Analysis of the field tests efficiency of indoor environmental control and energy saving technology: the cases of Solar Decathlon China 2018

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Abstract. The International Solar Decathlon initiated by the US Department of Energy in 2002 has been conducted for 17 years, but the literature on the use of field test big data to study the performance of design projects during the competition is scarce. This paper summarizes energy saving technologies used in past Solar Decathlons in the literature. The indoor environment test data of 5 demo participating teams of Solar Decathlon China (SDC) 2018 are organized and analyzed. The energy consumption and indoor environment data of buildings of SDC 2018 are comprehensively compared with those of past solar competition buildings. The energy consumption characteristics and indoor thermal environment characteristics of this zero-energy building are summarized. An energy evaluation index for unit energy consumption, namely energy consumption per square meter per day, is proposed. The unit energy consumption of buildings during the solar competition is 0.28–0.51 kWh/(d·m²), with an average of 0.35 kWh/(d·m²). HVAC system energy consumption exceeds 50%. The unit energy consumption of the air conditioning system ranges between 0.13–0.23 kWh/(d·m²) with an average of 0.18 kWh/(d·m²). This can be used as a reference for future solar energy system capacity designs. According to the results of the analysis of the competition data, the recommendations for the construction of zero-energy houses for intermittent use are given in the design of the architecture design and the HVAC system. Furthermore, a control strategy to ensure indoor environment comfort and system energy saving has also been proposed.

1. Introduction
Nowdays, buildings are one of the main energy consumers. It is stated that in a recent study by the International Energy Agency (IEA), energy consumption by buildings accounts for more than 40% of primary energy consumption [1]. So energy-saving in buildings is one of main research topics in the whole world. The energy-saving technologies used by the solar competition teams in the literature and the energy consumption during the competition and the performance of the indoor environment are summarized. It is concluded that most of the literatures are about the introduction of building energy-saving design and simulation data, and there is a lack of comprehensive analysis and analysis of the test data during the competition of different teams. This article will analyze the indoor environmental test data of the five participating teams of SDC in 2018, and the energy consumption data of the team of Tsinghua University to analyze the performance of the participating buildings of different HVAC systems.

2. Design of five cases in Solar Decathlon China 2018
Solar Decathlon China 2018 was held in Dezhou, Shandong Province, China, from July to August. A total of 20 joint teams from 41 universities in 10 countries participated in the competition. This paper analyzes the indoor environment and energy engineering design and indoor comfort zone test results of five participating teams, including Team THU, Team TUBSEU, Team BJTU, Team Solar-Offspring,
Team SCUT-POLITO. Team THU’s WHAO House indoor environment related passive and passive design concept will be focused on, and the design of the other four teams will be briefly introduced.

The building area of WHAO house is 144 m², which is divided into four sections, namely First Bedroom, Second Bedroom, Hub and Multimedia room. The building wall structure is shown in Figure 1. The heat transfer coefficient is 0.31 W/m²·°C. The door and window adopt three glass and two hollow low-e structures, and the heat transfer coefficient is 1.6 W/m²·°C. The envelope structure is suspended with wooden board. There is a spacing of 150 mm as a buffer cavity area between the wooden board and the envelope structure. As shown in Figure 2-A, vents are provided above and below the board. Figure 2-B is a schematic cross-sectional view of the structure. In summer, the wooden board can effectively prevent the sun from directly hitting the wall, while the chimney effect will make the buffer air flow, taking away most of the heat generated by solar radiation, greatly reducing the building cooling load. The design cooling load is 156 W/m². The building uses a Variable Refrigerant Flow (VRF) system with a rated cooling capacity of 22.4 kW. The system includes an outdoor unit and six indoor units. VRF system is controlled according to the indoor temperature feedback control. The Hub and Multimedia rooms are equipped with fresh air purification system. Team TUBSEU has a building area of 141 m² and uses a cold radiant panel system with a total cooling capacity of 5 kW. Team BJTU has a building area of 160 m² and uses a VRF system with a total cooling capacity of 27.9 kW. Team Solar-Offspring building has an air-conditioning area of 120 m². It is equipped with a cold radiant panel and a return air system. The total cooling capacity is 11 kW. Team SCUT-POLITO uses the VRF system.

Figure 1. Structure detail
Figure 2. Ventilation diagram of the envelope structure

3. Result of the tests

3.1. Test results of indoor thermal environment of five cases

Solar Decathlon China testing time is 2nd - 17th, August, 2018. The daily maximum temperature reached 36 °C and the average temperature reached 30 °C. The relative humidity was up to 90% per day, and the outdoor absolute humidity ratio is 20 g/(kg · DA). The maximum radiation intensity in the horizontal direction reached 900 W/m². During the test period, the outdoor was in extreme high temperature and high humidity conditions, and the upper limit of the HVAC system design load had been reached every day, which was a hard test for the indoor thermal environment. While the indoor environment scoring standards set by the competition were very strict, other than this, the harsh outdoor environment also made the indoor environment extremely difficult.

Figure 3 shows the comparison of outdoor and indoor temperature & humidity test results. By comparing the outdoor environmental parameters with the indoor test parameters, it is found that indoor natural ventilation is impossible due to the outdoor high temperature and high humidity conditions and the required indoor environmental standards. Moreover, in order to reduce the energy consumption of building HVAC system, it is necessary to ensure the tightness of the doors and windows of the building. By reducing the amount of air leakage, the quality of the indoor environmental parameters can be improved and the energy of the HVAC system can be saved.
As shown in Figure 4-8, the indoor temperature and humidity test data of the five teams are marked in the comfort zone of the id diagram. At the same time, the score requirements for the comfort zone of the competition rules are also marked in the id diagram, so that the temperature and humidity of each team can be analyzed. The temperature test score is 40 points, and the humidity test is 20 points. Team THU temperature and humidity score 55.88 is ranked first among 20 teams. From the test results, the ratio of
the test parameter points of the humidity non-score is significantly higher than that of temperature, and the ratio of the humidity parameter full-score is obviously smaller than that of temperature. The proportion of the humidity test is significantly lower than the temperature score. The control of indoor humidity is the focus and difficulty of indoor environmental control. Among the five teams, Team THU and Team SCUT-Polito used VRF system (Due to energy balance problem, during some test time Team BJTU did not start up HVAC system, so it is not discussed here); Team TUBSEU and Team Solar-Offspring used radiant panels for cooling and fresh air dehumidification system. From the final score, the VRF system scores reached higher than the cold radiation system. There are very few parameter non-score points for Team THU humidity and temperature. The temperature points of reduced-score are basically distributed in the range of 25 °C-28 °C. The parameter points of Team TUBSEU are partly distributed in the range of 25 °C-28 °C, which leads to serious loss of points. Team Solar-Offspring humidity parameter points are mostly in the non-score zone. In addition, the temperature parameter is lower than the reduced-score zone. This situation leads that a large amount of electricity were consumed but a perfect score of comfort zone was not got yet. It may be caused by too long control feedback time of the radiation system. Team SCUT-POLITO is the team with the largest full-score points. The test results are similar to those of Team THU. The parameter points of some scores are basically distributed in the range of 25 °C-28 °C.

3.2. Test result of energy consumption and thermal environment of Team THU

Figure 10 shows the test results of energy consumption of Team THU during the competition. It is divided into eight parts to measure electricity consumption. During the competition, the total energy consumption in 15 days was 655.7 kWh, of which 525 kWh of the HVAC system accounted for 80%, and the Socket & Lighting system was 115 kWh, accounting for 18%, as shown in Figure 9. The energy saving of the HVAC system is crucial for the energy saving of the entire building. Due to the requirements of the building using period, the HVAC system run intermittently according to the indoor environmental test time. The daily peak of electricity consumption appeared after the HVAC system started up at 16:00 pm. As shown in Figure 11, after the HVAC system started up, the indoor temperature kept stabilized within the comfort zone after 20 minutes. The outdoor unit of VRF had a large instantaneous load and the power peak reached 7.5 kW, which was 1.5 times the rated power. During non-air conditioning hours, the indoor room temperature exceeded 30 °C. It could be seen that the use of passive technology during the test could just reduce the energy consumption, but could not create an indoor environment within the comfort zone alone.

Figure 10. Energy consumption test results of Team THU
Discussion and Conclusion

Based on the test results of the above SDC 2018, combined with the actual test data of past solar competitions in the literature, the characteristics of the indoor environment and energy consumption are summarized. The methods and experiences in architectural design, equipment system design, and indoor thermal environment control are analyzed and discussed.

The indoor environment and energy consumption are the focus of the solar competition and the focus of green building and zero-energy building research. The three buildings and WHAO House data with energy consumption during the competition are comparatively analyzed. Given that these cases have a similar operating condition with high temperature and high humidity, they are comparable. However, in these cases, the building area and running time are different. Here, a unit energy consumption evaluation index per square meter and per day electricity consumption is proposed to facilitate case comparison.

Table 1. Energy Consumption

| Team          | Area | Running Days | Total Consumption | HVAC Consumption | Unit Total Consumption | Unit HVAC Consumption |
|---------------|------|--------------|-------------------|------------------|------------------------|----------------------|
|               | m²   | day          | kWh               | kWh              | kWh/(d·m²)             | kWh/(d·m²)            |
| WHAO House    | 144  | 16           | 655.7             | 525.0            | 0.28                   | 0.23                 |
| STILE House   | 70   | 9            | 322.06            | 115.9            | 0.51                   | 0.18                 |
| GRoW Home     | 71.3 | 8            | 161               | 74.5             | 0.28                   | 0.13                 |
| Solark I      | 94   | 9            | 276.3             | 152              | 0.33                   | 0.18                 |
| Average       |      |              |                   |                  | 0.35                   | 0.18                 |

From Table 1, it can be seen that the unit energy consumption of each building during the solar competition was 0.28–0.51 kWh/(d·m²), and the average value was 0.35 kWh/(d·m²). This value will be useful in the designing of future solar systems for solar competition teams. In contrast, the HVAC system consumption in all cases was the largest share of the energy consumption, most of which exceeded 50%. The unit energy consumption of HVAC system was distributed in the range of 0.13–0.23 kWh/(d·m²) with an average of 0.18 kWh/(d·m²). Both the WHAO House and the Solark I use the VRF system and perform well in the comfort zone. The energy consumption per unit of the air conditioning system of both buildings was 0.18 kWh/(d·m²). It is easy to operate VRF system; it has a high SCOP, which makes it ideal for buildings with intermittent air conditioning. Furthermore, the three buildings in the literature also mentioned that the outdoor climatic conditions during the competition were extremely harsh, far exceeding the expected outdoor calculation conditions at the time of design. As a result, the installed capacity of the air conditioning system was insufficient, and the cooling load under extreme outdoor weather conditions could not be handled. Therefore, when designing an air conditioning system, considering the extreme weather conditions, appropriately increasing the installed capacity of the air conditioning system equipment is the key to maintaining the required indoor thermal environment conditions.
4.1. Architecture design

Owing to the high temperature and high humidity during summer, the airtightness of the building doors and windows and the external envelope structure considerably affect the indoor environment performance and HVAC energy consumption. Better air tightness can reduce the difficulty in maintaining the required indoor thermal environment conditions, and it can also significantly reduce the energy consumption of HVAC systems. The outward sunshade design plays an important role in the indoor thermal environment and energy conservation. Architects often simplify or neglect the exterior shade design because of the aesthetic appearance of the building, resulting in large energy consumption in the HVAC system and poor indoor thermal environment. The focus of building energy efficiency is the south and west outward shade design. The different functional spaces of the building should be relatively independent. The relatively independent spatial separation facilitates the independent control of the device partition and provides the possibility for energy saving of the device under different use conditions.

4.2. Energy consumption characteristics and optimization design strategy for HVAC system

It is difficult to maintain the required indoor thermal environment during extreme weather conditions occur during the competition. During the test period, the outdoor weather is extremely hot, and the cooling load will be large. The building using mode causes the HVAC system to start up intermittently; therefore the HVAC system has a large instantaneous cooling load, and the instantaneous power can reach 1.5 times the rated power. For the intermittent use of residential buildings, the requirements for the HVAC system are as follows:

1. Rapid system response, easily turned on and off, lower thermal inertia;
2. Rapid indoor cooling and strong dehumidification capacity;
3. Equipment design load are sufficiently large to deal with extreme weather conditions, and the design capacity of the air conditioner outlet end of the room is slightly larger than the capacity of the outdoor cold source side.

The radiant air conditioning system has a larger thermal inertia, a longer control feedback period, and a slower system adjustment speed, which is not suitable for the intermittent use of residential buildings. The VRF system features the requirements of this type of building for air conditioning systems. However, the VRF system control mechanism is the indoor temperature feedback control, which has limited processing capacity for indoor humidity, and cannot satisfy the requirements of indoor humidity when the outdoor humidity is too high, and the indoor wet load is too large. Owing to the VRF system temperature and humidity control coupling, excessive dehumidification can cause the indoor temperature to be too low. The VRF system with outlet end reheating can be used, and part of the high temperature refrigerant is used as the indoor end reheating source, which can improve the system COP, save reheating power consumption, and prevent the indoor temperature from becoming too low owing to the deep dehumidification. A drawback of this system is that the air conditioning pipeline is complicated, and it is expensive.

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