Study on the Thermal Environment of the YaoDong Dwelling in the Loess Plateau of China

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Abstract
YaoDong dwellings are distributed widely throughout the loess plateau in the north of China, and have many positive characteristics, such as good use of land, low cost, low impact on the environment, and a comfortable thermal environment. The aim of this study is to ascertain to what extent the indoor climate of YaoDong is a natural one regarding building design as a sustainable architecture. The authors carried out a survey in Zaoyuan village of Yan’an city in August 1999. They collected basic data regarding the natural conditions of the site, climate condition of the Yan’an area, and the thermal environment of YaoDong dwellings. The authors found that YaoDong had excellent characteristics regarding the thermal environment in the summer.

Keywords: China; loess plateau; YaoDong; thermal environment; summer season

1. Introduction
In the loess plateau of north China, cave dwellings called YaoDong are widely distributed. These dwellings adapt themselves to severe natural conditions such as the geography and climate of this area, and have been inherited by the present generation. It is said that about forty million people live in YaoDong now. However, with development of the economy and change of life style, there has been a trend for young people to leave the YaoDong dwellings in recent years.

On the other hand, while environmental problems become serious, the YaoDong dwelling is seen to have many merits such as; good use of land, reduction in the environmental load, reduced construction costs and good thermal characteristics.

The research team of Xi’an University of Architecture and Technology has paid attention to this excellent aspect of the YaoDong. Taking Zaoyuan village (in Yan’an city, SHAANXI Province) as a model area, they have been working to find a sustainable architectural system and investigated the village and dwellings in the loess plateau as part of their green architecture system research 1). The main purpose of their research is to improve the indoor environment of, and find a new style for YaoDong, which can satisfy modern life. In this research they also tried to find a method by which good use can be made of natural energy, by recycling possible natural resources in the area.

The Yoshida2)3) group carried out a consciousness and field survey regarding the thermal environment, quality of air, light and sound environment in the summer and winter in the YaoDong area. As a result of the survey, they confirmed that the YaoDong have excellent thermal environment characteristics such as insulation and large heat storage. On the other hand, they pointed out many problems such as lighting and ventilation problems. Based on these survey result, they proposed a new style of YaoDong for the purpose of improving the living environment.

In this study, the authors conducted another survey in the YaoDong area from the viewpoint of sustainable architecture. The object area is Zaoyuan village in Yan’an city; the time, August 1999. As a result, basic data regarding the natural conditions of the site and climate conditions of the Yan’an area, together with the thermal environment of YaoDong dwellings was collected.

2. General climate condition of Yan’an
Yan’an is located in the loess plateau of north SHAANXI Province, about 300 km north of Xi’an
(Fig. 1). According to the geographic date, Yan’an has a typical continental climate with large temperature difference between the day and night. There is little rainfalls, and drought often occurs. The precipitation for one year is from 490mm to 660mm and the precipitation in July, August and September is about 60% of the entire year. Therefore, except for July, August and September, there are many days with fair weather. The annual mean temperature is from 7.7 to 10.6°C, –6°C in January and 23°C in July. According to the weather bureau in Xi’an, in the past, the lowest temperature was recorded with –28.5°C in January, and the highest 39.9°C in July. The average of daily temperature range is about 14°C for one year. It is highest in the spring, and lowest in the fall. The amount of sunshine is comparatively long, with total sunshine hours during one year of from 2300 to 2570 hours. The quantity of solar radiation is 5,000 to 5,660 MJ/m² in one year, and is strong in the summer, and weaker in winter through one year.

As shown in the wind rose (Fig. 3), the main direction of the wind throughout most of the year (in summer from June to August and in winter from December to February) is from the southwest and west southwest.

3. Outline of the Survey

3.1 Survey Areas and Period

From August 20th to 21st, 1999, the authors carried out a survey of a typical YaoDong dwelling in ZaoYuan village, Yan’an city. ZaoYuan village is 1,000m above sea level, with a latitude 36°36’N, a longitude of 109°26’E, and is seven km northwest from the central part of Yan’an city.

3.2 Outline of Investigated Dwelling

Situated on a hill dwelling that the authors investigated is shown in Figs. 5 and 6. Five people of two families; a couple with a son and the man’s parents live in this dwelling. Two rooms (Room A and Room B) on the east side are independent without indoor access between the two rooms. The doors are facing south and there is a garden in the front. The roof is covered with soil and there are weeds growing on it.

3.3 Survey items and method

The authors took interior measurements of the air temperature, humidity, speed of air movement and surface temperature of the ceiling, floor and walls under the living conditions of the families. They also measured the outside air temperature, humidity and wind velocity. The measurement items, points, gauges and the method are shown in table 1. The time step is 10 minutes for automatic measurement, and one hour for the others.

4. The Survey Result

4.1 Solar Radiation

Fig. 1. Outline of the loess land and Yan’an city

Fig. 2. Solar radiation and sunshine hours of Yan’an

Fig. 3. Wind rose of Yan’an city
The quantity of solar radiation from August 20th to 22nd becomes greatest at noon on one p.m., and the value exceeds 3MJ/m². Although it rained in the evening on August 22nd, other days had almost clear skies throughout the survey period. (Fig. 7)

4.2 Temperature and Relative Humidity

Figure 8 shows the air temperature and solar radiation. Figure 9 shows the relative humidity and figure 10 the air temperature and humidity outside of Assman’s psychrometer.

The outside air temperature became highest from three to five p.m., the temperature was 34.4℃ at three p.m. The lowest temperature was 16.4℃ at seven p.m. The daily temperature range was 18℃. On the other hand, the highest relative humidity was 62% at around seven p.m., when the lowest relative humidity occurring between two and five p.m. at about 15%.

The maximum air temperature inside became highest at four thirty p.m., the back of Room A was 29.3℃, the front of Room A was 30.7℃, and the back of Room B was 29.2℃, while the front of Room B was 30.5℃. The lowest air temperature of Room A was 20.3℃ at the back, 21.6℃ at the front, while Room B was 19.7℃ at the back, and 20.9℃ at the front around seven a.m.. The daily temperature range of the back of Room A was 9℃, the front of Room A was 9.1℃, the back of Room B was 9.5℃, and the front of Room B was 9.6℃. Although differences in both rooms were observed, the extent of fluctuation was 8.4-9℃ smaller than that on the outside.

Regarding the relative humidity of the inside, Room A fluctuated from 18.6% to 39.8%, and Room B from 14.3% to 39.4%. According to the other reference2), the inside humidity of YaoDong contrasted also, although the reading is from 51% to 68%, higher than ours. The humidity of Room A was a little higher than that of Room B. The reason may be explained by the fact that Room A is mainly used for family activities, such as eating, living, and service, while Room B is only used for sleeping.

The outside air temperature change was intense, while the inside air temperature remained stable compared with the outside. The inside air temperature was kept below 30℃, when the outside maximum air temperature was about 35℃. A five degree centigrade decrease was observed. The humidity level of the YaoDong was also lower than that of the outside. Therefore, it can be said that the YaoDong can mitigate the maximum air temperature and as a result, provide a good thermal environment.

4.3 Indoor Surface Temperature

Figures 11, 12 and 13 show the indoor surface temperatures.

The surface temperature of the ceiling was at its highest value during the daytime, and fluctuated from 26℃ to 28℃. The temperature front wall is lower than other place before two p.m., and became highest at around four p.m., the temperature of Room A was 29.5℃, of Room B 28℃. This resulted from the heat capacity effect of the
The difference of Room A and Room B results from the influence of shade from the cottage in front (Figs. 5 and 6). The floor surface temperature was lowest, fluctuating from about 22°C to 24°C. The next lowest one was the back wall, the side wall, and the ceiling. The difference between the ceiling and floor was about 4°C. The both east and west walls are the same. The surface temperature becomes higher in accordance with the height even for the same wall (Fig. 13). It was observed that there is a tendency for the inside surface temperature of YaoDong to become gradually high from the floor to the wall, and ceiling.

There was also a tendency for the surface temperature of the wall to become gradually high from the back wall, to the side wall, and to the front wall. (Figs. 11, 12 and 13)

4.4 Wind Velocity Inside and Outside

Regarding the outside wind velocity, the highest was 0.8 m/s, the lowest 0.4 m/s, and the average velocity was 0.6 m/s. The highest inside air flow speed was 0.2 m/s, the lowest 0.13 m/s, and the average 0.17 m/s. Figure 14 shows that the variation of wind velocity was small both indoors as well as outside.

4.5 Evaluation of the Inside Environment

A person was assumed to rest seated in summer with a condition of Met=1, clo=0.5. We calculated the ET*, SET* (Fig. 15) and PMV (Fig. 16) to evaluate the

| Items          | Point | Used devices  | Method               |
|----------------|-------|---------------|----------------------|
| Room Temp.     | A, B  | Thermo Recorder RH | 10 minutes time steps for automatic measurement |
| Room Humid.    | A, B  | Thermo Recorder (T&D TR-17) |
| Air Velocity   | Center of Room | Anemo-thermo meter (RLEN + AM-09 Type) |
| Surface Temp.  | A, B  | Radiation Thermometer (MINOLTA - 905) | One hour time step for manual measurement from 08:00 to 18:00 |
| Outside Temp.  | A, B  | (°C) | Assman's psychrometer (T&D TR-72) |
| Outside Humid. | A, B  | (%) | (T&D TR-72) |
| Wind velocity  | A, B  | Anemo-thermo meter (RLEN + AM-09 Type) |

Fig. 7. Solar radiation during the survey period

Fig. 8. Temperature and the solar radiation (Aug. 20th to 21st)

Fig. 9. The relative humidity (Aug. 20th to 21st)
inside thermal environment. The results showed that $\text{ET}^*$ is about 27°C at three or four p.m. when the outside air temperature is about 35°C. The $\text{SET}^*$ is about 26.5°C at the same time.

The PMV was a little cool in the morning, and changed to a little hot in afternoon when the outside temperature became high. The value is between ±0.5, which showed a comfortable indoor thermal condition.

5. Conclusions
The survey regarding the thermal environment characteristics of the YaoDong dwellings was carried out in the ZaoYuan village where located in the loess plateau of China. Through analysis, the authors confirm
confirmed that YaoDong had good characteristics as follows:
1. The quantity of solar radiation is high.
2. The inside air temperature is quite stable, even though the daily range of the outside air temperature is large.
3. The relative humidity in YaoDong was very low.
4. The inside surface temperature has a tendency to become high from the floor to wall, and to the ceiling.
5. There was a tendency for the surface temperature of the walls to become gradually high from the back wall, to side wall, and to the front walls near the window.
6. Both the outside and inside wind velocities were small.
7. Although the maximum outside temperature reaches 35℃, the interior can maintain a comfortable thermal environment.

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