Energy-saving analysis of envelope structure of traditional dwellings in Garze prefecture, tibetan area of western Sichuan plateau

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Abstract
Taking the traditional dwellings in Garze Prefecture of Western Sichuan Plateau as the simulation object, the energy consumption is simulated by DesignBuilder, and the heating energy consumption of the existing typical dwellings with or without sunroom is compared and analysed. Different envelope structures with stone, Grass-added clay, compacted clay, aerated concrete, and light mortar masonry clay brick masonry as the main body, and the effects of four different external wall insulation materials on the heating energy consumption, carbon emissions, and economic costs of local dwellings at different thicknesses. The results show that the minimum energy consumption of the four insulation materials is polyurethane board, and the maximum energy consumption material is polyvinyl chloride rigid foam plastic. For the thickness of the insulation material, the four insulation materials achieve the best energy consumption performance at 150 mm. With the increase of the simulated thickness, the energy consumption of the same type of insulation material gradually decreases. Among the five kinds of building envelope materials, Grass added clay is a kind of green building material with local materials, low cost and excellent performance. Its comprehensive performance of heating energy consumption and carbon emission is obviously better than that of the rest. It can be made into Grass-added clay bricks for the construction of residential exterior walls for promotion.

Keywords
chuansi plateau; traditional dwelling; heating energy consumption; carbon emission; economic cost

Introduction
Garze Prefecture in the Tibetan area of the western Sichuan Plateau belongs to the severe cold C area. The average temperature of the coldest month is -2.2 °C, and the average temperature of the hottest month is 15.5 °C. The daily average difference is large. The traditional residential building has a long heating period and high energy consumption in winter, but it can be used without refrigeration in summer. Restricted by the local topography and economic development level, the conventional energy supply is scarce, and the central heating technology is difficult to apply. However, the percentage of sunshine in winter in Garze Prefecture is 70 %, the total annual solar radiation is more than 6500 MJ / m², and the solar sunshine hours are more than 1700 hours[1]. Rich solar radiation resources provide good conditions for using solar energy to solve winter heating problems and improve comfort in severe cold areas.

There are many factors affecting building heating energy consumption and carbon emissions, such as sunroom, exterior wall building materials, and thermal insulation materials. The influence of various factors on energy consumption can be accurately and efficiently simulated by computer simulation software. Zhao Yanan[2] used DeST simulation software to simulate the annual hourly load of a school in Jinan, and studied the influencing factors of campus building energy consumption.

Yu Hanting[3] simulated the energy consumption of typical rural houses in severe cold regions through EnergyPlus, and compared the differences in energy and economic costs of existing typical rural houses with different materials as the main body. Zhang Jun et al. [4] proved that PCES can objectively reflect the energy consumption distribution of buildings through engineering cases. Sun Fengmei[5] used DeST-H software to study the factors affecting residential energy consumption in Changsha and gave energy-saving measures. Zhu Dandan et al. [6] verified that the simulation of DeST and EnergyPlus is better than DOE-2 through the comparative analysis of several simulation software. In summary, the research shows that it is feasible to consumption simulation software to analyze the influencing factors of building heating energy consumption.

In recent years, DesignBuilder, a building simulation analysis software secondary developed with EnergyPlus as the core, has been gradually applied to architectural design with the advantages of convenient modeling interface, complete data database, reliable energy consumption simulation function and intuitive simulation results. Through the analysis and research on the energy saving of the envelope structure of traditional
dwellings in Garze Prefecture (severe cold area), five different exterior wall structures and four kinds of exterior wall insulation materials are compared. The heating energy consumption, carbon emission and economic cost are compared and analyzed, and a more suitable envelope structure is obtained. It provides a theoretical basis and method for the energysaving design of traditional dwellings in the western Sichuan Plateau.

**Construction of traditional residential model**

**Establishment of building models**

The building plane is 'one' shaped, with a construction area of 273.79 m², a floor height of 2.7 m, and a north-south orientation. In order to avoid the loss of indoor hot air caused by the direct entry of outdoor cold wind, an additional sunshine room is set up on the south side of the living room and the second floor corridor. The building plan is shown in Figure 1. There are three bedrooms on the first and second floors, which meet the local people's living needs for the number of rooms. In order to obtain more sunshine, the south-facing bedroom increases the window area; the fire pond is the center of the living room, which meets the Tibetan people's living characteristics of 'living around the fire' and avoiding cold and heating; the jingtang is a room for religious activities in which people do not live[7]. In the design of the building facade, the local unique minority regional characteristics and architectural art style (Figure 2,3) are retained, and the building foundation model is constructed.

**Building model enclosure structure parameter setting**

The typical weather data of Garze Prefecture in the Chinese Standard Weather Data (CSWD) of Designbuilder was used, and winter was selected as the typical climate for simulation. The indoor thermal environment parameters set the building heating schedule from October of the current year to March of the next year. The heating rooms were the bedroom and
the living room, with the indoor temperature set at 20°C. The rest of the rooms were not heated. According to the code GB55015-2021[8], thermal performance parameter limits for residential building envelope in cold zone C with less than 3 stories, the external wall limit is 0.3 W / (m²·K), the roof limit is 0.2W/(m²K). According to the code GB50176-2016[9], building material thermal physical performance calculation parameters, determine the main material parameters of the simulated envelope structure.

Results and analysis
The influence of material type of building envelope on heating energy consumption
1. Simulation scheme: According to the GB50176-2016 standard and the existing residential buildings in Garze Prefecture, the external wall materials are determined as: grass clay, stone, rammed clay, aerated concrete, light mortar clay brick masonry.
2. Simulation data and results analysis: when the Grass-added clay is used as the enclosure structure material, the heat load of the model test period is 3810.20kwh; when using stone, the heat load of the model test period is 3983.91kwh; when the compacted clay material is used, the heat load of the model test period is 3983.91kwh; when aerated concrete is used, the heat load of the model test period is 3567.96kwh; when light mortar is used to build clay brick masonry material, the heat load of the model test period is 3856.56kwh; the results show that the enclosure structure has a great influence on the indoor thermal environment and heating energy consumption in this area, and different material types have different effects on the heating energy consumption of the enclosure structure. Among the above materials, aerated concrete has the lowest energy consumption, followed by Grass-added clay, as shown in figure 4. Combined with the local geographical natural climate and economic conditions, when aerated concrete cannot be selected, Grass-added clay can be selected as the local envelope material.

Figure 5 shows the simulated energy consumption. The heating load in the test period of the model without sunroom is 4496.82kwh. The heat load with sunroom is 3567.96kwh, 21% lower than that without sunroom. Figure 6 shows the living room indoor temperatures with and without the sunroom. The indoor temperature of the first floor living room increased in every month after adding the sunroom, and the indoor PMV value also increased gradually. Which suggest that the sunroom can capture more solar radiation to increase the indoor temperature in winter and reduce the heating energy consumption.

The influence of sunroom on heating energy consumption
1. Simulation scheme: Figure 2 shows the models with and without the sunroom. The simulated data during the heating period (from October of the current year to March of the next year) were compared. The sunroom was designed on the upper and lower floors in the south direction of the building. The transparent part was Generic clear 6mm single-layer ordinary transparent glass with solar heat gain coefficient (SHGC) of 0.819 and heat transfer coefficient of 5.778 W/m²·K. The sunroom located at the south side of the living room at the entrance of the first floor, whose depth was 1.8 meters. The two enclosed space was to avoid the outdoor cold wind directly enter into the room, but also to prevent the indoor hot air going out. The corridor on the second floor was designed as another sunroom with a depth of 1.5 meters, which increases the window area of the corridor on the second floor and improves the indoor lighting and air environment by obtaining more sunlight. Outside the corridor is the roof of the first floor, which can be used as a recreational place for local residents and a drying platform for grain, and also leaves room for further simulation of different depths of the sunroom (Figure 2b).

Figure 5 Energy consumption simulation data with and without sunroom (the data was extracted from Designbuilder)
Influence of insulation material type on heating energy consumption

In the external envelope structure of the building, the energy loss through the external wall of the building accounts for about 1/4 of the total energy consumption of the building. The wall insulation structure of the external wall of the building is more beneficial to the energy saving of the building, which can effectively reduce the energy loss. At the same time, it can also appropriately improve the living comfort of the internal occupants.

1. Simulation scheme: The simulation time is selected from the heating period, that is, from October of the current year to March of the next year. The roof and windows of the building and other external envelope structures are simulated according to the current situation, and only the influence of replacing different types and thickness of external wall insulation materials on building energy consumption is studied. Four kinds of materials, polystyrene foam plastics (EPS), extruded polystyrene foam plastics (XPS), polyurethane rigid foam plastics and polyvinyl chloride rigid foam plastics, were selected for comparative study to explore the effects of different types of external wall insulation materials and their different thicknesses on building energy consumption. The wall structure layer material of the building model is aerated concrete, and the four thermal insulation materials are simulated with three thicknesses of 60 mm, 120 mm and 150 mm.

Simulation data and results analysis: as shown in figure 7, under the insulation thickness of 60mm, 120mm and 150mm, the minimum energy consumption value is polyurethane rigid foam, followed by XPS, followed by EPS, and the maximum energy consumption value is polyvinyl chloride rigid foam plastic. Therefore, when these four materials are used as insulation materials for residential buildings in severe cold areas, the minimum energy consumption value is polyurethane rigid foam plastic, and the maximum is polyvinyl chloride rigid foam plastic. In the thickness range of the experimental simulation, the four kinds of insulation materials have reached the best energy consumption of this type of material when the thickness is 150 mm. It can be seen that the energy consumption of the same type of insulation material decreases with the increase of thickness. In summary, through simulation and analysis, it can be seen that the same type of insulation material, the greater the thickness, the smaller the energy consumption. In the selection of thermal insulation materials, as shown in the above simulation, the energy consumption is the smallest when polystyrene plate is used.

Carbon dioxide emissions and economic costs of heating during building operation

1. The heating method is electricity: when calculating the energy saving rate of the envelope structure according to the JGI-T4492018[10], the annual heating energy consumption of the design building and the reference building during the operation period should be calculated according to the following formula:

\[ E_{H,bld} = \frac{Q_{H,bld}}{Q_1} \]

\[ E_{H,bld} \] : Building annual heating energy consumption (kWh); \[ Q_{H,bld} \] : the annual cumulative heat consumption of the building (kWh), determined by simulation calculation; \[ Q_1 \] : the conversion weight of the comprehensive efficiency of the heating system, according to Table 5.2.4, the conversion weight of the comprehensive efficiency of the heating system in the cold region is 1.6. According to the simulation results of the material type of the envelope structure on the heating energy consumption, the energy consumption of aerated concrete is the lowest. Through the simulation calculation \[ Q_{H,bld} = 3568.96\text{(kWh)}, E_{H,bld} = 2230.6\text{(kWh)} \]. According to the GB / T51366-2019[11], Sichuan Province belongs to the Central China regional power grid, with a carbon emission factor of 0.5257 kg / kWh, so the heating carbon dioxide emission during operation is 1172.6 kg. The price of electricity is between 0.56 and 0.62 yuan. Calculated at 0.6 yuan, the annual electricity cost is 1338.4 yuan.
2. The heating method is household coal: According to GB55015-2021, the comprehensive efficiency conversion weight of the heating system is 0.88. According to the simulation results and the above formula

$$E_{hBD}= 4055.64 \text{(kWh)}$$

combined with the GB / T51366-2019, the carbon dioxide emission factor of anthracite unit calorific value is 94.44tCO2 / TJ, 1kWh 3.6 * 10^6J, 1TJ 10^12J, so the carbon emission is 1378.82kg. The 1kWh coal consumption is equal to 0.0001229 tons, and the coal consumption during the operation period is 0.5 tons. The price of bituminous coal is calculated at 510 yuan / t, and the coal consumption during the operation period is 255 yuan per year.

3. The heating method is biomass (wood, hay, etc.): According to the GB55015-2021, the comprehensive efficiency of the heating system is converted into a weight value of 0.8. According to the simulation results and the above formula

$$E_{hBD} = 4461.2 \text{(kWh)}$$

combined with the GB / T51366-2019, the effective carbon dioxide emission factor of wood is 95tCO2 / TJ, 1kWh 3.6 * 10^6J, 1TJ 10^12J, so the carbon emission is 1520kg. The 1kWh timber consumption is equal to 0.00040 tons, the timber price is calculated at 839.44 yuan / t, and the annual timber cost is 1494.9 yuan.

Simulation data and result analysis: From the above simulation, it can be seen that during the operation of the building, the carbon emission is the smallest when the heating mode is electric, and the carbon emission is the largest when the biomass such as wood is used. The economic cost of using household coal is the lowest, as shown in figure 8.

![Figure 8: Carbon emissions simulation data of different heating methods](https://doi.org/10.26868/25222708.2023.1136)

2.5 Carbon dioxide emissions of building materials

1. On the premise of the same insulation material. The software is used to dynamically simulate and compare the carbon emission factors of the external wall building materials in the construction process when the external wall building materials are Grass-added clay, stone, compacted clay, aerated concrete, and light mortar masonry clay brick masonry. The simulation is based on the premise that the thermal insulation material is determined as the 150 mm thick polyurethane rigid foam plastic with the smallest energy consumption.

When the building exterior wall material is Grass-added clay, the material consumption is 149.78 tons, the clay carbon emission factor is 2.69 kgCO2e / t, and the carbon emission is 402.91 kg. When the building exterior wall material is stone (shale rock), the material consumption is 256.76 tons, the carbon emission factor is 5.08 kgCO2e / t, and the carbon emission is 1304.34 kg; when the building exterior wall material is compacted clay, the material consumption is 192.57 tons, the clay carbon emission factor is 2.69 kgCO2e / t, and the carbon emission is 518.01 kg. When the building exterior wall material is aerated concrete, according to the model simulation, the material area is 214 m², the thickness is 0.5 m, so the volume is 107 m³. Taking C30 as an example, the carbon emission factor of building materials is 295 kgCO2e / m³, and the carbon emission is 31565 kg. When the building exterior wall material is light mortar masonry clay brick masonry, the area is 214 m², the thickness is 0.5 m, the volume is 107 m³, the carbon emission factor of building materials is 250 kgCO2e / m³, and the carbon emission is 26750 kg. It can be seen from the simulation results that when the building exterior wall material is aerated concrete, the carbon dioxide emission is the largest, and the carbon emission is the smallest, which is the local Grass-added clay.

![Figure 9: Carbon emissions of different exterior wall building materials](https://doi.org/10.26868/25222708.2023.1136)

2. On the premise of external wall materials consistent. In the building life cycle, the building exterior wall materials are not modified and updated. The above experimental simulation results show that the energy consumption of aerated concrete is the smallest, followed by Grass-added clay; From the perspective of carbon emissions, the carbon emissions of Grass-added clay are the smallest, and the aerated concrete is the largest. Considering the two factors of energy consumption and carbon emissions and improving the living environment and quality of life of local people, aerated concrete exterior wall materials were selected to compare and analyze the carbon dioxide emissions of different insulation materials with a thickness of 150 mm. When the insulation material is polystyrene foam (EPS), the material consumption is 0.642 tons, the carbon emission factor is 4620 kgCO2e / t, and the
carbon emission is 2966.04 kg. When the insulation material is extruded polystyrene foam (XPS), the material consumption is 1.123 tons, the carbon emission factor is 5020 kgCO2e / t, and the carbon emission is 5637.46 kg. When the insulation material is polyurethane rigid foam, the material consumption is 1.123 tons, the carbon emission factor is 5220 kgCO2e / t, and the carbon emission is 5862.06 kg. When the insulation material is polyvinyl chloride rigid foam, the material consumption is 4.172 tons, the carbon emission factor is 7300 kgCO2e / t, and the carbon emission is 30455.6 kg. From the simulation results, it can be seen that when the insulation material is polyvinyl chloride foam, the carbon dioxide emission during the construction process is the largest, and the smallest is polystyrene foam, as shown in Figure 10.

Figure 10 Carbon emissions of different insulation materials

Conclusion

Based on DesignBuilder software, the energy consumption and carbon emission of traditional dwellings in Garze Prefecture, Tibetan area of Western Sichuan Plateau during heating period were simulated. The influence of sunroom on building energy consumption and the influence of different exterior wall materials on heating energy consumption and carbon emissions are analyzed. The results are as follows:

(1) After the application of additional sunroom, the heat load of the building model is reduced from 4496.82 kwh to 3568.96 kwh when there is no sunspace, indicating that under the premise of unchanged envelope structure, in areas with strong solar radiation and severe cold climate, the sunspace is an important factor affecting the energy consumption of winter heating in Garze area.

(2) The building envelope structure has a great influence on the heating energy consumption and carbon emissions in this area. Different material types have different effects on the heating energy consumption and carbon emissions of the building envelope. In the case of the same indoor design temperature and heating mode, when the five materials of Grass-added clay, stone, compacted clay, aerated concrete and light mortar masonry clay brick masonry are used as external walls, from the perspective of heating energy consumption, aerated concrete heating energy consumption is the smallest, followed by Grass-added clay, stone is the largest; from the perspective of carbon emissions, Grass-added clay is the smallest and aerated concrete is the largest. Combined with local geographical, natural climate and economic conditions, Grass-added clay is selected as the local envelope material when aerated concrete cannot be selected. At the same time, it can be considered to make Grass-added clay, a local raw soil material, into grass clay bricks to improve the seismic performance of buildings. The hay and straw are derived from local plants, without extremely complex processing procedures, and can be bundled with local materials. The building construction cost is low and the construction investment recovery period is short.

(3) In the case of electricity, household coal, biomass ( hay, wood ), the carbon dioxide emissions of electricity is the smallest, followed by household coal, wood is the largest; the economic cost of using household coal is the lowest.

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