Thermal comfort and thermal adaptive behaviours in office buildings: A case study in Chongqing, China

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Abstract. A field study on adaptive behaviours for thermal comfort was performed in office building in Chongqing, China, from June to August, in which a total of 341 valid datasets were collected for further analysis. The results showed that although the separated air-conditioners were in use during working hours, the mean indoor air temperature during summer time was 27.78 °C, which was not with the summer thermal comfort zones specified in ASHRAE 55 standard. However, 93.5% of subjects regarded surrounding thermal environment was comfortable as a result of actively utilizing adaptive actions comprising technical (e.g. turning on air-conditioners, ceiling fan, etc.) and personal (e.g. having cold drinks, adding clothes, etc.) aspects. Air-conditioners was the most popular environmental control in summer. People would like to operate several environmental strategies simultaneously to alleviate thermal discomfort.
The clothing insulation values of occupants drops to 0.4clo from 0.6clo in response to the indoor air temperature changing from 22°C to 32°C. The findings in this investigation are benef it for understanding of the interaction between occupants and ambient thermal environment and providing guidance on building energy efficiency.

1. Introduction
From the point of view of adaptive thermal comfort theory, in real environment people tend to restore their thermal comfort by either adapting to surrounding thermal conditions or adjusting physical environment to satisfy themselves[1-2]. These conscious and unconscious actions taken by occupants are classified into behavioural adaptation[3]. Apparently, behavioural adaptation has a significant impact on thermal comfort achievement and building performance as well. Therefore, better understanding of adaptive actions conducted by occupants will be of great benefit to building design, operation and maintenance with the aim of improving building energy efficiency.

Due to the observable and sometimes measurable characteristics with the assistance of advanced technologies, behavioural adaptations of occupant in naturally ventilated buildings are intensively studied by researchers in world-wide. The experiment by Macfarlane[4] in the humid tropics of Australia was one of the early examples of such a topic. He concluded that wearing light clothing and lowering physical activity levels helped local residents achieve acceptable comfort. Indraganti et al.[5] performed an investigation on thermal comfort in offices in India and noticed that bahavioural adaptation played a key role of achieving thermal comfort. A field study was conducted during summer time in dormitory buildings in Changsha, China by Wu et al.[6] and found majority of subjects would like to operate windows and fans to maintain thermal comfort during survey period. In addition to qualitative studies, many
researches focused on developing stochastic models to predict the probabilities of given environmental controls utilization under certain thermal conditions[7-9]. However, most of the studies are conducted in non-air-conditioned space and assume that adaptive responses of occupants in air-conditioned environment are rare and consequently could be ignored. In fact, in centralized air-conditioned space, subjects’ adaptive behaviours are few due to the lower perceived environmental control level[10] and very limited adaptive opportunities[11]. On contrary, people’s adaptive opportunities in buildings with separated air-conditioners are restricted as that in buildings with HVAC system. The building can be air-conditioned or naturally ventilated, which is determined by whether the separated air-conditioners are in use or not. Such phenomenon is quite common in China. Therefore, in order to understand the adaptive behaviours of occupants in buildings, which were originally designed as naturally ventilated and later install separated air-conditioner, a filed study covering from June to August was carried out in offices buildings in Chongqing, China.

2. Methodology
Questionnaire survey together with environmental parameters measurement were applied in this investigation to gather sufficient data.

2.1. Questionnaire survey
The questionnaire consisted of three sections. Section one was designed to collect background information about participants, such as age, gender, the length of living in Chongqing, activity and clothing levels. Since all subjects in this study were doing sedentary activities during survey period, 1.1 met was determined as metabolic rate value. Clothing insulation was quantified in unit of clo by checklist provided in questionnaire. Subjects’ thermal perceptions in terms of thermal sensation, thermal acceptability, thermal preference and thermal expectation were included in section two. The answers to these questions were designed as 7-point scale covering from -3 to +3 or 5-point scale covering from -2 to +2 with neutral status value of 0. Section was mainly used to assess subjects’ perceived environmental control level in their offices and to investigate the use of environmental controls. The questionnaire survey was performed 2-3 days per week. A total of 48 subjects comprising 31 males and 17 females provided 341 valid datasets.

2.2. Environmental parameters measurement
Indoor air temperature ($T_a$), globe temperature ($T_g$), relative humidity (RH) and air velocity ($V_a$) were measured at the interval of one second. The instruments used for measurement were Dwyer 485 digital hygrometer for air temperature, heat stress WBGT meter (HT30) for globe temperature and relative humidity and Testo 425 anemometer for air velocity, respectively. Air temperature and air velocity were measured at the heights of 0.1m, 0.3m and 0.6m for seated person. Globe temperature and relative humidity were collected at the vertical level of 0.6m for seated person. The duration of each environmental variables measurement was no less than three minutes after the instruments stabilized. The values would be then averaged for further analysis. A place adjacent to subjects but avoid direct sunlight and ensure proper circulation around the instrument sensors was selected as the measurement position. Physical environmental parameters measurement was applied simultaneously with questionnaire survey.

3. Results

3.1. Basic information of surveyed building
The Surveyed building was located in Chongqing University, which was originally designed as naturally ventilated building. This building was a four-floor office building with north-south orientation, brick–concrete structure and single-glazed windows with aluminium alloy frames used by administrative staff and lecturers.
3.2. Indoor thermal conditions and thermal perceptions of occupants

Figure 1 shows the variation of monthly mean indoor air temperature and the distribution of thermal sensation votes (AMV). The monthly mean indoor air temperature increased from 27.2 °C in June via 29.7 °C in July to 30.5 °C in August. The mean indoor air temperature during summer time was 27.78 °C. Apparently, although the air-conditioners were in use, particularly in July and August, the indoor thermal conditions were not in the thermal comfort zone specified in ASHRAE 55 standard[12]. As a result, 38.1% of occupants regarded thermal environment as ‘slightly warm’ at least. If central three categories of thermal sensation vote are regarded as comfort, 93.5% of subjects would be in comfortable state. This phenomenon can be attributed to acclimatization to local hot and humid summer and lower thermal expectation.

![Figure 1. Indoor thermal conditions and thermal sensations.](image)

3.3. Adaptive behaviours

Personal adjustment. Clothing adjustment is a typical personal adjustment in response to the variations of indoor thermal conditions. Since the subjects in Chongqing used wood chair in summer, the insulation of chair was not considered in this study. Figure 2 depicted the variation of clothing insulation against indoor air temperature.

![Figure 2. The variations of clothing insulation values.](image)
In general, subjects preferred to wear light clothes in warm environment. That was to say, with the increasing in indoor air temperature, the clothes worn by subjects were less. However, there was a two-stage tendency of clothing insulation values in response to indoor air temperature. The values of clothing insulation dropped quickly from 0.6clo to 0.4clo accompanying with indoor air temperature increased from 22 °C to 26.5 °C. After that, with the growing up of indoor air temperature, the clothing insulation values changed litter but stabilized around 0.4 clo. The tendency of clothing insulation values demonstrated in figure 2 proved that the clothing level of occupants was directly determined by ambient thermal stimuli. In fact, non-physical factors, such as social, economic, cultural and living habits, also influenced occupants’ clothes selection.

3.3.1. Technical adaptation. In this study, the investigation on behavioural adaptation in terms of technical dimension comprised the use frequencies of environmental controls and supplement strategies. In order to understand occupants’ interaction with environmental controls, the availability and operation purpose of environmental controls would be investigated. The results were illustrated in table 1 considering the factor of orientation.

Table 1. The availability and operation purpose of environmental controls operation.

|                     | Availability (%) | Operation Purpose                      |
|---------------------|------------------|----------------------------------------|
|                     | South | North     |                                      |
| Air-conditioner     | 97.3  | 100       | For cooling (52.4%); For Fresh Air (47.6%); Others (0%) |
| Cooling Fan         | 36.4  | 37.8      |                                      |
| Window              | 100   | 100       | For Avoid Direct Sunlight (81%); For Cooling (14.3%); Others (4.7%) |
| Sun-shading Devices (e.g. curtain, blinds) | 83.8  | 63.6      |                                      |

All subjects could access to windows. And all windows in surveyed offices were operable. Due to the hot and humid characteristic in summer season in Chongqing, nearly all surveyed offices installed separated air-conditioners. As a result, the availabilities of cooling fan in offices were lower, comparing with air-conditioner availability. There was significant difference in sun shading device between offices in the south side and that in the north side. This could be attributed to reason that the duration of south side offices exposing to sunlight was longer. With respect to environmental operation purpose, subjects opening windows were mainly for cooling, and then followed by securing fresh air, accounting for 52.4% and 47.6%, respectively. Avoiding direct sunlight was the dominant purpose for occupants to use sun shading device. Around 20% of participants operated sun shading device for cooling (14.3%) or for other reasons (e.g. for privacy).

Figure 3 demonstrated the use frequencies of environmental controls considering the effect of orientation. The utilization frequencies of environmental controls were defined as the ratio of the times that a certain environmental control is used to the total times during the survey period. Air-conditioners were the most frequently used environmental control for occupants in the south side offices, and then followed by cooling fan and sun-shading devices. People in the south side offices were reluctant to operate windows to adjust ambient thermal environment, which was in agreement with that in the north side offices. There were two possible reasons: the higher outdoor temperature imposed constraint on windows operation; secondly, in order to ensure the efficiency of air-conditioners, necessary airtightness needed to be guaranteed. In the north side offices, subjects preferred to use cooling fan more frequently than turning on air-conditioners. Since the offices in the north side were basically under the shadow during day time, subjects could operate windows as an effective way of improving indoor thermal conditions and thus seldom utilized sun shading devices. In addition to the use frequencies of environmental controls, the dynamic process of environmental controls was also investigated. Air-conditioners as the most popular environmental control were in use over the whole temperature range in summer. People would like to open window in response to the indoor air temperature changing from 24.17 °C to 29.97 °C which
corresponded to outdoor air temperature of 21.70 °C to 36.60 °C. When the outdoor temperature varied from 21.70 °C to 38.50 °C, occupants were tended to use sun-shading devices. Cooling fan was usually operated by subjects in response to the outdoor air temperature increasing from 25.60 °C to 38.50 °C.

When operating a certain environmental control was not sufficient to satisfy occupants, they would like to take other actions as supplements

Table 2. Window use frequencies in conjunction with other adaptive actions.

|                     | North Availability/Accessibility | South Availability/Accessibility |
|---------------------|----------------------------------|----------------------------------|
| No Other Adaptive Actions | 11.5 n/a                         | 4.6 n/a                          |
| Cooling Units (e.g. cooling fan, air-conditioner, et al) | 61.5 n/a                         | 49.1 n/a                         |
| Clothing Adjustment  | 11.5 n/a                         | 11.6 n/a                         |
| Cold Drinking       | 15.5 n/a                         | 24.9 n/a                         |
| Changing Activity Level | 0.0 n/a                          | 9.2 n/a                          |
| Others              | 0.0 n/a                          | 0.0 n/a                          |

Table 2 summarized supplement strategies when windows were in operation. Due to the higher outdoor air temperature in summer in Chongqing, although all windows in surveyed offices were operable and accessible in this case, around half of occupants (61.5% and 49.1% for the north and the south side offices, respectively) would like to use cooling units (e.g. air-conditioners and cooling fan) as supplement. Then followed by having cold drink and changing clothe.

As shown in table 3, when sun-shading devices were available in surveyed offices, changing location had the first priority to be taken as supplement, accounting for more than half of subjects no matter the offices were in the north or in the south side. A quarter of respondents in the north side offices preferred do nothing. But for the subjects in the south side offices, they would like leave the room (25.2%) rather than do nothing (7.2%). In case of no sun-shading devices or unavailable, occupants in both sides took changing location as their first supplement strategy, and then followed by adjusting monitor and leaving the room.
Table 3. Sun-shading devices use frequencies in conjunction with other adaptive actions.

|                              | North Availability/Accessibility | South Availability/Accessibility |
|------------------------------|---------------------------------|---------------------------------|
| No Other Adaptive Actions    | 25.0 NO                         | 7.2% NO                         |
| Change Locations             | 64.3 40.0                       | 52.5 57.9                      |
| Adjust Monitor               | 3.6 48.0                        | 13.7 21.1                      |
| Leaving the Room             | 7.1 12.0%                       | 25.2 21.1%                     |
| Others                       | 0.0 0.0                         | 1.4 0.0                        |

Table 4. Cooling fan use frequency in conjunction with other adaptive actions.

|                              | North Availability/Accessibility | South Availability/Accessibility |
|------------------------------|---------------------------------|---------------------------------|
| No Other Adaptive Actions    | 17.4 0.0                        | 18.2 0.0                       |
| Cooling Units (e.g. cooing fan, air-conditioner, et al) | 26.1 69.2 | 47.7 49.3 |
| Clothing Adjustment          | 43.5 23.1                       | 15.9 13.2                      |
| Cold Drinking                | 13.0 7.7                        | 13.6 29.4                      |
| Changing Activity Level      | 0.0 0.0                         | 4.6 7.4                        |
| Others                       | 0.0 0.0                         | 0.0% 0.7                       |

Table 4 illustrated cooling fan use frequency in conjunction with other adaptive action. It was obviously that even the cooling fan was available in both sides’ offices, around 17.5% of occupants wouldn’t take any other adaptive actions as supplements. If they wanted to utilize environmental controls as supplement, they would first resort to clothing adjustment (north side offices) or operating air-conditioner (south side offices). But when cooling fan was not available, subjects were more active to perform technical or personal adaptations to satisfy themselves. Most of them preferred to turn on air-conditioners.

Since occupants were very occasionally to take adaptive actions as supplement when the air-conditioners were in use, the air-conditioner use frequency in conjunction with other adaptive action did not summarized here.

4. Conclusions

An investigation on adaptive behaviours considering the influence of orientation was carried out during summer time in office building in Chongqing. The findings gathering from this study are summarized as below:

- The indoor thermal condition in investigated offices in summer is poor. Indoor air temperatures are normally not within the comfort zone specified in ASHRAE 55 standard, although the air-conditioners are in use, particularly in July and August.

- Local people have acclimatized to hot and humid summer and consequently are able to tolerant higher indoor air temperature. This is in accordance with the distribution of thermal sensation votes. 93.5% of subjects’ thermal sensation votes are within the central three categories of thermal sensation vote in ASHRAE’s 7-point scale. Only 2.3% and 2.1% of subjects regard indoor thermal environment as warm and hot, respectively.

- In order to attenuate the discomfort caused by ambient thermal stimuli, people are active to perform various adaptive actions in terms of technical and personal adaptations. Clothing adjustment presents a tendency with two-stage. Air-conditioners are found to be the most
popular environmental control used by occupants in the south side offices. Then followed by cooling fan. The results are reversed for the occupants in the south side offices. The adaptive behaviours are dynamic process in response to the variations in thermal environment.

- Subjects are tend to use other environmental controls as supplements when a certain adaptive action is not sufficient to help them to restore thermal comfort. The effect of orientation is demonstrated when investigate the supplement strategy. With respect to different environmental control, people in offices with different orientations may resort to various supplement strategies.

- Both physical factors, such as thermal stimuli and non-physical factors, such social, cultural and economic, will result in the differences in adaptive behaviours.

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