The Passive Design Strategies and Energy Performance of a Zero-energy Solar House: Sunny Inside in Solar Decathlon China 2013

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Abstract
This paper describes the passive design strategies of Sunny Inside, which is a zero-energy solar house designed to participate in Solar Decathlon China 2013. Ecological atrium design, shading design, natural ventilation design, heat storage system design and thermal insulation design of Sunny Inside are introduced and analyzed respectively. The discussion of the building's energy performance is based on the measured and simulated data by using several building simulation softwares in the study. Ecotect software is used to optimize the house's shading design through simulating the shading conditions. Phoenics software is used for simulating the natural ventilation design of Sunny Inside. Designbuilder software is used in building envelope design to analyze the building’s energy consumption. The results show that Sunny Inside is reasonable in passive energy efficiency design.

Keywords: passive design strategies; energy performance; Solar Decathlon; zero-energy house

1. Introduction
This paper describes the passive design strategies of a zero-energy solar house, named Sunny Inside. Sunny Inside is a project undertaken by a large group of interdisciplinary students and faculties of Xiamen University. It was designed to participate in the first Solar Decathlon China Competition in Datong, 2013.

The international solar decathlon competition on solar building technology is open to global universities, which is launched and hosted by the US Department of Energy. It aims to challenge collegiate teams to design, build and operate solar-powered houses that are energy-efficient and attractive. The scoring system of the competition is divided into ten parts, including five subjective rating items marked by the jury evaluation: architecture, engineering, market appeal, communication, solar application; and five objective items marked by instruments: comfort zone, appliance, energy balance, hot water and home entertainment. The scoring system made a comprehensive assessment for the houses from the aspects of design, technology and sustainability.

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Accompanied with the Solar Decathlon Competitions many researches have been carried out on zero-energy houses. Some papers focused on the application of new materials and equipment. For example, Joara et al. (2014) and Young et al. (2014) studied the application of building integrated photovoltaic (BIPV) technologies in Solar Decathlon Europe houses. Kazanci et al. (2014) and Aldegheri et al. (2014) explored the utilization of new types of solar panels. The application of PCM materials in the energy system is also a research hot spot (Rodriguez et al. 2012, Real et al. 2014, Lin et al. 2014). Soriano et al. (2014) designed a new construction system for assembled sustainable buildings. Other researches focus at the integration of various design strategies (Peng et al. 2015; Zhang et al. 2014), especially the passive strategies to reach the net zero-energy goal (Edwin et al. 2014; Irulegi et al. 2014; Umberto et al. 2014). Due to the character of the competition, every entry has its unique design strategies that are worth studying.

Sunny Inside is a single-family wooden house which combines traditional Chinese building style with innovative energy-efficient technologies. Its design was based on the climate of Datong city. It won two of the ten rating items in the competition, including energy balance and hot water. Sixty-one poly-silicon solar panels are installed on the roof of Sunny Inside, emphasizing the design concept of building integrated photovoltaic. The rated power of the solar panels is 15kw. Fig.1. shows the south facade of Sunny Inside.
2. Passive Design Strategies of Sunny Inside

2.1 Ecological Atrium

The name "Sunny Inside" means that we want the house to be full of sunshine and be close to nature. The building has a T-shaped ecological atrium, which is located in the center of the house and connects all the other rooms (Fig.2.). Each room has large glass doors and windows open to the atrium, creating abundant space levels. Sunshine passes through the skylight and enters the atrium, resulting in light and shadow in the atrium changing throughout the day, offering different life experiences and diverse enjoyments of the living space.

The design strategy of buffer space (GZ Brown 2000) is used in the T-shaped atrium. By using passive energy efficient techniques, such as sun shading, natural ventilation, heat storage and the greenhouse effect, the atrium serves as a thermal buffer between the indoor and outdoor environment. So the house can adjust sunlight, ventilation rate and thermal environment inside the house, thus maintaining thermal comfort and creating a good living environment.

2.2 Shading Design

Datong, the competition site of Solar Decathlon, is rich in solar energy. The solar radiation intensity is very high in August. So shading design becomes one of the important passive design factors to fulfill the indoor temperature and humidity standard in the competition. Sunny Inside has a double layer roof, the upper roof stretching out at the south loggia to provide shade for doors and windows. The skylight of the atrium is made of special XIR glass which can reflect 99% of infrared rays and has a shading coefficient of 0.24. When the solar radiation intensity is too high, the electric sunshade roller curtain outside the skylight can close over the skylight to achieve a better shading effect. There is a 30cm cavity between the roller curtain and the skylight glass acting as a ventilation layer.

The indoor sunshade window curtains can be turned on or off according to the room luminance by an intelligent control system, which can be controlled conveniently by Android phones or IPAD.

2.3 Natural Ventilation Design

The design of natural ventilation is also an important issue in Sunny Inside. Natural ventilation can take away the indoor heat and humidity and provide fresh air to improve indoor thermal comfort conditions when the outdoor climate is comfortable. It is particularly important to Xiamen, a city with a hot and humid climate, and is also one of the important factors for a building to realize the function of thermal comfort control.

The T-shaped atrium cuts through the house from east to west to provide a path for natural ventilation. And the skylight installed at the middle of the T-shaped courtyard guides air to flow out. Every room has doors and windows open to the atrium, forming a draught for natural ventilation.

CFD software Phoenics is used for ventilation simulation and improves the design of Sunny Inside. Fig.3. shows wind pressure diagrams, wind velocity vector graphs at 1.5m height, and the section plane from the south at the atrium. The simulation conditions are as follows: doors and windows are all open and the initial wind direction is from the southeast which is the dominant wind direction of Xiamen in summer. It can be seen from the wind pressure diagram that there is a high draught head between the windward and leeward side which means a good ventilation effect can be achieved by opening the windows and doors. The wind speed graph shows that indoor air flows smoothly under the dominant wind direction, especially in the atrium. Around the skylight, there is some airflow, but its wind speed is low under the influence of airflow on the roof. A deflector can be set on the roof to guide the airflow and enhance the ventilation around the skylight. The wind in the bedroom is strong. The doors and windows can be opened or closed to adjust the indoor air distribution.

The two-layer roof of Sunny Inside is also one of the design points for natural ventilation. There is a 600mm ventilation layer between the upper PV panels and the lower roof, which can take away heat inside the layer to cool the surface temperature of the roof and improve
energy efficiency. Because the PV panels’ generating efficiency increases when the temperature drops, this design can also improve the efficiency of the PV system (Fig.4).

2.4 Heat Storage System Design

For the convenience of disassembly and transportation, most houses in Solar Decathlon use light materials in walls with poor thermal stability. So the houses have difficulty in resisting the impact of outdoor climate change. To handle this problem, heat storage materials are used in Sunny Inside to store heat for flexible use according to the change of weather conditions outdoors.

The stone wall facing the south entrance of the atrium acts as a sensible heat storage. It is made of natural travertine which can enhance the heat stability of the atrium, and also plays the role of a screen wall in the Chinese traditional residence. The skylight above the stone wall can be opened. In winter, the stone wall can store heat from the sunshine in the daytime and send it out at night, using the greenhouse effect. Airflow can be guided outside through the skylight when it is open in the summer and transition seasons (Fig.5.).

Phase change materials are also used in Sunny Inside for latent heat storage. These materials are used in a special ventilation system which utilizes the large temperature difference from day to night during the competition in Datong. The cold energy of air in the night is stored by the system into the phase change materials and released in the daytime. There are four ducts under the atrium and one duct above the ceiling of the living room. In the ducts under the atrium we
use materials with a phase transformation point at 23°C and phase change latent heat value of 187kJ/kg, packaged by aluminum foil bags, and a fan is used in each duct for ventilation. In the duct on the ceiling of the living room, two types of phase change materials are used with phase transformation points at 19°C and 23°C respectively, packaged in stainless steel tubes. Air inlets, outlets and electric air valves are set on each duct to control ventilation conditions. The air temperature at night during the competition can drop to 15°C, so we open the outdoor air vents and use cold air outside to cool the phase change materials. At noon the outside air temperature can increase to 30°C, so we shut down the outdoor air vents, and open the indoor air vents to cool the indoor air. This system can partly replace the air conditioner (Fig.6.).

2.5 Thermal Insulation Design

Thermal insulation design plays a significant role in realizing the zero energy consumption target. We established a real-sized model of Sunny Inside by the energy analysis software Designbuilder. Through the analysis, the relation of thermal resistance of envelope with all year round HVAC power consumption can be drawn, as shown in Fig.7.

We designed the thermal resistance of the building envelope and structural hierarchy based on the simulation data, the material properties and the construction technology. The specific envelope structure of Sunny Inside is shown in Table 1. During the construction, the junction gaps of building components are filled with polyurethane foam to avoid the negative influence of a thermal bridge towards building energy consumption and air permeation.

3. Energy Performance and Discussion

3.1 Computer Analysis of Energy Consumption

Designbuilder software is used to simulate Sunny Inside's energy consumption all year round, as shown in Fig.8.

The electricity generation of Sunny Inside can be calculated monthly through the software PV system. As shown in Fig.9., the electricity generation can fully meet the needs of the house, compared to the power consumption. The energy production throughout the
year is 17202 kWh, 6327 kWh more than the energy consumption, which means Sunny Inside can achieve the goal of zero energy consumption.

3.2 Sunny Inside’s Energy Performance during the Competition

After nearly two years’ preparation, Sunny Inside was transported to Datong in early July 2013. After 13 days’ intensive construction, the final on-site tests were taken from August 2nd to August 11th. Fig.10. shows the solar radiation intensity on the competition site measured by a meteorological station and the instantaneous electric power generated from 9:00 of August 1st to 24:00 of August 11th. It was sunny and cloudy all these days except for August 7th, which was rainy with low solar radiation intensity. The peak intensity of solar radiation during these days was close to 1000W. The peak instantaneous power can exceed 12kW, close to the 15kW rated power of Sunny Inside’s photovoltaic system.

Outdoor air temperature and humidity measured by the meteorological station during the competition are shown in Fig.11. The outdoor air temperature is about 16°C at night and 30°C at noon, which means a large diurnal temperature difference. In order to reach the 22-25°C indoor temperature standard, air conditioning and heating are both needed during the day. So it is reasonable to use phase change materials to control the indoor temperature. Dehumidifiers are needed because the humidity outside often exceeds 60%, beyond the prescribed scope in the competition. The air conditioning system was rarely used during the competition because most of the time it was enough to use the passive methods for thermal regulation, such as opening the skylight of the atrium for ventilation and using the phase change material ventilation system to maintain the indoor temperature.

During the competition Sunny Inside generated the most electric power among the 19 teams (Fig.12.). Power consumption was rare, more than only two other teams. The net electrical energy was 380.15kWh, significantly more than the other teams, which meant Sunny Inside had a reliable photovoltaic system and an excellent building energy efficiency design.

4. Conclusions

By analyzing the design concepts and energy saving technologies of Sunny Inside, the article exhibits the way of using passive design strategies to achieve the goal of zero energy consumption in buildings. A pleasant environment and flexible spaces are shown in Sunny Inside, which embodies the concept of sustainability and ecology. The design strategies in Sunny Inside can be summarized as follows:

(1) By using flexible design an ecological atrium can control the thermal environment inside buildings,
thereby creating a thermal buffer space between the indoor and outdoor environment, which is a good method for designing green buildings.

(2) Shading design, especially the adjustable shading design that can control indoor solar heat gain, should attach importance to energy efficient buildings.

(3) Natural ventilation can take away the heat and humidity indoors when the outside climate is comfortable, so it has great potential in reducing the energy consumption of air conditioning in hot and humid climates.

(4) Thermal insulation design and heat storage design are both important ways to stabilize the indoor thermal environment. Heat storage design is also a good way to use natural energy for indoor thermal regulation, but it is more suitable for cities with great diurnal temperature differences.

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