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A Study on the Thermal Performance of the Earthen Tower in Summer

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This paper focuses on the thermal properties of earthen towers, unique traditional dwelling buildings at Yongding, in Fujian, China. The main climate factors affecting indoor thermal environment in the area are discussed. The architectural details of the earthen tower functioning as thermal defence in summer are analysed. A computer simulation programme, developed especially for the condition of building and climate in Fujian, is used to study the thermal interaction between building structure, occupancy and climate. The results from various rooms in two typical forms of the building show that the thermal performance of the earthen tower is excellent.

INTRODUCTION

THE EARTHEN towers of Hakkas in western Fujian, China, have a strong appeal to tourists and researchers from all over the world because of their exquisite architecture, excellent construction techniques and special status in the world's traditional residential buildings (Fig. 1) [1]. Many investigations and surveys have been done in areas, such as: the evolution of the earthen tower, the development of construction techniques, the architecture and built form of the buildings, decoration on details and relationship with the culture of local Hakkas. Some papers have mentioned the excellent indoor thermal condition of the earthen tower in summer. But the thermal performance, indoor climate and building climatology have not been studied.

For the traditional residential building, convenience, comfort and economical construction are the main aims of the building's owner. Cultural influences and the local climate are the main factors which affect the architecture of local dwellings. One of the most important functions of the dwelling is to provide a comfortable indoor environment. So the study on the buildings' thermal performance is an aspect of the research on traditional residential buildings [2].

The computer simulation based on numerical analysis has been a prevalent way of research on buildings' thermal performance for its prompt and convenient computation. In this paper, NVBTCP program (Naturally Ventilated Buildings' Indoor Climate Predicting), a computer model based on Mathews' theory [3] and developed especially for the building and the climate condition in Fujian [4], has been chosen to simulate the thermal performance of different rooms in extreme summer weather conditions. Most data required for simulation by the computer model are measured or tested practically and many results have been compared with that of on-site testing. The comparison shows that the simulation is successful and the results are reliable. The thermal properties of some structures, such as gable roof, earthen wall and circular external gallery, and architecture of the building have been studied systematically.

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BUILDING CLIMATE OF EARTHEN TOWER

One of the most interesting and at the same time complicating factors about building climatology is that of scale. In this paper, Barry's method of climate system division is adopted. The data tested and analyzed statistically over two decades by the county station at Yongding are used to describe the regional climate. After a modification of the data from the local station, the data are used to describe the topographic climate of the area where the specific earthen tower is located, and input for the simulation.

The characteristics of summer climate at Yongding

The climate at Yongding belongs to the hill and valley type in the middle subtropical climate, and is noted for its mild winters and long summers. The main thermal function of the traditional dwelling is to prevent the indoor environment from overheating in summer.

The air temperature increases gradually from January and reaches its peak in July with relatively high humidity and a clear sky. For an example of thermal defence of a building in summer, the climate of a clear day in July presents a typical condition.

Solar radiation in summer

Radiation, temperature, humidity and wind, are the aspects of climate of immediate interest when we are concerned with the thermal design of a building. The hourly values of irradiation on various surfaces in summer at Yongding (located in an area from 24′23″N to 25′05″N), are shown in Table 1. We can see that the irradiation is quite strong. But for most days of the summer at Yongding, when the skies are partially or heavily

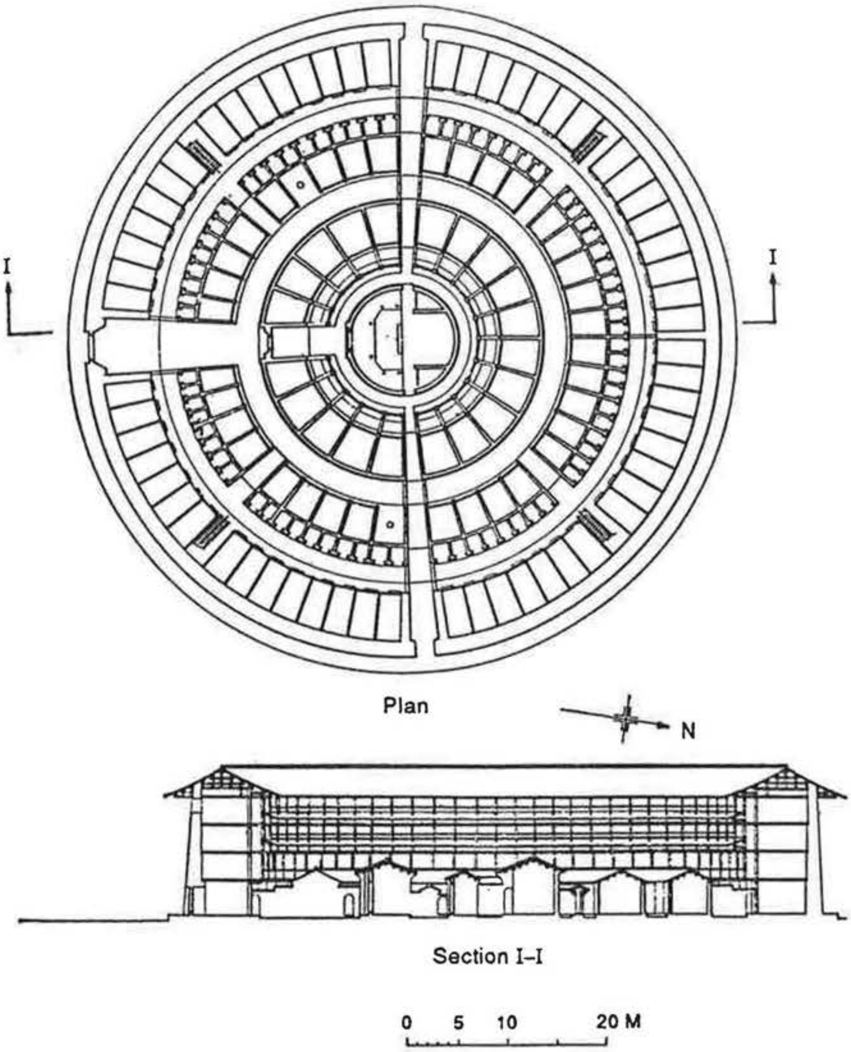

Fig. 1. The largest earthen tower—Chengqi Tower, Plan (above), Section.

Table 1. Irradiation on various surfaces at Yongding

Hour	Irradiation on					Diffuse irradiation
	Horizontal	N-wall	E-wall	S-wall	W-wall	
6	71.21	32.29	45.54	24.24	24.24	48.48
7	269.18	130.42	331.04	52.50	52.50	104.99
8	482.83	151.80	503.99	65.60	65.60	131.19
9	675.17	126.75	526.99	72.37	72.37	144.73
10	827.43	90.03	443.32	76.08	76.08	152.16
11	926.99	78.01	290.46	95.43	78.01	156.03
12	966.08	78.69	101.50	109.26	78.69	157.38
13	941.70	78.27	78.69	100.59	248.55	156.55
14	855.73	82.04	76.66	76.66	412.57	153.33
15	714.82	118.33	73.44	73.44	515.30	146.88
16	530.42	148.49	67.57	67.57	520.74	135.13
17	319.56	142.12	56.44	56.44	386.32	112.89
18	111.94	57.66	32.90	32.90	102.90	52.79

overcast, the irradiation values are smaller than those in Table 1.

Cloudiness at Yongding is generally high. During July, August and September, cloudinesses are 7.1, 7.1 and 6.7 respectively, and the number of days on which cloudiness is less than 20% are only 1.2, 1.7 and 2.3 respectively. The cloudiness also shortens sunshine hours in the area. The mean value of the daily sunshine hours is only 57% of the mean length of day between sunrise and sunset during these months. Therefore the summer is not so severe at Yongding.

Air temperature

The characteristic of air temperature changes from place to place over the county. One of the reasons is altitude. The difference in altitude between the highest and the lowest village is more than 500 meters, and influences local temperature patterns. Take for example Chengguan, Hukeng and Hushan the altitudes of which are 180, 348 and 550 meters respectively, and the mean air temperatures in July are 28.4°C, 27.3°C and 26.4°C respectively.

Another factor of temperature influencing buildings' thermal performance is the diurnal temperature variation. Along with solar radiation in areas of hills and valleys, the diurnal variation at Yongding which is greater than 10.0°C in July, August and September, results in hot days and cold nights. So a big value of thermal storage is required for a small swing of indoor temperature.

Wind

Wind force and direction will affect the thermal regime of a building in two ways; it will determine the surface resistance and hence the insulation of the shell, and affect the air change rate due to infiltration through openings, and hence the total heat balance, especially in a naturally ventilated building.

The wind rose shown in Fig. 2 represents the wind directions and percentages of time in July, at Yongding. In summer the mean wind speed is 2.2 m/s. The low wind speeds occur generally at night and come randomly from any direction, while the higher speeds are likely to come during the day, especially after noon, from the prevailing direction in the month. In a micro-climate, factors such as ground topography, height of the building, interaction with other buildings etc., affect the wind velocity and the manner in which it acts upon a given building and must

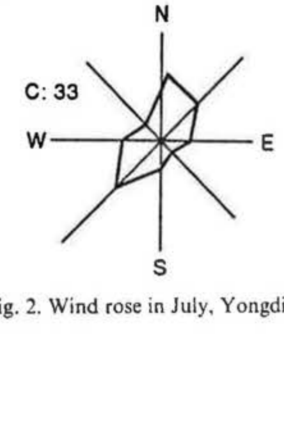

Fig. 2. Wind rose in July, Yongding.

be taken into account when we calculate the PMV-index. Hence the better computer simulation must use the wind data in the micro-climate. Figures 10 and 11 show an example of wind speed curve of a test room inside the earthen tower in an extreme summer day. The curve is obtained by modifying the wind data of local meteorology station with the test in the particular room.

THERMAL DEFENCE FUNCTIONS OF EARTHEN TOWER

In the previous section, we have made a summary of the environment around an earthen tower in summer. Now we will consider the earthen tower, the fabric of which and some elements play important roles in thermal defence in summer, acting as modifiers that change the unsuitable summer exterior to a thermally comfortable interior.

Roof

The roof of the earthen tower is called a Nine Purlins Roof which is peculiar to Hakkas. Its eaves are exceedingly large, often reaching 2 to 3 meters, and this huge overhang provides shade for the fabric at most times of the sunshine day. For example, the south wall is completely shaded, the west and the east walls of the top storey are shaded more than 80% of the sunshine day. Hence the direct irradiation on fabric is quite weak and the solar-air temperatures on all surfaces are fairly low.

The supporting outer earthen walls of most towers are constructed just below the lower chord. The attic, which is a void between roof and ceiling, is completely open to the exterior and naturally ventilated (Fig. 3).

Besides the circular and the square earthen towers, another form of earthen tower which is called "Santang Wu" has all the characteristics we have mentioned. Moreover there are dormer windows on both gables as ventilation apertures.

All those functions reduce the influence of irradiation of the roof on the rooms of the top storey.

External gallery

The external gallery, on the inner side of the circular building, provides an excellent shading for the plank wall of which thickness, thermal capacity and storage ability are very small. For economic reasons, all timber components of earthen towers are kept unpainted. The surface of the plank wall has become dark brown as years elapse, and its absorptivity of solar radiation can reach 0.87. So the defence function of the gallery for the plank is more important than that of eaves for the thick outer earthen wall.

Mass external wall

The remarkable characteristic of the earthen tower at Yongding is its massive external wall constructed by ramming earth. For most three or four-storey earthen towers, the thickness of the wall is almost 1.5 m at the ground storey and about 0.9 m at the top storey. The thermal resistance, storage and capacity of such a thick wall are much larger than 240 brickwork which is another type of external wall in Fujian.

ventilated because there is no window on the external wall. But there is breeze along the gallery on the ground floor occasionally. The breeze, with the low mean radiation temperature, creates a pleasantly cool place where the people of Hakkas are fond of resting and chatting.

THERMAL SIMULATION FOR THE TYPICAL ROOMS OF EARTHEN TOWER

Local people generally call earthen towers "circular tower" and "square tower". But in fact, there are three main kinds of plan forms for the earthen towers (Fig. 1, Fig. 5a and Fig. 5b). From the viewpoint of thermal comfort, the earthen towers shown in Fig. 1 and Fig. 5a belong to the same kind, for there is one row of rooms around the building, the natural ventilation in the rooms is generally great, but that in Fig. 5b belongs to another kind with less ventilation. The two typical earthen towers shown in Fig. 1 and Fig. 5b are chosen for computer simulation.

In the first kind of earthen tower, the thermal performances of 8 rooms, north, east, south and west on the fourth floor and the third floor are simulated for a clear summer day, 12 July. In another, that of 6 rooms, indicated in Fig. 5b, are simulated. All windows and the door of the room are fully opened. Owing to the great thermal inertia of the earthen tower, the simulations were executed continuously for three days and the results of the last day taken as the final thermal performance of the rooms. This method has eliminated the influence of initial state of the walls, of which the thermal resistance and storage are very great when the numerical methods are applied.

The data of the occupant are fixed by investigation with the local dwellers. The values of activity level and clothing thermal resistance during a typical summer day are shown in Fig. 10.

Indoor air temperature

To determine some parameters which affect the forcing temperature on the rooms in the simulation program, two measurements were carried out in the circular earthen tower. After the adjustment, the forcing temperatures are set as,

$$T_{ff} = 0.65\ T_{sa} + 0.35\ T_e \quad \text{for the top storey}$$

and

$$T_{ff} = 0.4\ T_{sa} + 0.6\ T_e \quad \text{for the third storey,}$$

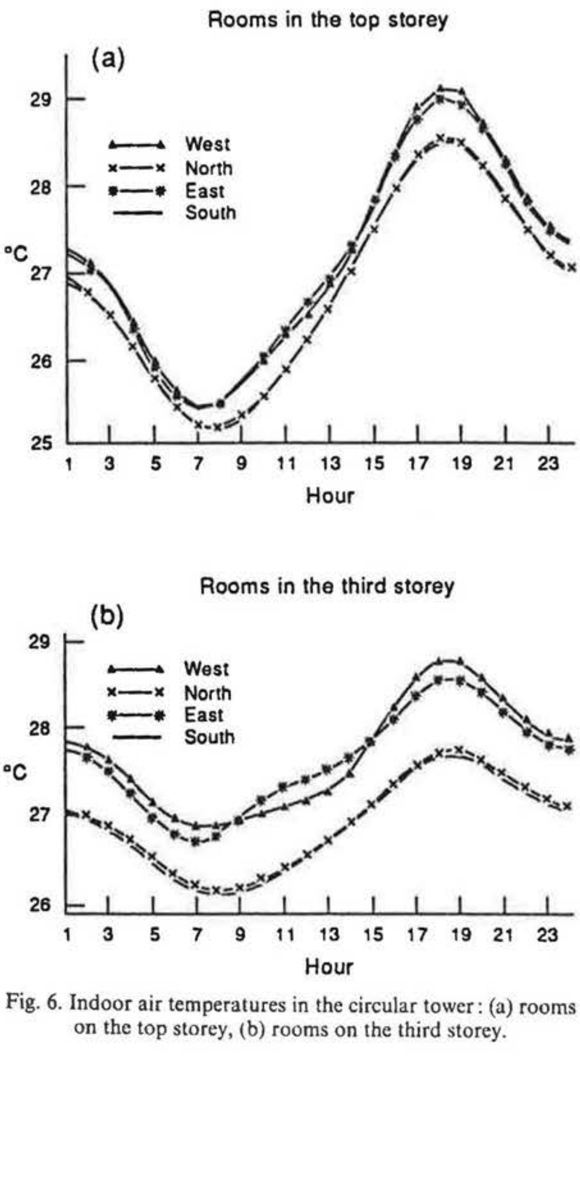

Fig. 6. Indoor air temperatures in the circular tower: (a) rooms on the top storey, (b) rooms on the third storey.

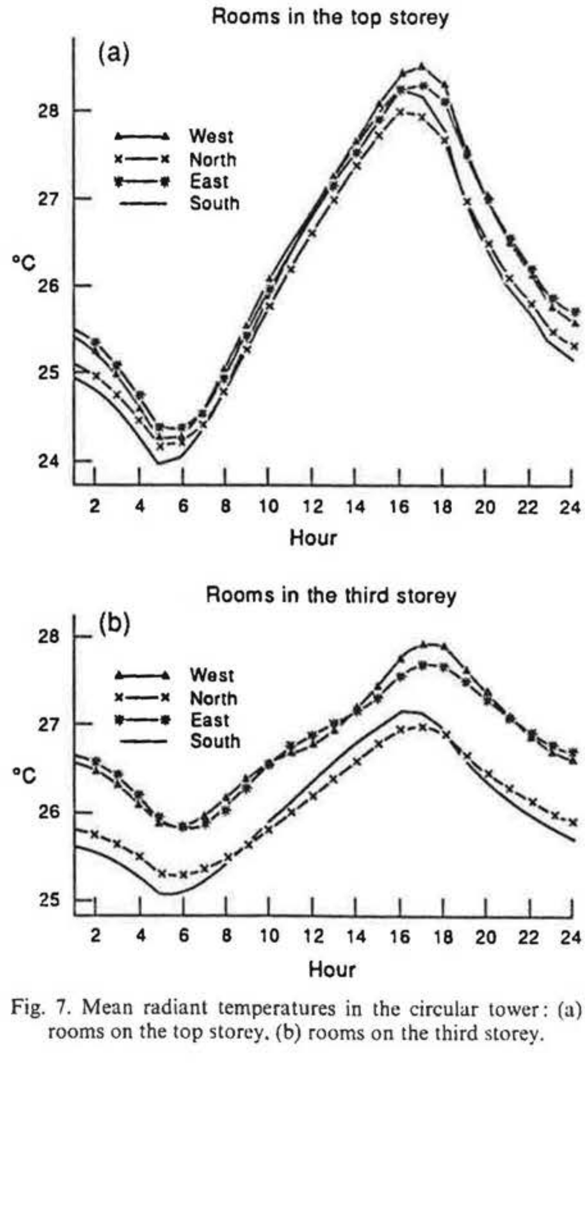

Fig. 7. Mean radiant temperatures in the circular tower: (a) rooms on the top storey, (b) rooms on the third storey.

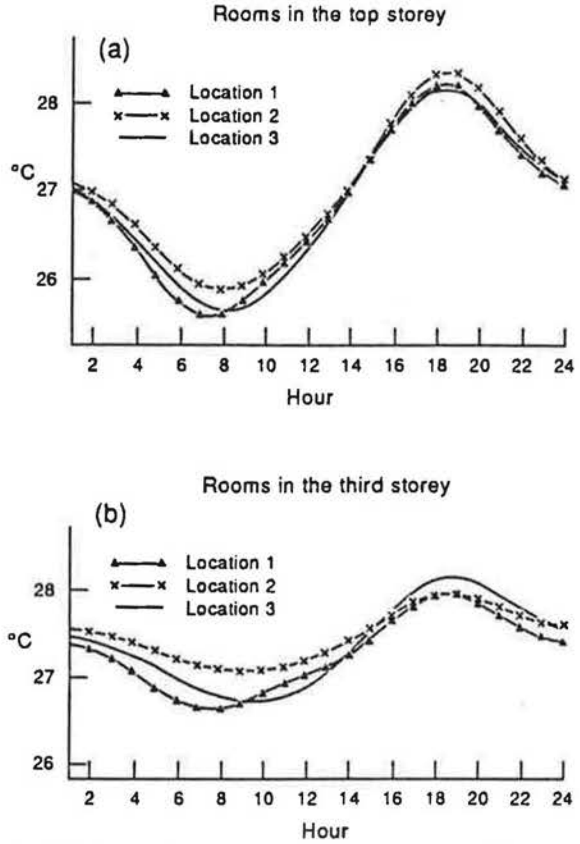

Fig. 8. Indoor air temperatures in the square tower: (a) rooms on the top storey, (b) rooms on the third storey.

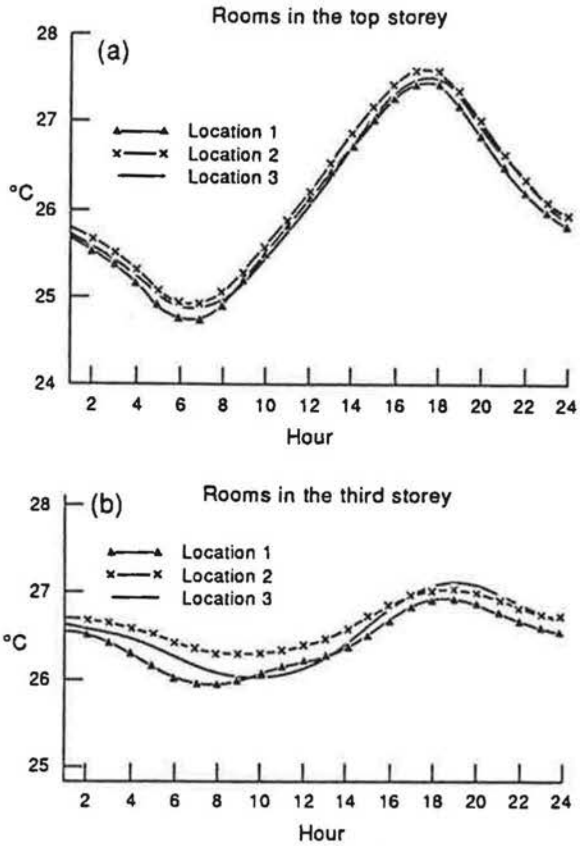

Fig. 9. Mean radiant temperatures in the square tower: (a) rooms on the top storey, (b) rooms on the third storey.

Tsa is the solar-air temperature on the external surface of the designated wall and Te is the outdoor air temperature. The indoor air temperatures of the 8 rooms are shown on Fig. 8.

For the square earthen tower, no measurement has been done, but from experience we could set the forcing temperature as follows,

in top storey,

$$Tff = 0.65\ Tsa + 0.35\ Te,$$

for the rooms at the two ends (Fig. 5a as 1 and 3),

$$Tff = 0.7\ Tsa + 0.3\ Te$$

for the room in the middle (Fig. 5a as 2),

in the third floor

$Tff = 0.4\ Tsa + 0.6\ Te$ for the rooms at the two ends,

$Tff = 0.65\ Tsa + 0.35\ Te$ for the room in the middle.

The simulation results of the indoor air temperature of the 6 rooms in the square tower are shown in Fig. 10.

From the results of simulation, we can see that air temperatures in the north room and the south room are

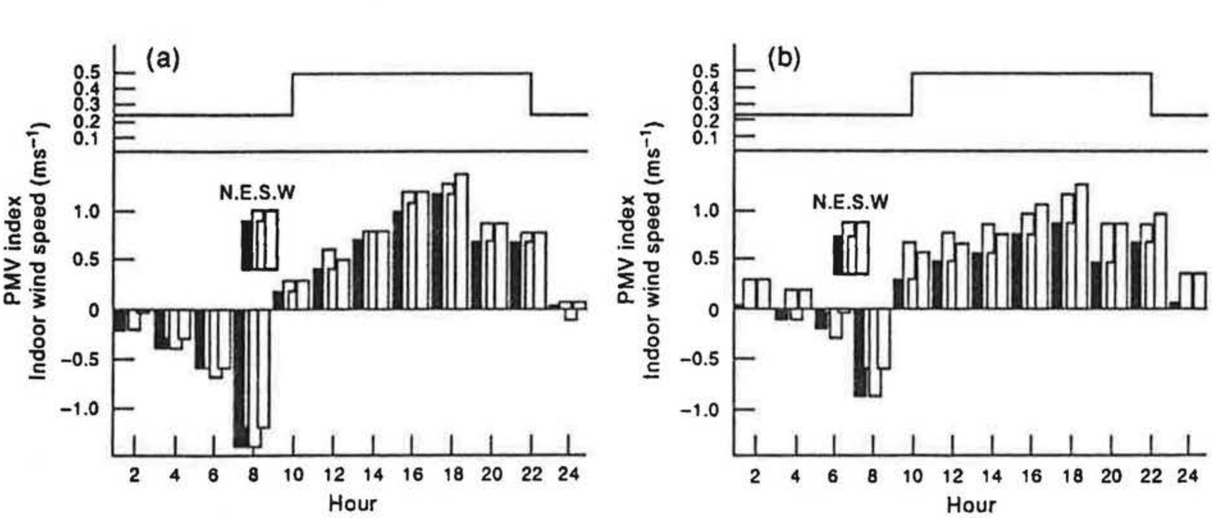

Fig. 10. PMV-index in the circular towers: (a) rooms on the top storey, (b) rooms on the third storey.

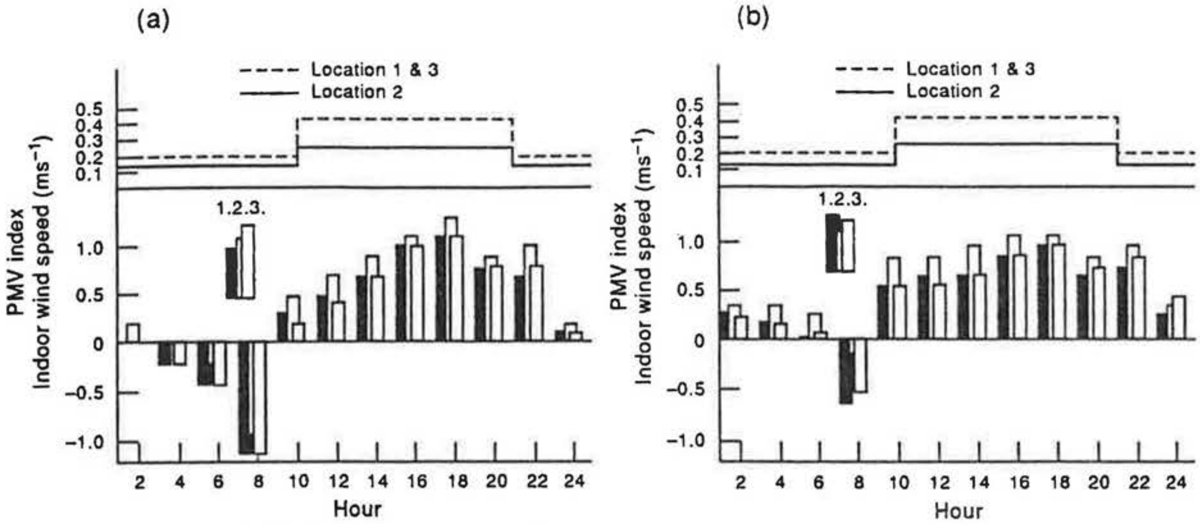

Fig. 11. PMV-index in the square towers: (a) rooms on the top storey, (b) rooms on the third storey.

lower than those in the east and the west, in the circular earthen tower. The difference becomes more obvious on the third storey where the forcing temperatures are dominated only by the solar-air temperature on the walls exposed to outdoor environment.

Mean radiant temperature

The mean radiant temperature is one of the six factors affecting occupant's thermal comfort, according to Fanger's theory. In the earthen tower, the temperatures on the inner surface of rammed earthen walls are only influenced by indoor air temperature because of their great thermal inertia. The temperatures on the inner surface of the plank wall are not so high as they should be, because the other side of the wall is usually under the shadow of the external gallery. For the east and west rooms, the plank walls will absorb some irradiation in the morning and late afternoon because of the low solar altitude. Temperatures on the surface of the ceiling of the top storey are also not high because of good ventilation in the attic.

In early morning and late afternoon, the direct irradiation will enter the east and the west rooms through the windows on the external rammed earthen walls. That will make the mean radiant temperatures of the rooms higher than those of north and south rooms.

PMV-Index

Fanger's PMV-index is widely accepted for evaluating indoor thermal environment. The computer program simulates the thermal sensation of the occupant in a specific room based on Fanger's equations, and calculates the PMV-index once every two hours (Figs 10 and 11).

An investigation among the occupants of different age and sex in Chengqi Tower has been made. The investigation includes a series of carefully arranged questions concerning the thermal sensation in the rooms in summer. Most results of calculation are consistent with that of the investigation.

The indoor thermal environments in earthen towers (both real and simulated) during a typical summer day are fairly satisfactory.

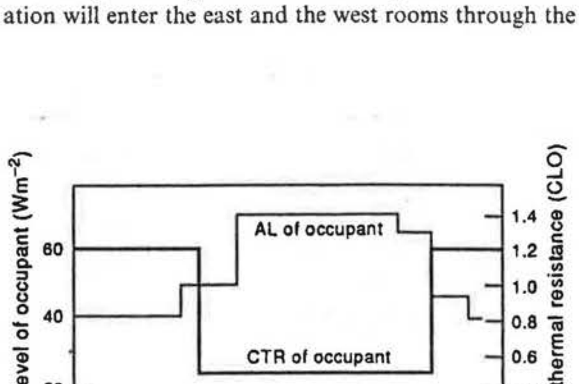

Fig. 12. Personal thermal parameters of the occupants in summer.

CONCLUSION

Because of their architecture, construction and materials the earthen towers at Yongding possess excellent thermal properties which create a comfortable indoor thermal environment in summer. Remarkably, these traditional dwellings were built without the benefit of consultation with architects or thermal engineers. The PMV index in most of the rooms of earthen towers are smaller than that of ISO-DIS 7730 issued by International Standard Organization.

From the analyses, we can see that the building's thermal inertia, external gallery and natural ventilation are three main thermal defences for better indoor environment under the hill and valley climate condition.

Moreover, the three rammed earthen walls and plank ceiling, floor and wall possess very good properties in mass transfer and play important roles in achieving a suitable indoor humidity in humid days in the early summer. But this area is still awaiting systematic study.

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