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The resilient design for traditional residential building in Northern Shaanxi of China

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ABSTRACT

The indoor lighting environment and energy consumption is a big issue for traditional residents of Yaodong in Yan'an city in China. In order to promote the living environment of Yaodong, the retrofitted scheme uses passive ecological measures such as natural lighting and attached sunspace to make full use of solar energy during the winter. In summer, facing to the problem of high indoor air temperature, the building uses a wall with thermal insulation and a roof that draws on the traditional residence of Yaodong. In addition, the added windows can improve indoor ventilation and reduce the excessive indoor temperature and humidity in summer. Besides, this design is entirely using renewable energy. In this research, simulation software BESTenergy, Ecotect and RETScreen are used to evaluate the effects of the comprehensive design method for improving indoor lighting, thermal comfort, and annual energy consumption. All of the additional building resilient design will be based on the adaptation to traditional building design and living style of the local people. From the overall analysis of the whole year, these retrofit measures will be conducive to the improvement of indoor lighting and thermal comfort and reduce the energy consumption. It's demonstrated that the resilient house has better adaptability to UHI, compare to local ordinary urban dwellings.

Keywords: Resilient Building Design; Yaodong; Indoor thermal environment; Building Simulation

Introduction

The IPCC's fifth assessment report shows that the surface temperature has increased by 0.12 ℃ per decade for nearly 60 years, which is about twice the temperature increase rate of the past 100 years. Compared with global warming, urban areas have experienced more intense warming, forming UHI with significantly higher urban temperatures than surrounding rural and suburban areas. Shaanxi province is located in a high latitude area of China, which is experiencing hot summers. In 2018, the averaged summer air temperature reached up to 24.7℃, which is 1.2℃ higher than the standard averaged summer air temperature during June to August. Yan'an is located in the hilly and gully region of the Loess Plateau in northern Shaanxi. It belongs to the plateau continental monsoon climate, with the semi-arid region in the north and the semi-humid region in the south. There is a large annual temperature difference and a large daily temperature difference, which is characterized by hot days and cold nights, hot summers and cold winters. The influence of Yan'an urban development on the annual average temperature has appeared since 1993. From 1993 to 2002, the urban impact was lighter, and the annual average temperature contribution rate of heat island effect was 38.1%. From 2003 to 2008, the

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heat island effect was obvious. The temperature increasement is above 1℃, which is close to the UHI of the big city, and the temperature difference (heat island intensity) between Yan'an and the suburbs is gradually increasing. The effect of heat island effect on the temperature of the four seasons is basically the same.

In order to improve the indoor thermal comfort environment, Yan'an residents widely use indoor air condition and heating systems to adjust the indoor environment, resulting in a sharp increase in building energy consumption. Artificial heat source is one of the important reasons for UHI. Reducing building energy consumption and using clean energy to reduce greenhouse gas emissions have a positive effect on UHI mitigation. With the acceleration of urbanization, the intensity of UHI has increased year by year. Therefore, the adaptation of building design to the outdoor climate is becoming to be an important issue. On the other hand, in rural areas of northern Shaanxi in China, many people are still living in traditional Yaodong, which is a traditional residential style. The natural ecological advantages of Yaodong are cultivated land saving, low cost, low technique requirement for construction and high thermal insulation properties, and the disadvantages could be raised such like the lack of safety, waterproof, lighting and ventilation problems. The concept of adaption to local climate conditions and their regional characteristics make Yaodong of high protection value, but as China's urbanization process, many peasants abandoned Yaodong living forms, and new buildings styles are taking it over. The aim is to develop a transformation method for traditional Yaodong in northern Shaanxi to meet the needs of modern life without losing their original ecological nature and further improve its indoor thermal comfort, reduce building energy consumption, and improve its adaptability to the more severe UHI phenomenon that may occur.

Methodology

Determination of building model

In order to analyze whether the resilient design for traditional residential building is superior to most local urban dwellings and improves the shortcomings of traditional Yaodong, including its actual energy consumption and adaptability in UHI, lighting and humidity, two control groups of traditional Yaodong and ordinary urban dwellings with equal areas were set up for simulation and comparative analysis to study their indoor thermal comfort in the same climatic conditions in Yan'an in this research.

The first is a typical traditional Yaodong (model A). A typical three-cave Yaodong was selected as a prototype in Nanniwan Town, Yan'an City. It is oriented from north to south, with three caves and each with a width of 3.5m and a depth of 9m. The total construction area is 94.5m² and the volume is 302.61m³. In addition to the south side wall of the selected Yaodong, the other exterior walls and roof are rammed earth, and the inner walls between the three caves are brick walls of 240mm. The building has only windows on the south wall, and the window material is 6mm double-layer insulating glass. In the simulation, the exterior walls and the roof are regarded as 50cm thick rammed earth, and the U-value of window material is set to 2.7 W/m²K.

The second is a local ordinary single-storey urban dwelling (model B). According to the general practice of urban residence in Yan'an, a single-storey house with the same area and internal space as the traditional three-cave Yaodong is designed. The height of the house is 3.5m and the volume is 330.75m³. It has three windows on the south wall and three windows on the north wall. The window-wall ratio of the south wall is 20.38%. The exterior walls of the house mainly consist of 250mm concrete and 40mmEPS insulation layer. The inner walls are also brick walls of 240mm. The roof consists of 20mm cement board, 40mm EPS insulation layer and 260mm concrete, and the glass is the same as Yaodong.

For the new single-layer resilient house based on Yaodong, the width, depth and area are the same as the former two, with the height of 4m and the volume of 378 m³. On the south side of the building, a sunspace with a depth of 1.5m and a height of 4m is set as a buffer zoon to reduce building energy consumption. The north wall of the building has three small windows for improving the natural daylighting. The window-wall ratio of the north wall is 4.01%. The glass adopts 6mm+12mm+6mm double-layer low-e glass with U-value of 1.72 W/m²K, visible transmittance of 0.74 and solar heat gain coefficient of 0.67. The exterior walls of the building are composed of cement board, 30mm timber board, 40mm polyurethane foam, 30mm timber board and 15mm Plywood from the outside to the inside. The roof of the building is covered with the same material as Yaodong. In the summer, the shading device is introduced on the south side of the building. The software model of the three buildings is shown in Figure 1.

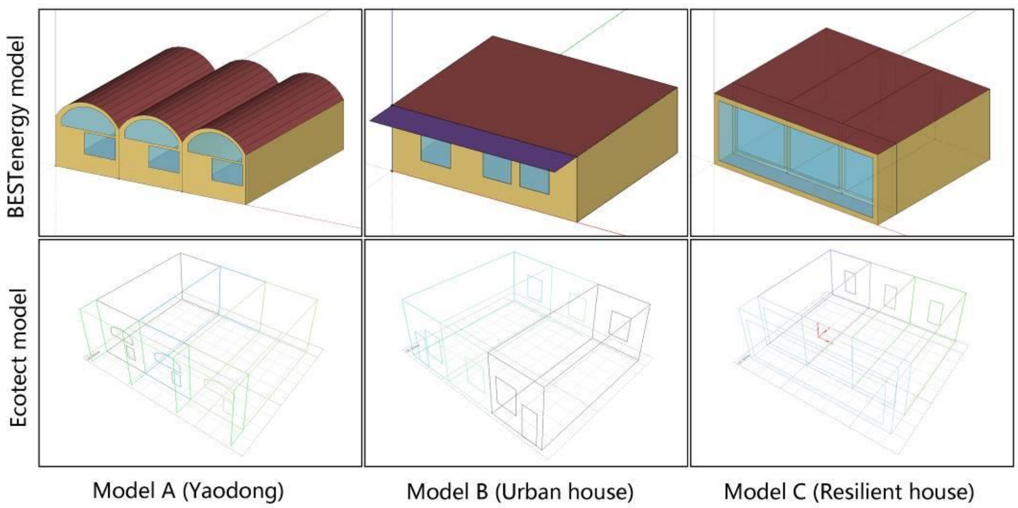


Figure 1. Images of three simulation models.

Simulation software

This research used BESTenergy to simulate building cooling energy demand (CED) and heating energy demand (HED), Ecotect to simulate building lighting and RETScreen to simulate the use of renewable energy.

BESTenergy is an open-source, free-redistributable building energy simulation software. It provides a SketchUp-based interface which runs dynamic building energy simulation by running EnergyPlus 8.9 calculation engine.

Ecotect uses the finite difference method and uses the grid to divide the analysis plane into multiple analysis units according to user needs and analyze each node. The software can analyze the lighting of the model based on the solar radiation intensity, building thermal parameters, etc.

RETScreen is a clean energy management software system for energy efficiency, renewable energy and cogeneration project feasibility analysis as well as ongoing energy performance analysis. The RETScreen software used in this study includes GSHP (Ground Source Heat Pump), PV (Photovoltaic) and SWH (Solar Water Heating). RETScreen and BESTenergy can work well together, because the important input parameters of RETScreen such as annual heating or cooling energy load and design heating or cooling load can be calculated from the simulation results of BESTenergy.

Parameters setting for simulation

Through the BESTenergy simulation of three building models, this research calculates the annual CED and HED and the growth rate in winter and summer when the temperature rises, to see if the resilient house based on Yaodong can reduce building energy demand and their temperature sensitivity of UHI effects. In the evaluation of building energy demand, the ratio of energy demand and the corresponding building volume. Energy demand coefficient (λ) is used as a measure of building energy efficiency. The calculation method is shown in Eq.1, where i is the start hour of the calculation, n is the end hour of the calculation, EDn is the nth hour of building energy demand, and V is the building volume.

$$\lambda = \frac{\sum_{i}^{n} ED_n}{V} \tag{1}$$

According to the weather data of Yan'an City, continuous warming dates in winter and summer are selected and shown in Table 1. The λ_{HED} and λ_{CED} of the three models are calculated respectively. Linear regression is performed to investigate the correlation between air temperature, λ, and the growth rates, to determine the adaptability of each model to the UHI or enhanced UHI intensity. The details of input for BESTenergy simulation is shown in Table 2.

Table 1. Selected days for the air temperature-daily λ correlation analysis

Summer days	July 8	July 9	July 10	July 11	July 12	July 13
Air temperature	23.5℃	24℃	25.5℃	26℃	27℃	28℃
Winter days	Jan. 9	Jan. 10	Jan. 11	Jan. 12	Jan. 13	Jan. 14
Air temperature	-3.5℃	-3℃	-2℃	-0.5℃	0.5℃	1.5℃

Table 2. Details of the input parameters for the BESTenergy simulation

People Occupancy Rate	Activity Level	Electric Equipment Thermal Load	Ventilation Airflow Rate	Zone heating, Variable temperature	Zone cooling, Variable temperature
0.04 people/m²	Seated at rest	4W/m²	0.3/h	18:00-08:00, constant 20℃	18:00-08:00, constant 26℃

In addition, Ecotect was used to simulate daylighting of three building models, analyzing if the resilient house can use natural daylighting to reduce lighting energy consumption. BESTenergy was used to simulate the relative humidity inside the building throughout the year to analysis the differences of humidity, and uses RETScreen to simulate the use of geothermal energy and solar energy, and calculate the energy consumption and CO_2 emissions reduction. The ground source heat pump was introduced to provide energy for the whole year, and the solar energy was used to provide the energy required for the ground source heat pump, lighting, equipment and the hot water. Among them, the lighting electricity is calculated according to the residential building as 3KWh/m²year and the equipment electricity as 15KWh/m²year, so the lighting energy demand is 1.134MWh/year and the equipment energy demand is 5.67MWh/year.

The selected ground source heat pump is the horizontal one, with low cost and no water pollution. The parameters of the selected solar photovoltaic panel are: mono-Si PV module type, 19.2% Nominal PV module efficiency and one PV panel's power with 60 cells that is 0.315 KW. The parameters of the selected solar thermal panel are: glazed collector type, gross area of one collector is 2.42 m², aperture area of one collector is 2.26 m², Fr coefficient is 0.76, Fr UL coefficient is 3.74 (W/m²)/℃, and the slope of solar collector is 25°. Water heating load is considered for a house of 3 occupants, and the desired water temperature is 60℃. The estimated hot water use is 180L/d. RETScreen can calculate reduced CO_2 emissions based on the current state of China's energy structure. In 2017, China's energy structure was composed by 68.6% coal, 7.6% oil, 5.5% natural gas and 18.3% clean energy.

Results

Building cooling and heating energy demand

Simulation results are shown in Table 3. The CED of model A is 55.1 KWh lower than model B, and 148.1 KWh higher than model C. The HED of model A is 2.23 MWh higher than model B, and is 6.05 MWh higher than model C. The energy demand coefficient (λ) is calculated to provide more accurate total energy consumption.

Table 3. Statistical results of annual CED and HED for three simulation models

	Annual CED and HED	Annual CED	Annual HED
model A	13273.0KWh	3702.8KWh	9570.1KWh
model B	11095.1KWh	3757.9KWh	7337.2KWh
model C	7071.0KWh	3554.7KWh	3516.3KWh

The Annual $\lambda_{\text{CED and HED}}$ are shown in Table 4. The λ_{CED} of model A is 0.8KWh/m³ higher than model B, 2.8KWh/m³ higher than model C. The λ_{HED} of model A is 9.4KWh/m³ higher than model B, 22.3KWh/m³ higher than model C. This is to say, local urban single-story house is more energy-efficient than traditional Yaodong, in both of summer and winter, and the energy performants of resilient house is the best. In the energy consumption differences in summer is lower than that in winter. This is because the actual roof of the Yaodong is usually thicker than 500mm, and even some of the exterior wall of Yaodong is embedded in the mountain. Therefore, the simulation results are higher than the reality. On the other hand, the insulation layer of residential walls in Yan'an is generally thick, while Yaodong has no insulation layer. The resilient house, which draws on the experience of traditional Yaodong and improved, is superior in all respects to original Yaodong and local urban house of equal area.

Table 4. Calculation results of annual $\lambda_{\text{CED and HED}}$ for three simulation models

	Annual $\lambda_{\text{CED and HED}}$	Annual λ_{CED}	Annual λ_{HED}
model A	43.9KWh/m³	12.2KWh/m³	31.6KWh/m³
model B	33.5KWh/m³	11.4KWh/m³	22.2KWh/m³
model C	18.7KWh/m³	9.4KWh/m³	9.3KWh/m³

The daily λ of three models are shown in the Figure 3. The data of model A is relatively scattered. In the daily $\lambda_{\text{CED and HED}}$ comparison chart, the median, lower quarter and minimum values of model A are similar to model B. In the comparison diagram of daily λ_{CED}, the lowest value is even lower than model B and model C. This may be because the wall of traditional Yaodong is more thermally inert, although the overall thermal insulation effect is not as good as that of an urban residential building with thermal insulation, but it is more resistant to temperature fluctuations. The CED of the three models were calculated separately from July 8 to July 13. The results are shown in Table 5. It can be seen that the CED increases with increasing temperature, and the calculation of its daily λ value is shown in Table 6.

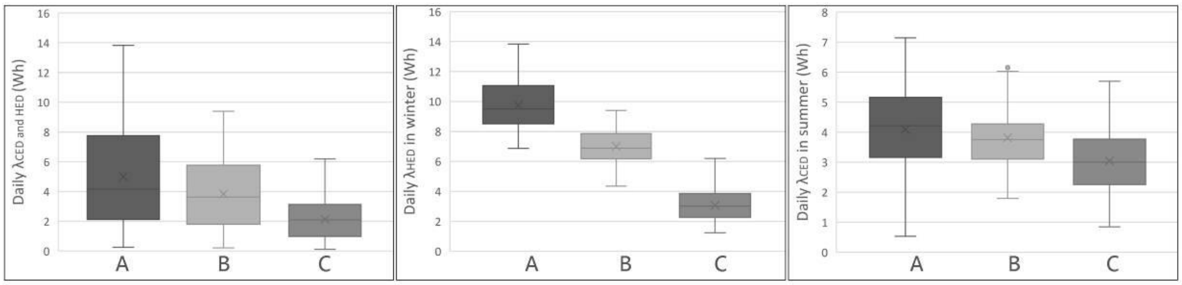


Figure 3. Statistical results of annual daily $\lambda_{\text{CED and HED}}$ comparison for three simulation models.

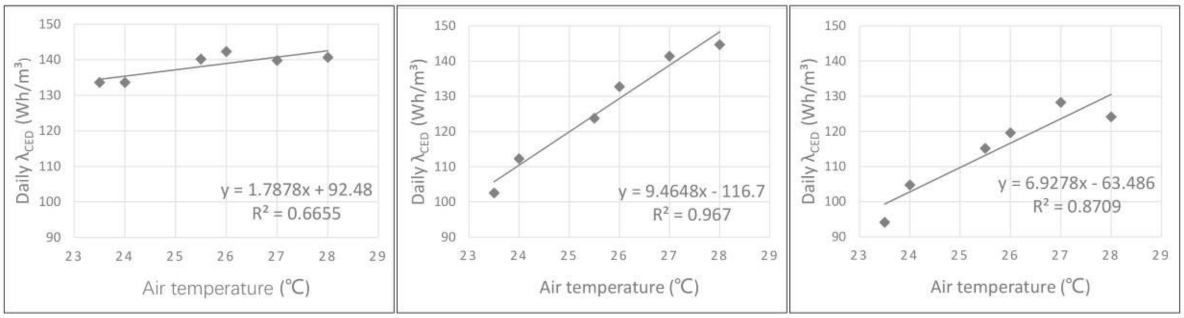
Table 5. Part simulation results of summer daily CED for three models

Daily CED (Wh)	July 8 (23.5℃)	July 9 (24 ℃)	July 10 (25.5℃)	July 11 (26℃)	July 12 (27℃)	July 13 (28℃)
Model A	40438.3	40432.1	42419.5	43062.0	42302.6	42574.6
Model B	33913.0	37131.4	40935.6	43908.5	46762.6	47843.8
Model C	35575.4	39601.9	43524.5	45205.0	48463.7	46926.5

Table 6. Calculation results of Daily λ_{CED} for three models

Daily λ_{CED} (Wh/m³)	July 8 (23.5℃)	July 9 (24 ℃)	July 10 (25.5℃)	July 11 (26℃)	July 12 (27℃)	July 13 (28℃)
Model A	133.6	133.6	140.2	142.3	139.8	140.7
Model B	102.5	112.3	123.8	132.8	141.4	144.7
Model C	94.1	104.8	115.1	119.6	128.2	124.1

Regression analysis was performed on these days in summer between λ_{CED} values and air temperature, and the results are shown in Figure 4. The R^2 of the daily λ_{CED} growth rate fitting lines of the three models were respectively 0.67, 0.97 and 0.87, indicating that the air temperature and daily λ_{CED} in summer have a high correlation. The growth rate of daily λ_{CED} of model A increases with air temperature to 1.79 KWh/m³ ℃, model B is 9.46 KWh/m³ ℃, and model C is 6.93 KWh/m³ ℃, indicating that model A will has the strongest adaptability under the intensity of UHI, model C is the second, and model A is the worst. It proves that the main material of Yaodong, loess, is a weather-adapted building material, and the concrete used in urban houses is highly sensitive to temperature rise. The renovation scheme only uses loess roofing, so λ_{CED} grows faster than Yaodong when summer temperatures rise, but is slower than urban dwellings. The HED of the three models were calculated separately from J January 9 to January 14. The results are shown in Table 7. It can be seen that the HED decreases with increasing temperature, and the calculation of its daily λ value is shown in Table 8.



Model A (Yaodong) Model B (Urban house) Model C (Resilient house)

Figure 4. Air temperature-daily λ correlation analysis comparison of 6 select summer days for three simulation models.

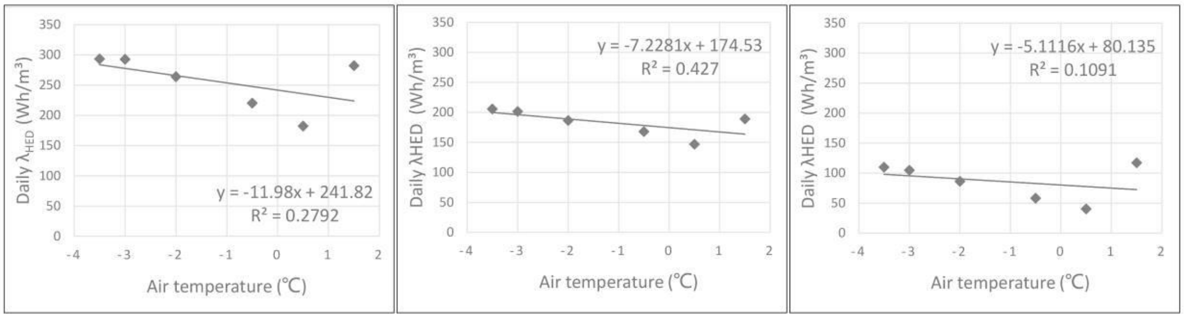
Table 7. Part simulation results of winter daily HED for three models

Daily HED (Wh)	Jan. 9 (-3.5℃)	Jan. 10 (-3℃)	Jan. 11 (-2℃)	Jan. 12 (-0.5℃)	Jan. 13 (0.5℃)	Jan. 14 (1.5℃)
Model A	88752.7	88555.2	79895.5	66677.0	55149.8	85406.4
Model B	67995.8	66656.2	61691.0	55597.0	48594.0	62549.5
Model C	41528.9	39559.4	32623.2	21967.5	15269.6	44323.7

Table 8. Calculation results of Daily λ_{HED} for three models

Daily λ_{HED} (Wh/m³)	Jan. 9 (-3.5℃)	Jan. 10 (-3℃)	Jan. 11 (-2℃)	Jan. 12 (-0.5℃)	Jan. 13 (0.5℃)	Jan. 14 (1.5℃)
Model A	293.3	292.6	264.0	220.3	182.2	282.2
Model B	205.6	201.5	186.5	168.1	146.9	189.1
Model C	109.9	104.7	86.3	58.1	40.4	117.3

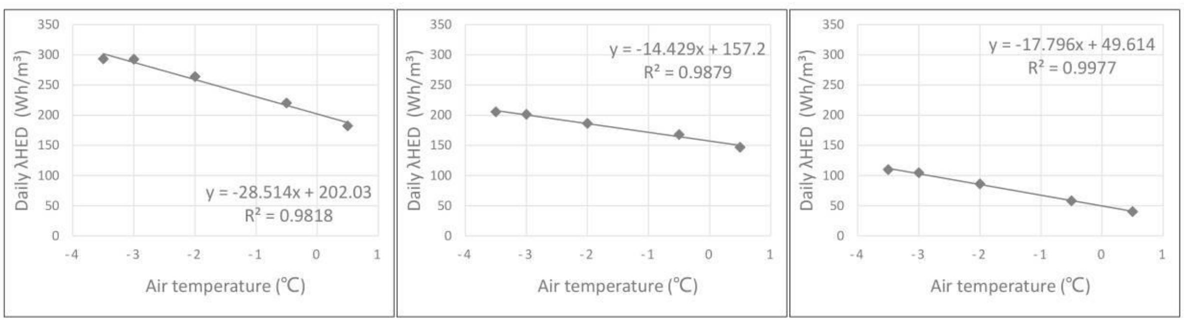
A regression analysis of the λ_{CED} value and air temperature is shown in Figure 5. It can be seen from the figure that the R^2 of the three regression lines are all lower than 0.43, and the degree of the deviation of the point of January 14 (1.5 ℃) is large. This may be because the change of indoor temperature lags with the outdoor temperature, resulting in the trend of energy consumption and outdoor air temperature are inconsistent.



Model A (Yaodong) Model B (Urban house) Model C (Resilient house)

Figure 5. Air temperature-daily λ correlation analysis comparison of 6 select winter days for three simulation models.

In order to accurately observe the daily λ_{HED} with the increasement of temperature, the last point was removed. The results are shown in Figure 6, in which all three models showed high correlation (R^2 greater than 0.98). Among them, model A has a linear slope of -28.51, model B is -14.43, and model C is -17.80. This indicates that in winter, Yaodong's energy consumption decreases rapidly with increasing temperature, followed by the resilient house, and urban residence showed the slowest speed.

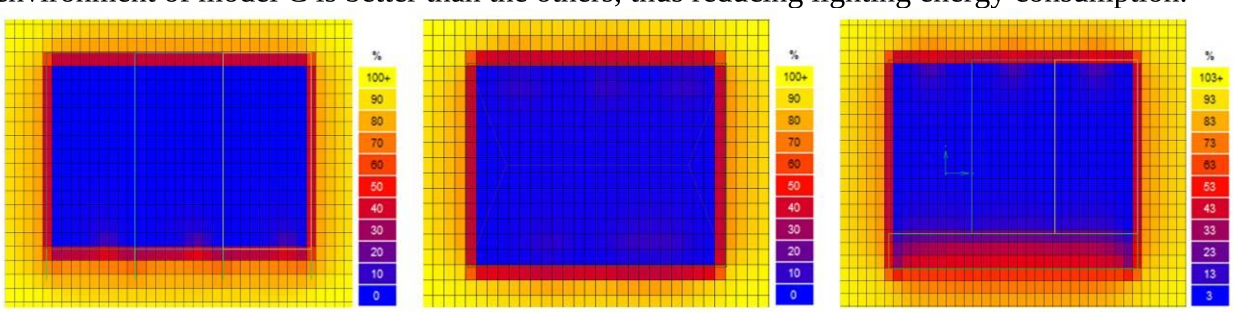


Model A (Yaodong) Model B (Urban house) Model C (Resilient house)

Figure 6. Air temperature-daily λ correlation analysis comparison of 5 select winter days for three simulation models.

Daylighting and humidity analysis

The daylighting simulation results are shown in Figure 7. The indoor natural lighting environment of model C is better than the others, thus reducing lighting energy consumption.



Model A (Yaodong) Model B (Urban house) Model C (Resilient house)

Figure 7. Simulation results comparison of natural daylighting for three models.

The relative humidity simulation of different schemes (Figure 8) shows the average relative humidity of model A is 33.1%, model B is 32.5% and model C is 32.0%. The numbers of comfortable days in humidity (30%-70%) of three models are all 191 days. The image shows that the humidity of the three models in winter is not much different. In the summer, model A has the highest humidity, which is close to the threshold of the comfort zone. Model C is similar to model B and is lower than model A. Therefore, retrofit scheme improves the indoor thermal comfort environment by improving the humidity.

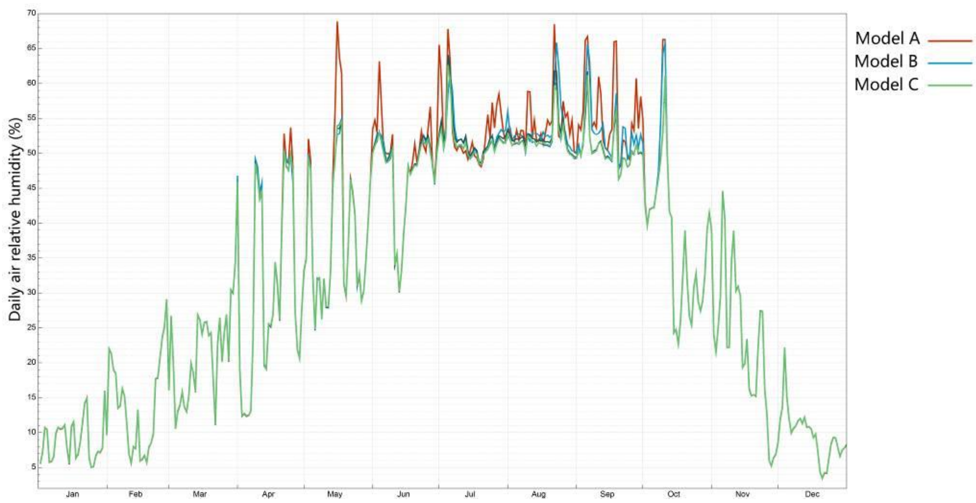


Figure 8. Simulation results comparison of daily air relative humidity for three models.

The usage of clean energy

According to the simulation results using BESTenergy, the annual HED is 3.52MWh and annual CED is 3.56MWh. Combined wiht RETScreen GSHP, the energy use with ground source heat pump for the resilient house is 1.2MWh/yr for space heating, and 0.9MWh/yr for cooling, 2.1 MWh/yr in total, which is only 29.7% of energy demand without GSHP. The total energy use for lighting, equipment and ground source heat pump is 8.91 MWh/yr, and 24 solar panels are required. Nominal PV array power is 7.56KWp, which can deliver 9.24 MWh/yr renewable energy and PV array area is 39.4m².The energy demand for hot water in resilient house is 3.8 MWh/yr. A total of 8 solar thermal collectors are needed, which can deliver energy of 3.8MWh/year and total gross collector area is 19.4m². This is to say, the net building energy consumption of our house is near zero.

In addition, the net GHG emission reduction is 1.84t CO_2/yr on heating system, 0.24t CO_2/yr on cooling system, 6.86t CO_2/yr due to the usage of photovoltaic panels, 1.17t CO_2/yr due to the adoption of solar hot water, and its 10.12t CO_2/yr in total.

Conclusion

This paper takes the transformation of Yaodong, a traditional residential building of China as an example, explored the climate adaptive design scheme for increasingly UHI environment in cities. Three simulation methods are used for evaluation. BESTenergy is used to simulate the three-year CED and HED, comparing the total energy demand and examining the changes in energy demand during climate changes in winter and summer. The indoor relative humidity was simulated by using BESTenergy, and the indoor natural lighting was compared by using Ecotect simulation. RETScreen software is used to optimize the design of clean energy including geothermal energy and solar energy for reducing building energy consumption, improving indoor thermal comfort, and reduce CO_2 emissions.

The Annual CED and HED showed the energy consumption coefficient λ_{CED} and λ_{HED} of traditional Yaodong are both larger than those of local ordinary urban residence. These two coefficients of local urban residence are both larger than those of transformation based on Yaodong. It shows that the retrofit scheme has greatly reduced the energy consumption level of the original Yaodong, especially for heating. The air temperature-daily λ correlation analysis showed during UHI period, Yaodong has the best adaptability, because the rise speed of CED in summer is slower than the other models, and the reduce speed of HED in winter is faster. It is demonstrated the advantages of the proposed transformation scheme.

The natural lighting and indoor relative humidity of resilient house provides insufficient lighting and excessive humidity in summer. The renewable energy usage bases on the above optimization scheme, the use of ground source heat pump saves energy consumption of 4.97 MWh per year, the use of PV panels saves 8.90 MWh per year, the use of solar thermal collectors can save energy by 3.8 MWh per year, and saving 17.68MWh in total. Meanwhile, the CO_2 emissions reduction is 10.12 t CO_2/yr.

Some of the limits should be studied in the further. Firstly, the building model volume of BESTenergy software is usually larger than the reality, leads to a larger simulation results of energy consumption. Secondly, the setting of indoor structure in the model is simple, and the practicality of the single-storey house in the city is insufficient. Therefore, the resilient design that explores more practical residential types should be carried out in the future.

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