Study on Thermal Behavior of an Experimental Low-energy Building in the Hot Summer and Cold Winter Zone of China

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Abstract
This paper is based on a study of the expansion part of the architecture department building in Huazhong University of Science and Technology (hereinafter referred to as the experimental building). Thermal environment parameters, building energy consumption and other aspects of the experimental building are monitored. The results show that indoor air temperature can be improved to about 14°C in winter and 28°C in summer by the thermal regulation system, which was limited by the underground soil temperature in Wuhan. Because of the function of the under floor air distribution system, an uneven air temperature distribution is formed in the experimental building. The building energy consumption is 10.7kWh/(m²*a), much lower than the ordinary office buildings in Wuhan. In general, the experimental building can achieve a certain indoor thermal environment with low energy consumption, meeting the requirements of buildings with no-strict thermal comfort demands in the rural areas of hot summer and cold winter zone of China. A heat pump or auxiliary heating/cooling source should be added in the system to achieve a more comfortable indoor environment.

Keywords: low-energy building; thermal behavior; thermal regulation system; hot summer and cold winter zone of China

1. Introduction
China is a country with a large population and relatively poor resources. Since the twenty-first century China has stepped into a rapid development period of urbanization. The expansion of cities leads to a construction boom, which results in a rapid increase in building energy consumption. According to statistics from the Building Energy Efficiency Research Center of Tsinghua University (2014), building energy consumption accounts for 19.1% of the total energy consumption in China. With the advancement of Chinese urbanization and the improvement of people's living standards, building energy consumption will increase faster. If the building energy consumption per unit area in China reaches 80% of the current level in the United States, it will account for 45% of the total energy output of China, which is unacceptable and will seriously hinder the development of China's society, economy and urbanization. So it is of great significance to improve building energy efficiency and to promote the development of low energy buildings in China.

Since the 1980s, China has carried out a three-step policy in building energy efficiency. Many building design codes were published in China as a guide for energy saving in buildings, and building energy conservation was extended to the whole country. In recent years, standards are becoming more strict concerning building energy consumption in China. Practice and research on low energy buildings and zero energy buildings have become popular in China, such as research on the Super Low Energy Cost Demonstration Building in Tsinghua University (X.H Liu et al. 2004; D.X. Li and Z.N. Zhou 2005), the Shenzhen IBR Building (X.Y . Yuan et al. 2010), the Wanke Center in Shenzhen (H. Yang et al. 2012), and also the researches on zero energy solar houses in the 2013 Solar Decathlon China competition (U. Berardi and T. Wang 2014; Y. Jin et al. 2014; Z. Hong et al. 2014). These researches focused on the application of new energy efficiency technologies and renewable energy in buildings, leading the future trend of low carbon development, however some of the technologies are considered to be expensive (X. Yuan et al. 2013). In most areas of China, cost is an important consideration in building construction, so we need adaptable low-cost energy efficiency technologies to promote their application, which is the starting point of designing the experimental building.
2. Design of the Experimental Building

2.1 Climate Context

The experimental building mentioned in this paper is located in Wuhan, China, where the Yangtze River and the Hanjiang River meet at longitude 113°41'-115°05' east and latitude 29°58'-31°22'. Rivers and lakes surround the city, causing it to be hot and humid in summer and cold and wet in winter. The climate of Wuhan gives a good representation of the weather conditions in the hot summer and cold winter climate zone of China. The annual average temperature is 17.7°C. The coldest period is in January and the monthly average temperature is 3°C. The hottest period is in July and the monthly average temperature is 28.8°C. The extremely high temperature can reach 40°C in summer, with high humidity and no-breeze, for this reason Wuhan is well known as one of the "stoves" in China.

2.2 The Experimental Building

The experimental building is built on the roof platform of the architecture department building in Huazhong University of Science and Technology. The building has a dual structure inner space, with a sloping roof facing south, on which solar panels lay. Thin film photovoltaic solar cells are plated in these panels and are connected to the city power grid through an inverter. A light steel structure is used as the building skeleton and lightweight materials are used in the walls for thermal insulation, a raised wooden floor is used indoors to leave enough space for pipelines and the under floor air distribution system. Fig. 1. shows the plans of the building. The total area of the building is 240m².

The experiment building is a low cost, net-zero energy building aimed to satisfy the non-strict thermal comfort demand of buildings in rural areas in the hot summer and cold winter zone of China. The cost per square meter is about 1,700CNY (including the solar panels), much lower than similar low energy...
2.3 The Thermal Regulation System

An experimental low cost thermal regulation system is used in the building. Renewable geothermal energy is used in this system for thermal regulation, and no heat pump is used in the system, to control the cost and energy consumption. The system consists of three parts: The underground heat source, the under floor air distribution system and the dynamic hollow wall. Fig.2. is the schematic diagram on the process of thermal regulation in the building, and shows pictures of different parts of the system.

2.3.1 The Underground Heat Source

The underground heat source provides the cold/heat energy needed for thermal control in the experimental building. As noted from experiment data in various regions, with every meter of soil depth increase, the soil temperature variations will be delayed for 20 to 30 days, the variation amplitude decreases in an exponential law, but the average temperature is consistent with the average air temperature. The average annual air temperature of Wuhan is moderate, so it is suitable for cities like Wuhan to use underground energy for heating in winter and cooling in summer. Through reasonable usage, the energy consumption in summer and winter can compensate each other and maintain a balance throughout the year.

The underground heat source in the experimental building consists of the underground heat exchangers, the heat storage tanks, the water pumps, the water supply pipelines, etc. Eight U-type vertical buried pipes 60 meters in length are used as the underground heat exchangers. Two water tanks which can store 18 tons of water are used as the heat storage tanks and are connected to the buried pipes and the indoor water system. An underground water pump and an indoor water pump are installed in the system to control the underground water circulation and the indoor circulation respectively.

2.3.2 The Under Floor Air Distribution System

The experimental building uses the construction of a raised wooden floor on the first floor to leave enough space for pipelines, and sets two air ducts with a section size of 50cm x 50cm under the floor along the north and south walls. The air inlet is on the east wall of the building, and connected to the air ducts through a heat exchanger. Ten air inlets with a size of 100cm x 25cm are uniformly placed on the floor under the windows. A fan coil is installed in each inlet with three air volume levels. The fan coils are connected to the indoor water system for heat exchange, and connected to the water tanks of the underground heat source.

2.3.3 The Dynamic Hollow Wall

The experimental building uses lightweight materials in the exterior walls for thermal insulation. Foam concrete slabs with 100mm thickness are used as the inner layer of the exterior walls, and a 40mm layer of polyurethane is used as the outside layer, forming a 60mm air layer between the two layers for ventilation. The hollow layer inside the wall is connected with the air exhaust pipes, by which waste air is sent into the wall before being exhausted outdoor. The roofs of the experimental building also have a hollow construction, with a 60mm air layer between the photovoltaic panels outside and the foam concrete slabs inside. The waste air in the hollow wall flows through the hollow layer of the roof and is exhausted outdoors through the unpowered fans on the roof, though this waste heat of the air can be used for thermal insulation. This design can also take away the heat inside the hollow layer to cool the PV panels. Because the PV panels' generating efficiency increases when the temperature drops, this design can improve the efficiency of the PV system.

2.3.4 Thermal Regulation Method of the System

As shown in Fig.2., the thermal regulation system of the experimental building consists of two types of circulation: the water circulation and the air circulation. The water circulation transfers the underground energy to the building for thermal control. The underground water pump should be opened for at least two hours before running the air system, to pump water from the heat storage tanks to the U-type pipes underground for heat transfer, and to make the water in the tanks reach the required temperature for indoor thermal regulation. Because there is no heat pump in the system, the underground energy is used directly for thermal regulation.

When indoor thermal control is needed, the indoor water pump and the under floor air supply system should be opened together to send water from the water tanks to the water-air heat exchangers for heat transfer. The outdoor fresh air flows through the heat exchanger to be heated or cooled by the water system, and be sent indoors from the inlets for thermal regulation. Then it is exhausted by fans and flows through the heat recovery ventilator. After that the waste air is sent into the hollow layer of the dynamic walls.

The thermal regulation system was operated and tested mainly in summer and winter to test its performance. During the transmittance seasons, passive methods were used for thermal regulation and this system was not open.

3. Experimental Set Up

The thermal environment parameters, such as air temperature, surface temperature of walls and windows, energy consumption, etc., were monitored on summer and winter days from 2010 to 2011, at runtime of the thermal regulation system.
Meteorological data were monitored using Energy EnviroMonitor station, which can measure air temperature (range: -45~60°C, accuracy: ±0.5°C), air humidity (range: 0~100%RH, accuracy: ±3% RH), solar radiation intensity (range: 0~1800w/m², accuracy: ±5%) etc. T-type thermocouples were used to monitor the internal and external surface temperature of walls, windows and roofs. Two data loggers (DataTaker DT600, range: 250~1800°C, accuracy: ±0.1%) were used for recording data. RHLOG-T-H air temperature and humidity recorders (temperature range: -25~55°C, accuracy: ±0.3°C, humidity range: 0~100% RH, accuracy: ±5%RH) were used for indoor parameters monitoring. Energy consumption was measured with ammeters. The positions of the measuring points are shown in Fig.3. The accuracy of the instruments is the main cause of the experimental errors, so the authors calibrated the instruments before the tests.

The experimental building was used 6 days a week during the test periods, with 5 sitting occupants, 2 desktop computers and 3 laptops in the first floor rooms.

4. Experimental Results and Discussion

To facilitate the comparison, we only used test data on summer and winter days with extreme outdoor weather conditions, to show the main thermal behavior character of the building.

4.1 Thermal Behavior of the Building, in Winter

The winter data for comparison is from January 2nd to January 7th 2011. Fig.4. shows the indoor and outdoor air temperature, air humidity and solar radiation intensity. We can see that the outdoor air temperature fluctuated from -2°C to +2°C most of the time, with cloudy weather and poor solar radiation, which represents the extreme cold weather conditions in Wuhan.

By comparing the measuring points temperature with the operation time of the thermal regulation system, it is observed that the temperature increased rapidly after turning on the system, the measuring point temperature of Hall-1.5m rose to 14°C in an hour, and was gradually stable after that. The measuring point temperature of Hall-4.5m was relatively lower. The indoor air temperature decreased gradually after shutting down the thermal regulation system, and dropped to 8°C before the next startup of the system.

Solar radiation can influence the indoor air temperature when the system runs. As can be seen in Fig.4., the solar radiation intensity was high on the fifth and the sixth days of the experiment, the indoor temperature continued to rise until noon. But on the fourth day when the solar radiation was low, the indoor air temperature remained roughly stable during the running time of the thermal regulation system. The air temperature variation in the hall of the second floor was relatively low, because there were no air inlets on the second floor. The average temperature on the second floor during the operation time of the thermal regulation system was 1.2°C lower than on the first floor. The air humidity outdoors dropped from 85 to 30 percent during the experiment period, but the indoor air humidity had a relatively small fluctuation range between 40 to 60 percent.

Fig.5. shows the temperature on the surfaces of the indoor inlet and outlet water pipes, and the water temperature in the heat storage water tanks. We can see that the water temperature can reach 18°C before startup of the thermal regulation system. When the system ran, the temperature on the surface of the outlet pipe was about 1.5°C lower than that on the inlet, and the water temperature in the water tanks dropped gradually. Several hours are needed to recover the water temperature in the water tanks, so the thermal regulation system needs to be shut down after a long running period.
Fig.6. shows the distribution of indoor air temperature in the experimental building. The experiment was taken on January 2nd 2011. Eight measuring points were selected for analysis at different heights, above the air inlet, in the office room, and in the hall of the second floor. As shown in this figure, there were temperature differences among the measuring points. The temperature at Inlet-0.2m had the highest air temperature, about 0.6°C higher than that of Inlet-1.5m, and 1°C higher than that of Inlet-2.8m. The air temperatures on measuring points with different heights in the office were very close to each other, and relatively lower than those above the inlet. The air temperatures on measuring points on the second floor were the coldest, and rose more slowly than other points after start-up of the system. We can see that the indoor air temperature distribution was uneven in the experimental building. The temperature was relatively higher near the air inlets, and was colder at the second floor points.

From the experiment, we can see that since there was no heat pump in the system, the ability for thermal regulation was limited. The indoor temperature can only reach 14°C and does not satisfy the general comfort set point temperature of 18°C in winter in China. However, for buildings in the rural area, this temperature can be acceptable (Building Energy Efficiency Research Center of Tsinghua University 2012).

4.2 Thermal Behavior of the Building, Summer

The indoor thermal environment parameters of the experimental building were recorded from August 9th to August 14th, in the summer of 2010. It was sunny on these days, with strong solar radiation, and a high outdoor air temperature which exceeded 36°C at noon. The weather conditions of these days can represent the extreme hot climate in Wuhan.

Fig.7. shows the indoor and outdoor air temperature during the experiment period. We can see that the air temperature in the hall (Hall-1.5m) dropped rapidly after start-up of the thermal regulation system, the indoor air temperature dropped gradually in nearly an hour before stabilizing to about 28°C. There was an 8°C difference between the indoor and outdoor air temperature at noon. The indoor air temperature increased rapidly after shutting down the system. At night the indoor temperature was higher than outdoors. It also can be seen from the figure that the solar radiation intensity exceeded 800w/m² at noon. The 28°C air temperature was higher than that specified in relevant building codes, and it rose gradually with the operation of the system. However it is acceptable in the rural areas of China (Y. Zhou et al., 2013).

Fig.8. describes the inner and outer surface temperature on the south wall and south windows.
The outer surface wall temperature (South wall-out) was influenced by the strong solar radiation, and rose sharply after sunrise. At about 2:00pm each day it reached the peak value, about 47°C on average. The surface temperature on the south window (South window-out) had the same trend as the wall, but the peak temperature was about 2°C higher. The inner surface temperature on the south wall (South wall-in) had a four-hour delay in the temperature variation than that on the outside surface. But for windows, there were no such delays. The temperature difference between the inside and outside south wall surface could reach up to 17°C, much larger than the air temperature difference mentioned above. Due to its higher heat transfer coefficients, at night the inner surface temperature of the windows (South window-in) dropped faster than the wall. The temperature fluctuation on the surface of the west wall was relatively larger and the peak temperature exceeded the south wall, because there was no hollow layer in this wall.

Fig. 9 describes the temperature variation on the surfaces of the indoor air inlets. Similar to the winter conditions, there was a 1°C temperature difference between the inlet and outlet water pipes. It is also illustrated in the figure that with the operation of the thermal regulation system, the surface temperature of the water pipes increased gradually, which reflected the temperature rise in the water tanks after a long running period.

Fig. 10 describes the distribution of indoor air temperature in the experimental building. The experiment was taken on August 4th 2010. Five measuring points were selected for analysis. As shown in the figure, the average air temperature at the air inlet (Inlet-0.2m) was 26°C when the thermal regulation system was running. It can be seen from the figure that the farther away it is from the air inlet, the higher the air temperature can be. The second floor measure point (Hall-4.5m) reached 32°C during the day, which was far beyond the range of thermal comfort. In general, the indoor air temperature distribution was uneven, which shows the character of the thermal regulation system.

Fig. 11 describes the water temperature variation in the water tanks, and shows the running time of the underground and indoor water pumps. The underground water pump was turned on one night before the other equipment. The water temperature in the tanks then dropped about 4°C. In the daytime, the indoor pump and the air system was turned on, and the water temperature in the tanks rose rapidly. The underground pump could keep running or be turned off, according to the cooling loads indoors. It was important for the air system to run intermittently, and for the underground pump to run in advance because it needs time to recover the water temperature in the water tank, unless it exceeds the comfort temperature after a long period. As can be seen in this figure, on July 19th the water temperature in the water tanks rose continuously during the day, and the underground pump was closed that night, so the next day the water temperature was too high for cooling function. Also shown in this figure, the water temperature in the tanks fluctuated at around 23.5°C during this period, which reflects that the system was in dynamic heat balance.
4.3 Energy Consumption and Power Generation of the Building

The energy consumption of the thermal regulation system, the lighting system and office appliances were recorded separately by ammeters. Because the thermal regulation system was only operated under extreme weather conditions for testing, we can only make a rough estimate on its energy consumption based on the recorded data. From the electricity consumption data of the thermal regulation system in the summer of 2010, we can calculate that the average daily power consumption of the system was about 50kWh when the system operated for about 10 hours a day. The power of the thermal regulation system was then about 5kW.

Fig.12. shows the energy consumption and the PV electricity generation of the experimental building in a whole year from July 9th 2009 to July 9th 2010. The thermal regulation system accounted for 38% of the total energy consumption. The floor area of the experimental building is 240 square meters. So the energy consumption of the experimental building throughout the year was 10.7kWh/(m²*a), which is only about 12% of the 89.8kWh/(m²*a) average electricity consumption of ordinary office buildings in Wuhan (L. D. Wan et al. 2010). The thermal environment in the building cannot satisfy the comfort standard for office buildings, but can be acceptable for buildings in rural areas in the hot summer and cold winter zone of China.

The daily electricity generation of the experimental building in 2010 is shown in Fig.13. The electricity generation fluctuates every day, high in summer and low in winter, with 15.0kW on average. The total power output was 5466kWh in 2010. The PV system generated 43% more than the electricity consumption of the building, with a surplus of 1700kWh.

5. Conclusions

To study the thermal behavior of an experimental low-cost, low-energy building in Wuhan, tests were carried out to monitor the thermal environment parameters, building energy consumption and other aspects of the building. The conclusions of the study can be summarized as follows:

(1) According to the climate characteristics of Wuhan, the thermal regulation system of the experimental building can achieve a certain effect. The results show that indoor air temperature can be
improved to about 14°C in winter and 28°C in summer by the thermal regulation system, which cannot satisfy the general comfort standards, but can be acceptable for buildings in rural areas in the hot summer and cold winter zone of China. The indoor air temperature was limited to the underground soil temperature in Wuhan. So to meet the thermal comfort standard, a heat pump or an auxiliary heating/cooling source should be added in the thermal regulation system.

(2) Due to the characteristic of the thermal regulation system, the indoor air temperature distribution in the experimental building was uneven.

(3) The energy consumption of the experimental building is 10.7kWh/(m²*a), much lower than that of ordinary office buildings in Wuhan, and the electricity generation of the building fulfills more than it demands.

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