Field study of indoor environment quality in an open atrium with ETFE membrane in a healthcare facility

Haida Tang1, Chunying Li1, and Jianhua Ding1,2*

1 School of Architecture and Urban Planning/ BenYuan Design Research Center, Shenzhen University, Guangdong, China
2 School of Architecture, Southeast University, Jiangsu, China

Abstract. The hospital street is widely utilized in the modern health care facilities as a main traffic streamline to connecting all of the outpatient rooms and treatment departments for easy access. This study investigate the indoor environment quality of a typical hospital street, i.e., a high space atrium with ETFE membrane structure in the top. The investigation combines the on-site measurement and subjective survey. The results indicates that the indoor air temperature in the atrium reaches up to 32.6°C in a summer day causing thermal discomfort according to ASHRAE 55. The CO2, PM2.5, TVOC concentration in the hospital street comply with the Chinese standard for hospitals. The illumination in the corridors around the atrium is below the threshold of Chinese standard, i.e., 100 lux. Due to the vibration of the light ETFE membrane structure, the noise level in rainy days is as high as 79.5 dB which causes acoustic discomfort of occupants. This study is beneficial for the design of the hospital street design with the ETFE membrane structure.

1 Introduction

The aging acceleration of population in China results in a large demand of health care facilities in future. The improved environmental quality can increase productivity and reduce recovery times [1,2]. The hospital street, i.e., a high space atrium, is widely applied into healthcare facilities for humanitarian design of space and people flowing organization. The hospital street connecting almost every outpatient rooms plays an important role in the indoor environment quality of associated rooms, e.g., the thermal, acoustical and light environment [3,4].

This study aims to evaluate the indoor environment quality in an open atrium of an existing hospital with ETFE membrane structure in a hot and humid climate region by field study. This study is beneficial for proper architecture design of the hospital street.

2 Basic information

The university of Hong Kong Shenzhen hospital opening on July 1, 2012, is a major comprehensive public hospital. The location of the hospital (22 °N, and 114 °E) is in a hot and humid climate region. The hospital has a total area of 367,000 m² situated on 192,000 m² of land. Fig. 1(a) shows the aerial view of this health care facility. In the middle of the hospital, a high space atrium with a height of 24m plays a role of hospital street which constitutes a major traffic streamline connecting most of the outpatient rooms and testing departments. All the waiting areas of outpatients room face the atrium (i.e. the hospital street) side by side in four floors of the outpatient building for easy access. The hospital street occupies an area of 2510 m², with a length of 88 m and a width of 28 m, as shown in Fig. 1(b). The high space atrium has seven external doors connecting the outdoor and two gates connecting the entrance hall of the hospital in the first floor.
3 Methodology

3.1 Physical measurement

In typical summer conditions, the indoor environment parameters in the hospital street are comprehensively on-site measured. In sunny, cloudy and rainy days, the spatial distribution of the dry-bulb temperature, relative humidity, globe temperature, solar radiation intensity and illumination at a height of 1.2 m in the atrium is measured. And the CO$_2$, PM2.5 and TVOC concentration are also measured to investigate the indoor air quality. The noise level in the atrium is highly influenced by the ETFE membrane structure and is measured under sunny, cloudy and rainy outdoor condition.

The air infiltration flow rate is calculated by air velocity method. The air velocity distribution of the external doors in the first floor and the openings of the ETFE membrane structure are measured by anemometer. The air infiltration flow rate is the opening area times the average velocity.

In addition, the stratification of indoor air temperature in the atrium is continuously monitored. The temperature sensors are located from the occupant area in the first floor to the ETFE membrane structure in the high space atrium with a vertical interval of 2 m.

The heating effect of the ETFE membrane structure on the indoor thermal environment is investigated in this study. The transmissivity of the ETFE membrane is calculated by the ratio between the outdoor and indoor solar radiation intensity on the horizontal surface. The inner surface temperature distribution of the ETFE membrane is measured by an infrared thermal imager.

3.2 Subjective survey

The survey method used in this study is Post Occupancy Evaluation (POE). The subjective responses from patients, visitors and medical staffs will be compared with on-site measurement to evaluate the performance of hospital street.

Questionnaire surveys were carried out in the hospital street on July 2018, i.e., in a summer condition. The questionnaire survey consists of two parts: 1) basic information about gender, age, type of work; 2) satisfactory votes on indoor thermal, lighting, acoustic environment and air quality and sensation of temperature and noise. A seven-point Likert scale is utilized to quantify subjects’ satisfactory level with IEQ parameters, ranging from -3 to 3, with a neutral value of zero, which represents from very dissatisfied to very satisfied. In this subjective survey, 140 valid questionnaire responses including 55 patients, 72 visitors and 13 medical staffs. The age of the patients and visitors ranges from 15 to 60.

The combination of an objective and subjective approach is certainly the most complete and exhaustive method in building environment analysis and could be used in a human centre design.

4 Results

4.1 Indoor environment quality

The on-site measurement of the indoor environment quality was performed on typical sunny, cloudy and rainy days. The outdoor air temperature and solar radiation intensity under the three conditions are illustrated in Table 1.

| Time           | Sunny (2018.07.12) | Cloudy (2018.07.14) | Rainy (2018.07.13) |
|----------------|--------------------|---------------------|--------------------|
| Solar radiation intensity (W/m$^2$) | 913                | 132                 | 90                 |
| Temperature ($^\circ$C)    | 34.2               | 26.9                | 27.5               |

Fig.2(a) shows the spatial distribution of air temperature at a height of 1.2 m on the sunny day. The average air temperature is as high as 33.5$^\circ$C, which suppresses the ASHRAE 55 Standard. Fig. 2(b) shows the spatial distribution of the solar radiation intensity on
the horizontal surface in the atrium. Sunlight spots exist on the floor of the atrium. The average solar heat gain by direct solar radiation is 74.3 W/m². The incident solar radiation is the main reason of the high indoor air temperature. Fig. 2(c) show the spatial distribution of the illumination at a height of 1.2 m on the cloudy day. The illumination on the floor of the atrium is higher than 1000 lux, while the average illumination in the corridor around the perimeter of the atrium is 155 lux which is below the Chinese standard, i.e., code for design of general hospital (GB 50139-2014). The lighting uniformity in the hospital street needs to be improved and artificial lighting needs to be supplemented in corridors.

![Temperature distribution](image)

(a) Temperature distribution

![Solar radiation distribution](image)

(b) Solar radiation distribution

![Illumination distribution](image)

(c) Illumination distribution

**Fig. 2.** Spatial distribution of indoor environment parameters in the atrium of hospital street: (a) dry-bulb temperature; (b) solar radiation intensity and (c) illumination level.

Table 2 shows the CO₂, PM2.5 and TVOC concentration and the noise level in the occupant area of the atrium on sunny, cloudy and rainy days. The CO₂ concentration in the hospital street ranges from 480 ppm to 560 ppm, which is below the threshold value of 1000 ppm. The CO₂ concentration in the hospital street complies with the ASHRAE 170-2013 Standard and mirror an adequate outdoor air change rate and a good ventilation effect. The airborne pollutants including the PM2.5 and TVOC concentration are all below the threshold of the Chinese standard. It could be found that the noise in the atrium is seriously beyond the threshold of Chinese standard of 55 dB. Especially, the noise level in rainy days reaches up to 79.5 dB due to the vibration of the ETFE membrane and the echo in the atrium.

**Table 2.** Indoor air quality and noise level in the atrium.

|                | Sunny (2018.07.12) | Cloudy (2018.07.14) | Rainy (2018.07.13) |
|----------------|---------------------|----------------------|--------------------|
| Time           | 15:00               | 9:00                 | 9:00               |
| CO₂ (ppm)      | 549                 | 543                  | 558                |
| PM2.5 (mg/m³)  | 0.004               | 0.003                | 0.003              |
| TVOC (ppb)     | 243                 | 266                  | 180                |
| Noise A (dB)   | 69.5                | 71.3                 | 79.5               |

**4.2 Heat effect of the ETFE membrane**

The ETFE membrane consists of translucent and semi-translucent part. The transmissivity of the translucent and semi-translucent ETFE membrane is 0.72 and 0.26, respectively. The inner surface temperatures of the ETFE membrane on a sunny, cloudy and rainy day are shown in Fig. 3. In the sunny day, the inner temperature of the translucent and semi-translucent ETFE membrane could reach up to 49.3°C and 54.1°C, respectively due to the solar radiation. The inner surface temperature of the ETFE membrane in the sunny day varies from 30°C to 50°C. In cloudy days with low solar radiation and natural ventilation, the inner surface temperature of the ETFE membrane is only 26.0°C that is even lower than the indoor air temperature at the occupant height.

![Inner surface temperature of the ETFE membrane structure on sunny and cloudy days](image)

**Fig. 3.** Inner surface temperature of the ETFE membrane structure on sunny and cloudy days.

Fig.4(a) shows the dry-bulb temperature stratification in the high space atrium from July 10 to 15, 2018. During the day of sunny days, the air temperature increases with height. At the top of the atrium, the air temperature is even higher than the outdoor air temperature due to the heat convection with the ETFE membrane structure. Fig.4(b) illustrates the globe temperature variation in the centre of the atrium at the occupant height. In the sunny days, the globe
temperature could reach up to 40-45°C which is higher than the outdoor air temperature. It is the longwave radiation of the ETFE membrane and the direct solar radiation penetrating the ETFE membrane that cause such high globe temperature.

![Figure 4. Continuous measurement of indoor dry-bulb temperature and globe temperature: (a) temperature stratification; and (b) globe temperature.](image)

**4.3 Subjective survey results**

In a sunny day, cloudy day and rainy day described above, the thermal sensation of occupants is shown in Fig. 5. Occupants in the atrium generally sense warm and stuffy. The subjective responses accords well with the objective on-site measurement.

![Figure 5. Sensation of indoor thermal environment.](image)

Fig. 6 shows the acoustic sensation in the atrium. It could be found that the average noise level is medium in sunny and rainy days and slight in the cloudy day. According to the subjective feedbacks, the noise in the atrium mainly comes from the occupants’ talking in sunny days and the rainfall on the ETFE membrane in rainy days.

![Figure 6. Sensation of indoor thermal environment.](image)

The average satisfactory levels of indoor air quality and lighting environment are neutral, while that of the acoustic and thermal environment ranges between slightly dissatisfied and neutral. This finding confirms the fact that the adaptive thermal comfort theory does work in the high space atrium. The hospital street plays a role of traffic streamline that is a temporary place to stay for both of the patients and visitors. Through behavioural adjustment, physiological acclimatization and adjustment of psychological expectation, patients and visitors adapt to the indoor thermal environment.

**5 Discussion**

According to the results of the physical objective measurement and subjective survey, the incident sunlight from the translucent ETFE membrane results in the thermal discomfort of occupants and brings in a large amount of solar heat gain. However, the illumination level in the corridor of the hospital street is insufficient in cloudy days. The noise level in the hospital street exceeds the Chinese standard and causes acoustic discomfort of the occupants, especially in rainy days. The ETFE membrane structure is planned to be retrofitted to improve the indoor environment quality. Under the current ETFE membrane structure, another ETFE membrane with low transmissivity would seal the top of the atrium. The new ETFE membrane structure has openable windows for natural ventilation at night. Through adding the new ETFE membrane structure, the incident solar radiation into the atrium could be greatly reduced and the glare in the occupant area could be erased. The cavity between the two ETFE membrane structure could efficiently weaken the noise level. The real effect of the retrofitting will be on-site measured and described in future study.

**6 Conclusion**

This study investigate the indoor environment quality of the hospital street in hot and humid region through objective on-site measurement and subjective survey. The main results can be summarized as follows:
(1) In a typical sunny day, indoor air temperature and solar radiation intensity in the occupant area are 32.6°C and 108 W/m², respectively. The surface temperature of the ETFE membrane is as high as 54.6°C.

(2) The thermal environment of the hospital street is warm according to ASHRAE 55 due to the incident sunlight through the ETFE membrane.

(3) Due to vibration of the light ETFE membrane during rainfall, the noise level in the atrium are 79.5 dB during rainfall. The noise level is beyond comfort zone. This study is beneficial for the design of the hospital open atrium with ETFE membrane structure.

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