index for the application effect of a certain thermal design in different regions, and the application potential assessment usually relies on complex simulation calculations, which hinders the widespread practice of the technology. The use of an easily accessible index, which is based on local climatic conditions and can appropriately reflect the application effect of the building thermal design, has important guiding significance for the prediction and potential assessment in different regions and climate zones.

Solar energy resources are abundant in China [25], and could serve as an important energy supply for building indoor heating to replace the fossil energy. Solar radiation is a time-dependent energy source with intermittent and variable characteristics, and the traditional way of solar energy usage in buildings has the problem of inadequate utilization and low efficiency [26]. Gong et al. [27] recently proposed a novel passive solar house integrated with flat gravity heat pipes, which is called the heat pipe house. The heat pipe house takes advantage of ultrahigh thermal conductivity and the thermal diode characteristic of the heat pipe to realize the variable thermal conductivity of the envelope, as well as the heat capacity of the interior envelope. The heat pipe house transfers and stores the solar energy that is absorbed on the outer surface of the exterior envelope during the daytime and releases heat indoors at night, thus improving the utilization efficiency of solar energy for indoor heating by building envelopes. The simulation results showed that the average indoor operative temperature of the heat pipe house reached 16.7 °C during January in Beijing and was 6.8 °C higher than that of a reference house. The heat pipe house put forward a new way for buildings to use solar energy to completely meet the heating needs and passively achieve zero-carbon heating. Kou et al. [28] experimentally studied a real-scale lightweight heat pipe house with variable thermal properties and found that the heat pipe house integrated with heat storage materials greatly increased the effective proportion of solar energy for indoor heating from 8.7 % to 57.5 %. He et al. [29] proposed a hybrid model combining multivariate regression modeling and machine learning modeling for the rapid prediction of interior temperatures affected by heat pipe thermal diodes and solar cavities based on experimental data. In brief, the heat pipe house provides a new idea of solar heat utilization as a form of building integrated heat pipes (BIHP). The thermal properties of the heat pipe and the exterior and interior envelopes play a very important role in the practical application of BIHP, and the optimal combination of thermal properties of BIHP and its best effect varies in regions with different climatic conditions. However, the above studies only analyzed the benefits of BIHP with given thermal properties in Beijing and did not research the overall optimization of thermal properties of the building envelope and the solar application potential evaluation of BIHP in different regions.

In the present study, an efficient method based on PSO for the optimization of thermal properties of the BIHP interior envelope is proposed, and the impacts of key thermal properties of the heat pipe and the exterior and interior envelopes on the application effect of BIHP are analyzed. The optimal thermal properties of building envelopes and solar application potential of improving indoor thermal comfort by BIHP in different areas of northern China are obtained. The research framework is shown in Fig. 1. Previous research developed and validated numerical models (Part A), and this paper focuses on Parts B and C. This research aims to take the characteristics of climatic conditions into consideration and provide a global matching and optimization method for the effective and efficient utilization of solar energy to reach zero-carbon heating, and evaluate the application potential of solar energy by BIHP.

2. Model and methodology

2.1. Physical model

This paper focuses on BIHP, specifically a novel passive solar house integrated with flat gravity heat pipes. The structure and working principle of BIHP are shown in Fig. 2. The application of BIHP is not restricted by its orientation, and a south-facing building makes better use of solar radiation resources. The structure of a typical BIHP includes a glazing cover, a south external wall, an internal wall, and flat gravity heat pipes with a heat-collecting surface. The 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 fluid flow by gravity. The evaporator section is laid on the outer surface of the exterior wall and the condenser section is embedded inside the interior wall. The working principle of BIHP is as follows. During the daytime, the heat-collecting surface absorbs solar energy and heats up. The liquid working medium at the evaporator section absorbs heat from the heat-collecting surface and evaporates, and then the vapor flows to the condenser section embedded in the interior wall and condenses and releases heat there. Because of the height difference between the evaporator and condenser sections, the liquid working medium then returns to the evaporator section by gravity, and the cycle repeats. The heat pipes show ultra-high equivalent thermal conductivity in this process. During the nighttime, without solar radiation as the heat source, the condensed liquid working medium stays in the evaporator section and the heat transfer process of the heat pipe could be ignored. Because of this thermal diode characteristic of the gravity heat pipe, the heat loss from the indoor to the outdoor environment can be avoided. For the simulation of the above thermal process in BIHP, a numerical model was developed in the MATLAB environment and the reliability of the model was validated by experiments [27]. This study is based on the BIHP numerical model.

2.2. Analysis and evaluation parameters

The external wall combined with gravity heat pipes is the core component of the envelope with variable thermal conductivity in BIHP. Characteristics of the heat-collecting surface and time-varying equivalent thermal conductivity of the heat pipe are key thermal properties, which greatly affect the application benefits of BIHP from the perspective of heat collection and conduction.

The heat-collecting surface is the starting point for buildings to utilize solar radiation. The main heat-collecting surface of BIHP is the surface on the evaporation section of the heat pipes, while the main heat-collecting surface of the reference building (RB,
Fig. 1. Framework of the present study.

Fig. 2. Schematic diagram of (a) the structure and (b) the working principle of BIHP [27].
the building in the same structure as BIHP but without the heat pipe) is the outer surface of the external wall. Absorptivity $\alpha$ and emissivity $\varepsilon$ of the heat-collecting surface are important thermal properties. Besides, the thermal insulation performance of the external wall also significantly affects the heating effect of BIHP.

The equivalent thermal conductivity $k_e$ represents the apparent heat transfer performance of the heat pipe at a given size and temperature difference and lays the foundation of available heat into the indoor environment in BIHP. The value of $k_e$ can reach the order of $10^4$ W/(m·K) [30]. The $k_e$ of the heat pipe can be expressed as [31].

$$k_e = \frac{q_{HP} l_{HP}}{A_{sec}(T_{eva} - T_{con})} \quad (1)$$

where, $q_{HP}$ is the heat conducted by the heat pipe, W; $l_{HP}$ is the effective length of the heat pipe, m; $A_{sec}$ is the sectional area of the heat pipe, m$^2$; $T_{eva}$ and $T_{con}$ are the temperatures of the evaporator and condenser sections of the heat pipe, respectively, °C.

The area ratio of the condenser section at the interior wall $a_{HP}$ refers to the ratio of the surface area of the interior wall embedded with the condenser section of heat pipes to the inner surface area of the interior wall. It represents the proportion of the whole interior wall that can be used as a heating terminal. It is defined as [31].

$$a_{HP} = \frac{A_{wall,con,inn}}{A_{wall,inn}} \quad (2)$$

where, $A_{wall,con,inn}$ is the surface area of the wall embedded with the condenser section of heat pipes, m$^2$; $A_{wall,inn}$ is the inner surface area of the interior wall, m$^2$.

The three parameters in the optimization of the interior envelope include the thermal conductivity $\lambda$ and the volumetric specific heat capacity $\rho C_p$, and the embedding depth ratio of the heat pipe $\beta$. The heat transfer between two adjacent rooms is ignored, and the middle of the interior wall is treated as an adiabatic surface, as shown in Fig. 3. The embedding depth ratio of the heat pipe $\beta$ represents the depth of the embedding position from the inner surface of the interior wall and is defined as follows. The value of $\beta$ ranges from 0 to 1, with higher values indicating the heat pipes are embedded closer to the indoor environment.

$$\beta = 1 - 2 \frac{d_{HP}}{d_{wall}} \quad (3)$$

where, $d_{HP}$ is the depth of the embedding position from the inner surface of the interior wall, m; $d_{wall}$ is the thickness of the interior wall, m.

The indoor operative temperature $T_{op}$ is used to evaluate indoor thermal comfort. The operative temperature reflects the combined effect of the indoor air temperature and the mean radiant temperature of the inside surfaces of building envelopes. $T_{op}$ is defined as follows:

$$T_{op} = \frac{h_i T_i + h_r T_r}{h_i + h_r} \quad (4)$$

where, $h_i$ and $h_r$ are the convective and the radiative heat transfer coefficients, respectively, W/(m$^2$·K); $T_i$ is the indoor air temperature, °C; $T_r$ is the mean radiant temperature, °C, which can be calculated by the area-weighted average of the inner surface temperature of each building envelope as follows:

$$T_r = \frac{\sum_{j=1}^{6} A_j T_{wall,inn,j} + A_{win} T_{win}}{\sum_{j=1}^{6} A_j + A_{win}} \quad (5)$$

where, $A_j$ is the inner surface area of wall $j$, m$^2$; $T_{wall,inn,j}$ is the inner surface temperature of wall $j$, °C; $A_{win}$ is the area of the window, m$^2$; $T_{win}$ is the inner surface temperature of the window, °C.

The average indoor operative temperature $T_{op,ave}$ represents the overall temperature level of the indoor thermal environment in a period, and the daily range of indoor operative temperature $T_{op,dr}$ defined as follows represents the fluctuation of the indoor operative temperature in a day. The ideal indoor thermal environment in winter should be with a high average indoor operative temperature and a small daily range [32].

$$T_{op,dr} = T_{op,max} - T_{op,min} \quad (6)$$

where, $T_{op,max}$ and $T_{op,min}$ are the maximum and minimum values of indoor operative temperature in a day, respectively, °C.

The integrated discomfort degree of cold IDDc describes the combined effects of the degree and duration of indoor thermal discomfort caused by indoor operative temperature below the lower limit of the thermal comfort zone and is proportional to the heat load of the building [33]. IDDc during the whole heating season is defined as

$$IDDc = \int_{T_L}^{T_{op}} (T_L - T_{op}) d\tau, \ T_{op} < T_L \quad (7)$$

where, $T_L$ is the lower limit temperature of the thermal comfort zone, °C; $\tau$ is the time of the heating season, h. The temperatures when predicted mean vote PMV equals −1 and 1 are taken as the lower limit temperature $T_L$ and upper limit temperature $T_u$ of the thermal comfort zone, which are set as 18 °C and 28.4 °C, respectively [34].

The improvement degree of thermal discomfort IDTD is proposed as the evaluation index of the improvement degree of the indoor thermal environment by BIHP compared with the reference building, and is defined as follows. The value of $IDTD$ ranges from 0 to 1, with higher values indicating greater improvement of the indoor thermal environment.

$$IDTD = \frac{IDDc_{RB} - IDDc_{BIHP}}{IDDc_{RB}} \quad (8)$$

where, $IDDc_{RB}$ and $IDDc_{BIHP}$ are the integrated discomfort degrees of cold of the reference building and BIHP, respectively, K.h.

The ratio of radiation to temperature difference RRTD is the ratio of the local solar radiation intensity to the temperature difference between indoor and outdoor air temperatures [35], which
reflects the maximum potential contribution of solar radiation resources in a built indoor environment with a certain temperature difference at the local outdoor temperature level. The total size of the particle group is preset to 20 for time and cost ing the heating season, \( W/m^2 \)objection, \( T_{\text{ave}} \) is the calculation temperature for indoor heating, \( ^\circ\text{C} \); \( T_{\text{ave}} \) is the average outdoor air temperature during the heating season, \( ^\circ\text{C} \).

### 2.3. Particle swarm optimization algorithm

Different from conventional optimizations of the building envelope which only focus on thermal resistance and thermal capacity, the parameters of the interior wall of BIHP include the embedding depth ratio of the condenser section. Various matching combinations of these three variables lead to different heating effects of BIHP, and the optimal combination for indoor thermal comfort is different for diverse climatic conditions. High \( \lambda \) means that solar energy is more easily transferred to the indoor surface of the interior wall from the heat pipe, which is conducive to the indoor temperature rise during the daytime, but the heat storage of the wall is less, thus affecting the indoor thermal comfort at night. Large \( \rho_c \) means stronger heat storage capacity of the interior wall and is conducive to indoor thermal comfort at night and under continuous adverse weather conditions. But at the same time, the proportion of heat transferred indoors during the daytime would be less, restricting the temperature rise during the daytime. The embedding depth ratio of the heat pipe \( \beta \) represents the embedding position of the heat pipe in the interior wall, and the closer to the inner surface the embedding position is, the more favorable it is to release heat to the indoor environment during the daytime.

The proposed method based on PSO for the three-parameter optimization of the BIHP interior envelope can carry out global optimization by considering multiple variables simultaneously, which costs less computation and time than the exhaustive search method. \( \lambda, \rho_c, \beta \) are independent variables in the optimization. The three variables with value ranges form a closed three-dimensional space, in which a spatial coordinate (i.e., the position of a searching particle) is used to characterize a combination of the thermal properties of the BIHP interior wall. For example, the position of particle \( i \) at iteration \( n \) is recorded as

\[
\chi_i^n = (\lambda_i^n, \rho_c p_i^n, \beta_i^n), \quad i = 1, 2, ..., 20, \quad n = 1, 2, ..., 30
\]

where \( i \) is the particle number and \( n \) is the current iteration number. The total size of the particle group is preset to 20 for time and cost considerations, and the total iteration number is preset to 30 for convergence considerations.

The particle has a searching velocity on each variable dimension during the optimization process, and the velocity of particle \( i \) at iteration \( n \) is recorded as

\[
V_i^n = (\lambda_i^n, \rho_c p_i^n, \beta_i^n), \quad i = 1, 2, ..., 20, \quad n = 1, 2, ..., 30
\]

The fitness is the target parameter of particle swarm optimization, and in the present study is the integrated discomfort degrees of cold. The calculation process is as follows. Firstly, uniform random position and velocity parameters of the particle population are initialized. In each iteration, the verified BIHP numerical model is used to simulate the thermal process of the BIHP with the current combination of thermal properties of the envelope and obtain the IDDc value. Two minimum values of IDDc are tracked in each iteration to update the particle information. One is the minimum in the iteration history of each particle, recorded as the personal best IDDc\( \beta \), and the other is the minimum in the whole space in the whole iteration history, recorded as the global best IDDc\( \beta \). The position information of the personal best of particle \( i \) and the global best is recorded as \( \chi_i^n = (\lambda_i^n, \rho_c p_i^n, \beta_i^n) \) and \( \chi^g = (\lambda^g, \rho_c p^g, \beta^g) \), respectively. Then the velocity and position of each particle are updated, which are limited by the given value ranges:

\[
V_i^{n+1} = V_i^n + c_1 random_1(\chi_i^n - \chi_i^g) + c_2 random_2(\chi^g - \chi_i^n)
\]

The first part indicates the tendency of the particle to move in the direction of the previous iteration. The weight of the inertia factor linearly reducing in the iteration is introduced to improve the algorithm:

\[
w^f = W_{\text{max}} - (W_{\text{max}} - W_{\text{min}})n/N_{\text{max}}
\]

The second and third parts indicate the particle is attracted by the personal best and the global best, respectively. Learning factors \( c_1 \) and \( c_2 \) are preset to 2.

Then the position of each particle is updated and the next iteration is carried out. The algorithm exits and outputs the recorded global best value when the maximum number of iterations is reached. Fig. 4 shows the flowchart of the proposed optimization approach.

### 3. Results and discussion

#### 3.1. Simulation settings

According to climate zoning of passive solar heating in China [36], five representative cities of northern China from five different passive solar heating climate zones are selected in this study, which are Lhasa, Yinchuan, Beijing, Shenyang, and Harbin, as shown in Fig. 5. Relevant information of the selected cities is shown in Table 1. The climate data including outdoor air temperature and solar radiation intensity is obtained from the building energy simulation software DeST.

A south-facing middle top-floor room in a multi-layer BIHP is considered the typical room in the present study, as shown in Fig. 6. The west wall, east wall, and the floor are interior envelopes and the neighbor heat transfer can be ignored. The size of the room is 4 m (length) \( \times \) 3 m (width) \( \times \) 3 m (height), and the window-wall ratio is 0.3. The air change per hour is set to 0.5 when the indoor operative temperature is below 26 °C and 5.0 when the operative temperature exceeds 26 °C. The building envelopes meet the thermal design requirements of corresponding building climate zones in China [37]. Table 2 lists the thermal properties of the component materials of the building envelopes. The value ranges of the three parameters in the optimization of the interior envelope are obtained according to the thermal properties of conventional building materials [38]. The initial setting of the BIHP is that the east and west interior walls are made of concrete hollow blocks, and the heat pipe is embedded in the middle position between the inner surface and theadiabatic surface of the interior wall, as shown in Table 3.

The research process is as follows based on the above settings:

1. The impacts of characteristics of the heat-collecting surface, equivalent thermal conductivity of the heat pipe, heat transfer coefficient of the exterior wall, and area ratio of the con-

\[\text{IDDc} = \begin{cases} \lambda, & \text{if } \text{IDDc} < 12 \\ \rho_c p, & \text{if } 12 < \text{IDDc} < 20 \\ \beta, & \text{if } \text{IDDc} > 20 \end{cases}\]
denser section on the heating effect of BIHP are explored, and the thermal design principle of the above factors are obtained (taking Beijing as an example).

(2) Based on the thermal design principle determined in the first part, the proposed algorithm is used to optimize the design of the BIHP interior envelope in Beijing, and the optimal
combination of thermal properties and indoor operative temperatures of the reference building and the BIHP before and after optimization are obtained.

(3) Furthermore, the thermal properties of the BIHP interior envelope are optimized in the selected cities of northern China, and the application potentials of reducing IDDc and raising $\text{Top}_{\text{ave}}$ in these areas are pointed out, then the relationship between $\text{IDTD}$ and $\text{RRTD}$ is obtained.

### Table 1

Climatic characteristics of the selected cities.

<table>
<thead>
<tr>
<th>City</th>
<th>Heating season period</th>
<th>$Q_{\text{solar,ave}}$ (W/m²)</th>
<th>$T_{\text{out,ave}}$ (°C)</th>
<th>$\text{RRTD}_2$ (W/(m²·K))</th>
<th>Passive solar heating climate zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lhasa</td>
<td>Nov. 15th– Mar. 15th</td>
<td>257.7</td>
<td>0.8</td>
<td>14.97</td>
<td>Best A</td>
</tr>
<tr>
<td>Yinchuan</td>
<td>Nov. 1st– Mar. 31st</td>
<td>178.8</td>
<td>−1.6</td>
<td>9.11</td>
<td>Suitable A</td>
</tr>
<tr>
<td>Beijing</td>
<td>Nov. 15th– Mar. 15th</td>
<td>162.1</td>
<td>0.1</td>
<td>9.07</td>
<td>Suitable C</td>
</tr>
<tr>
<td>Shenyang</td>
<td>Nov. 1st– Mar. 31st</td>
<td>108.4</td>
<td>−4.5</td>
<td>4.81</td>
<td>Ordinary</td>
</tr>
<tr>
<td>Harbin</td>
<td>Oct. 20th– Apr. 20th</td>
<td>111.4</td>
<td>−9.0</td>
<td>4.13</td>
<td>Unfavorable</td>
</tr>
</tbody>
</table>

### Table 2

Thermal properties of the component materials [39].

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda$ (W/(m·K))</th>
<th>$\rho$ (kg/m³)</th>
<th>$c_p$ (J/(kg·K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete hollow block</td>
<td>0.44</td>
<td>1100</td>
<td>1050</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.74</td>
<td>2500</td>
<td>920</td>
</tr>
<tr>
<td>Brick</td>
<td>0.43</td>
<td>1800</td>
<td>750</td>
</tr>
<tr>
<td>PU insulation</td>
<td>0.03</td>
<td>45</td>
<td>1720</td>
</tr>
</tbody>
</table>

### Table 3

Parameters in the optimization of the interior envelope.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Value range</th>
<th>Initial value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>W/(m·K)</td>
<td>0.03–3.50</td>
<td>0.44</td>
</tr>
<tr>
<td>$\rho c_p$</td>
<td>MJ/(m³·K)</td>
<td>0.05–3.50</td>
<td>1.16</td>
</tr>
<tr>
<td>$\beta$</td>
<td>/</td>
<td>0.00–1.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>

### 3.2. Thermal properties of the heat pipe

#### 3.2.1. Absorptivity and emissivity of the heat-collecting surface

December 22nd (winter solstice) is chosen as the typical day for analysis. The absorptivity of the heat-collecting surface $\alpha$ determines the amount of absorbed heat under solar radiation. Fig. 7(a) shows that as $\alpha$ increases from 0.1 to 0.9, the average indoor operative temperature of BIHP $T_{\text{op,ave,BIHP}}$ and that of the reference building $T_{\text{op,ave,RB}}$ increase from 7.3 °C to 19.6 °C and 11.6 °C, respectively. The $\alpha$ has a greater impact on the indoor heating effect of BIHP compared to the reference building. This is because transferring a large amount of solar heat to the indoor environment is the guarantee of the heating effect of BIHP, and this com-

![Fig. 6. Diagram of the south-facing middle top-floor room in a multi-layer BIHP [27].](image)

![Fig. 7. Indoor operative temperatures of the BIHP and the reference building with different characteristics of the heat-collecting surface: (a) absorptivity and (b) emissivity.](image)
3.2.2. Equivalent thermal conductivity of the heat pipe

Fig. 8 shows that $T_{\text{op,ave,BIHP}}$ increases with the increase of the equivalent thermal conductivity of heat pipe $k_e$. As $k_e$ increases from $1 \times 10^3 \text{ W/(m·K)}$ to $2 \times 10^4 \text{ W/(m·K)}$, $T_{\text{op,ave,BIHP}}$ increases significantly from $12.6 \text{ °C}$ to $19.0 \text{ °C}$. $k_e$ further increases to $1 \times 10^5 \text{ W/(m·K)}$, and $T_{\text{op,ave,BIHP}}$ increases to $20.5 \text{ °C}$ by only 1.5 °C. The results indicate that the increase of $k_e$ can help to transfer more absorbed solar radiation heat into the interior wall and improve the indoor environment, but when $k_e$ is greater than $2 \times 10^4 \text{ W/(m·K)}$, the improvement of heat transfer performance of the heat pipe shows an obvious marginal decreasing effect on the benefits of average indoor operative temperature. The reason is that the equivalent thermal conductivity of heat pipe is ultrahigh compared to that of other conventional building materials. In the whole heat transfer process from the heat-collecting surface to the indoor environment, the benefit of ameliorating a single local section to the overall thermal process is restricted by other heat transfer sections. In general, it is recommended that $k_e$ of the heat pipe in BIHP is greater than $2 \times 10^4 \text{ W/(m·K)}$.

3.3. Heat transfer coefficient of the exterior wall

Fig. 9 shows $T_{\text{op,ave}}$ and $T_{\text{op,min}}$ of the BIHP and the reference building with different heat transfer coefficients of exterior walls $K_{\text{wall,ext}}$. (South wall and north wall). For the BIHP, the heat transfer coefficients of external walls decrease from 0.45 W/(m²·K) to 0.25 W/(m²·K), and the $T_{\text{op,ave,BIHP}}$ increases from 20.0 °C to 21.9 °C and $T_{\text{op,min,BIHP}}$ increases from 18.1 °C to 20.0 °C. For the reference building, the $T_{\text{op,ave,BIHP}}$ increases from 10.8 °C to 12.0 °C and $T_{\text{op,min,BIHP}}$ increases from 9.4 °C to 10.7 °C. Since the heat pipe introduces a large amount of solar heat into the interior wall, BIHP greatly alleviates heat loss to the outdoor environment than the reference building. The south exterior wall of traditional solar houses plays an integrated role in heat collection, storage, and release, but these multiple functions are decoupled for the exterior wall of BIHP, which only needs to undertake the thermal insulation function. Thus, the exterior wall of BIHP should be of low heat transfer coefficient to reduce heat loss.

3.4. Thermal properties of the interior wall

3.4.1. Area ratio of the condenser section at the interior wall

The maximum value of $a_{\text{HP}}$ is 0.7 for the typical building in the present study. Fig. 10 shows that with the increase of $a_{\text{HP}}$ from 0.3...
to 0.7, Topave,BIHP increases from 17.6 °C to 19.6 °C, and Ttop.tr,BIHP increases slightly from 5.5 °C to 5.8 °C. This indicates that extending or broadening the condenser section of the heat pipe in BIHP can effectively increase the area of the heat release terminal, thus improving the heat storage and release in solar utilization and the heating effect is better. The increase of αHP improves the indoor operative temperature level as a whole, and the maximum and minimum temperatures increase almost equally, so the daily range does not increase significantly.

3.4.2. Three-parameter optimization of the interior wall

The impacts of the above factors are analyzed by the controlled variable method, and in the following, the proposed method based on PSO is used to optimize the λ, ρcp, and β of the interior wall. See Table 3 for relevant parameter settings. According to the above analyses, the optimization of thermal properties of the interior wall is based on settings as follows: black paint (α = 0.9, ε = 0.9) as the heat-collecting surface, equivalent thermal conductivity of the heat pipe equals 2 × 10^4 W/(m·K) and the area ratio of the condenser section equals 0.7.

The optimization process is shown in Fig. 11, taking Beijing as an example. All particles are uniformly and randomly distributed throughout the whole spatial coordinate in the initialization, and 6 out of 20 particles are selected to show search trajectories. Although these particles have different initial positions and approach the optimal coordinate via different paths, they all finally reach locations near the optimal coordinate, which corresponds to the optimal design of the thermal properties of the interior wall. The global optimal solution gradually converges and remains stable after about 10 iterations, indicating the reliability of the proposed algorithm in searching global optimal solution. The whole calculation process costs only about 8 h on a common laptop, while the traditional exhaustive search method takes about 363 h.
calculation time of the proposed algorithm for the optimization of thermal properties of the interior wall is about 2.2% of that of the traditional exhaustive search, which indicates the high efficiency of the proposed method in searching the global optimum.

The optimal property values and the fitness in the whole iteration process are shown in Fig. 12, which can be divided into two stages. In the first 10 iterations, the optimal $\lambda$ fluctuates around 2.8 W/(m·K) and then rises to the upper limit which is 3.5 W/(m·K), the optimal $\rho C_p$ rises quickly to the upper limit of 3.5 MJ/(m$^3$·K), and the optimal $\beta$ fluctuates greatly between 0.58 and 0.65. In the subsequent iterations, the optimal $\lambda$ and $\rho C_p$ stay unchanged at the upper limit, while the optimal $\beta$ remains stable near 0.65. Therefore, the optimal combination of thermal properties of the interior wall is $(\lambda = 3.5 \text{ W/(m·K)}, \rho C_p = 3.5 \text{ MJ/(m}^3\text{·K)}, \beta = 0.65)$ in this case. $\text{IDDc}_{\text{min}}$ decreases significantly after the first 2 iterations, corresponding to the sharp increase of the optimal $\rho C_p$, and then decreases gradually and stabilizes at the minimum value of 1683 K·h, which is the best utilization achieved by BIHP in Beijing after optimizing thermal properties.

Fig. 13(a) shows the indoor operative temperature curves of initial non-optimized BIHP (subscript INI), optimized BIHP (subscript OPT), and the original building (subscript RB). The curves are plotted for the whole heating season and three days around the winter solstice in Beijing. Fig. 13(b) presents the indoor operative temperature curves for different buildings, including Harbin, Shenyang, Beijing, Yinchuan, Lhasa, and City (\(\Lambda\rho C_p\beta\)).
OPT), and the reference building, as well as outdoor air temperature and solar radiation during the whole heating season in Beijing. The yellow shadow represents the thermal comfort temperature zone. For the reference building, the $T_{op, RB}$ (green line) is obviously low due to the lack of heat pipes to introduce solar radiation heat into the room, and the average value during the whole heating season is only 13.7 °C. Especially in January, the coldest time of the year, $T_{op, RB}$ is between 0 °C and 10 °C and far below the lower limit of the thermal comfort zone (18 °C). For the initial BIHP, the $T_{op, INI}$ (blue line) could be greatly increased by introducing solar heat indoors through the heat pipe and the average value is 20.4 °C, which is 6.7 °C higher than that of the reference building. However, when overcast weather with low solar radiation occurs for several consecutive days, such as in mid-December and mid-January when solar radiation is significantly low, $T_{op, INI}$ is dramatically reduced and even to the same temperature level of the reference building around January 14th (pink circle), because the initial non-optimized envelope cannot provide sufficient heat storage to ensure continuous indoor heating. For the optimized BIHP, due to the enhanced heat storage capacity of the envelope, more solar heat can be stored in periods of intense solar radiation and released indoors to meet the heating demand under continuous overcast conditions. With an average value of 22.1 °C, $T_{op, OPT}$ (red line) is basically within the comfort zone during the whole heating season. $T_{op, OPT}$ is obviously lower than the comfort zone only in the middle of January, but still significantly higher than $T_{op, RB}$ and $T_{op, INI}$ at the same time. Besides, the indoor operative temperatures of all buildings can be well controlled not to exceed the upper limit of the thermal comfort zone since the ventilation can be increased by opening windows when the temperature is too high. It can be concluded that within the current thermal property range of building materials, BIHP cannot achieve zero-carbon heating in Beijing. As

---

**Fig. 15.** Improvement of $\text{IDDc}$ and $T_{op, \text{min}}$ by the BIHP of the selected cities.
an ideal working condition, the $T_{op}$ of a super large heat capacity BIHP with $\rho c_p$ of 16.0 MJ/(m³·K) is represented in the figure (orange dot line), and the envelope can provide enough heat storage capacity to maintain the $T_{op,\text{ref}}$ not lower than $T_1$ during the whole heating season, so as to realize zero-carbon heating in Beijing. However, the ideal material with such a large heat capacity is not seen in common building materials at present.

Fig. 13(b) shows the indoor operative temperatures of the initial BIHP, optimized BIHP, and the reference building from December 21st – 23rd. The $T_{op}$ increases obviously when solar radiation is sufficient and decreases gradually at night. The heat storage capacity of the optimized BIHP envelope is larger, and it can store more heat transferred from the heat pipe during the daytime, so the daytime temperature rise of the optimized BIHP is not as high as that of the initial BIHP. The stored heat is released indoors after sunset, so the temperature drop at night is much smaller than that of the initial BIHP. The results show that heat storage and release can be enhanced by optimizing the thermal properties of the interior wall, thus the indoor thermal environment is effectively improved.

The optimization results of thermal properties of the BIHP interior envelope in five cities are shown in Fig. 14. For Beijing, Yinchuan, Shenyang, and Harbin, the optimal results correspond to the maximum $\lambda$ and $\rho c_p$ within the given ranges, indicating that the interior envelope should have high thermal conductivity and large heat storage capacity in these areas. High thermal conductivity means that the heat transferred by the condenser section of the heat pipe can be easily brought into the indoor environment during the daytime, maintaining daytime room temperature within the comfort zone. Large heat storage capacity means that the interior envelope can store as much heat as possible during periods of abundant solar radiation to ensure indoor thermal comfort at night and in the case of continuous adverse weather conditions. The optimal $\beta$ of Yinchuan is smaller than that of the other three cities, that is, the condenser section of the heat pipe is embedded further from the inner surface by the indoor side of the interior wall. This is because Yinchuan has better solar radiation resources and less continuous adverse weather, and a higher proportion of the interior thermal mass could be used for heat storage. But for other cities, the main goal is to release the heat indoors as much as possible to raise the temperature rather than store the heat, so it is necessary to embed the condenser section of the heat pipe closer to the indoor environment. In addition, for Lhasa with the best solar radiation resources, the optimal target could be achieved though the optimal $\lambda$ and $\rho c_p$ of the interior envelope are much smaller than other areas.

Fig. 15 shows the $IDDC_{\text{initial}}$ and $T_{op,\text{min}}$ of the reference building, initial BIHP, and optimized BIHP of the five selected cities. It can be seen that BIHP can significantly reduce $IDDC$ and raise $T_{op,\text{min}}$ compared with the reference building, and can be further improved after optimizing the thermal properties of the interior envelope. In Beijing, the $IDDC$ of the reference building is 14016.3 K·h, and $IDDC$ of the initial BIHP can be greatly reduced to 3480.1 K·h, and is further reduced to 1682.6 K·h by the optimized BIHP. The $T_{op,\text{min}}$ of the reference building is $-0.5\,^\circ\mathrm{C}$, and $T_{op,\text{min}}$ of the initial BIHP is raised to 1.2 $^\circ\mathrm{C}$, and is further raised to 6.0 $^\circ\mathrm{C}$ by the optimized BIHP. BIHP could not completely meet the indoor thermal comfort in a passive way due to the continuous adverse weather conditions in the middle of January based on the analyses before. In Lhasa, because of the strong solar radiation on the south façade, the indoor thermal comfort of the reference building is good enough, while BIHP can reduce $IDDC$ to 0 and raise $T_{op,\text{min}}$ from 13.6 $^\circ\mathrm{C}$ to 17.3 $^\circ\mathrm{C}$ by initial BIHP and to 19.1 $^\circ\mathrm{C}$ by optimized BIHP. This indicates that BIHP can reach zero-carbon heating in Lhasa and requires no extra energy input to ensure indoor thermal comfort during the whole heating season. The results are similar in Yinchuan. The $IDDC$ is greatly reduced from 17848.0 K·h to 2083.5 K·h by initial BIHP and 172.6 K·h by optimized BIHP, and $T_{op,\text{min}}$ is raised from $-4.8\,^\circ\mathrm{C}$ to 10.3 $^\circ\mathrm{C}$ by initial BIHP and 15.2 $^\circ\mathrm{C}$ by optimized BIHP, indicating that zero-carbon heating is basically reached there. The results show that BIHP has good solar application potentials in Lhasa, Yinchuan, and Beijing, which can significantly improve indoor thermal comfort by solar radiation utilization, and the effect is further improved by optimizing the thermal properties of the interior envelope. On the other hand, for Shenyang and Harbin with relatively weak solar radiation resources, although the $IDDC$ can be significantly reduced by initial BIHP and can be further reduced by about 4000 K·h after optimizing the interior envelope, the remaining undercooling discomfort still needs additional energy input to compensate. The optimized BIHP is able to increase $T_{op,\text{min}}$ from $-5.8\,^\circ\mathrm{C}$ of the reference building to 0.3 $^\circ\mathrm{C}$ in Shenyang and from $-14.4\,^\circ\mathrm{C}$ to $-9.4\,^\circ\mathrm{C}$ in Harbin. However, the improved indoor thermal environment is still far lower than the thermal comfort zone, and more measures need to be taken to improve the indoor thermal environment.

Fig. 16 shows the $IDDC$ of BIHP in the selected cities. The $IDDC$ of BIHP are more than 30 % in all areas and are almost 100 % in Lhasa and Yinchuan. As an indicator that can reflect the local solar resource abundance and the application effect of traditional passive building solar technologies of the region, $RRTD_{\text{opt}}$ is also shown in the figure. It can be seen that $RRTD_{\text{opt}}$ is positively correlated with $IDDC$, suggesting that $RRTD_{\text{opt}}$ can be used to evaluate the solar application potential by BIHP to improve the indoor thermal environment in local climatic conditions in the early design stage. Since Yinchuan has few consecutive adverse weather conditions during the heating season, BIHP can significantly improve $IDDC$ in Yinchuan compared with Beijing though $RRTD_{\text{opt}}$ of Yinchuan is only slightly higher than that of Beijing. BIHP improves indoor thermal discomfort dramatically by introducing large amounts of solar heat indoors in areas with high $RRTD_{\text{opt}}$. In the selected cities, it can be concluded that BIHP is recommended in areas with $RRTD_{\text{opt}}$, higher than 5 W/(m²·K).

4. Conclusions

In the present study, the parametric analysis and optimization principle of the heat pipe and exterior envelope of BIHP are explored, and an efficient method based on PSO for the optimization of thermal properties of the BIHP interior envelope is proposed. The optimal thermal properties of the BIHP interior envelope in five cities of northern China are obtained, and the solar
application potentials by BIHP in improving the indoor thermal environment in different areas are pointed out.

The main results are as follows:

(1) In the practical application of BIHP, the heat-collecting surface should be of high absorptivity and low emissivity, with high absorptivity preferred, and the average indoor operative temperature of BIHP with black paint as the heat-collecting surface in Beijing is 8.0 °C higher than that of the reference building painted with black paint.

(2) The equivalent thermal conductivity of the heat pipe is suggested to be greater than 2 × 10^{-5} \text{W/(m·K)}, and a large area ratio of the condenser section is beneficial to increase the average indoor operative temperature.

(3) The heat transfer coefficient of the external wall should be decreased to reduce heat loss to the outdoor environment.

(4) Compared with the reference building, initial BIHP improves indoor thermal discomfort by at least 30 % and increases the minimum indoor operative temperature by 1.8 °C, while at least 36 % and 5.1 °C for optimized BIHP, respectively.

(5) The ratio of radiation to temperature difference is positively correlated with the improvement of indoor thermal discomfort, and BIHP is recommended in areas with the ratio of radiation to temperature difference higher than 5 W/(m²·K).

(6) BIHP can basically reach zero-carbon heating in Lhasa and Yinchuan.

This paper concentrates on the BIHP of conventional building materials with constant heat capacity, and the BIHP of building materials with variable heat capacity (such as phase change materials) will be investigated in further research.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 52278113).

References


[34] Design code for heating ventilation and air conditioning of civil buildings (GB 50736-2012). Beijing; 2012.


[38] Code for thermal design of civil building (GB50176-2016). Beijing; 2016.