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Residential adaptive comfort in a humid continental climate – Tianjin China

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ABSTRACT

The aim of this study was to understand occupant thermal comfort and air-conditioning (AC) usage behavior in mixed-mode dwellings in China. Longitudinal field measurements were conducted in 43 homes in Tianjin during the warm half of the year, May through November 2016. Room air temperatures and AC on/off events were recorded continuously using autonomous data-logging devices (iButtons). Occupants' "*right-here-right-now*" thermal responses were collected through an online questionnaire delivered intermittently to their smartphones throughout the survey period. A total of 4157 AC events and 1697 online questionnaires were collected and then matched against concurrent indoor and outdoor temperatures. Results indicate that thermal sensations of the Tianjin residents were *less sensitive* to variations of the room temperature, compared to findings from previous studies conducted in offices. The indoor temperature limits corresponding to 80% thermal acceptability for our Tianjin residential sample were estimated to be 21.0 °C (the lower limit) and 27.3 °C (the upper limit). Average "trigger temperature" for AC cooling in summer was 27.6 °C resulting in a cooling of the room by 4.1 °C on average, and the average trigger temperature for AC heating in winter was 18.6 °C heating the room by 6.6 °C. Our analysis also indicated that the householder's education level and household income were associated with their AC usage decisions.

1. Introduction

The international thermal comfort standard ASHRAE 55 [1] is based on a heat balance model of the human body developed by Fanger [2] using data obtained from human subjects in climate chamber experiments. The observation that it does not always provide an accurate prediction of the actual thermal comfort response of occupants in real world settings has emerged from many field studies [3–5]. In 2004, the adaptive comfort model was introduced to ASHRAE's Standard 55 as an alternative assessment method for the specific application to the indoor thermal environment of naturally ventilated buildings. Shifting away from the static comfort model developed by Fanger, the adaptive comfort model has gained popularity over the last 20 years [6]. However, the adaptive model was derived from data collected mainly from office buildings in various climate zones around the world [7], so whether it can be applied directly to residential contexts remains unclear. In office buildings, occupants' activities are fairly well defined and invariant while their control over the indoor environment is somewhat restricted. In contrast, occupants in their own home have a much wider range of adaptive comfort opportunities such as turning on/off AC, opening windows or doors for comfort ventilation, or changing their clothing insulation across a wider range [8,9]. Occupants' activities in the various rooms of their home tend to be much more diverse in terms of metabolic rate [10]. As a result of these contextual differences the comfort zone in houses can be expected to be wider than that in office buildings, as confirmed in a recent Australian residential comfort study reporting a 2K wider 80% acceptability zone than prescribed in ASHRAE Standard 55-2013 [11]. The current work further expands the Australian (Sydney) residential study carried out in a humid subtropical coastal climate [12] to the context of humid continental climate (Koeppen–Geiger *Dwa*) in Tianjin, China.

Split AC units have become very common domestic appliances in contemporary China, yet there are very few studies focusing on AC usage behaviors in this context [13] and no such studies conducted in Tianjin in the cold-zone of China's five-zone climate classification. The present study employed longitudinal field study research design to understand AC usage patterns, indoor thermal en-

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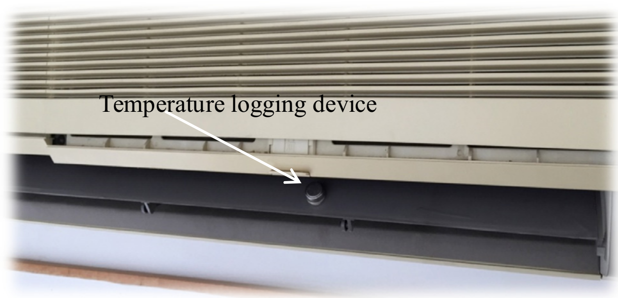

Fig. 1. iButtons placed at the supply air vent of an air conditioner.

Table 1
Summary of the smartphone questionnaire.

Questions	Answers
"Are you currently at home?"	-Yes -No (questionnaire terminates)
Location at home: *"Where are you right now?"*	-Living room/Dining room -Bedroom -Kitchen -Bathroom -Study -Others
Thermal sensation: *"How do you feel, right here, right now?"*	-Cold (−3) -Cool (−2) -Slightly cool (−1) -Neutral (0) -Slightly warm (+1) -Warm (+2) -Hot (+3)
Adaptive strategies: *"In this room here and now, do you have (you may select more than one)?"*	-Opening windows/doors -Turning on fans -Turning on AC -None
Clothing insulation (*clo*): *"Which best describes your clothing now?"*	-Very light (0.2) -Light (0.4) -Casual (0.6) -Heavy (1.0)

vironments and occupants' thermal perception in Tianjin's mixed-mode residential buildings.

2. Methods

Forty-three householders in high-rise apartment buildings in the Tianjin urban area were recruited for this study. Every home had at least one split system air conditioner (AC). Field observations were carried out from May 14th to November 20th in 2016.

During the first site-visit, a small temperature logger (iButton, Maxim Integrated) was installed in the supply air vent of each air conditioner (Fig. 1). Another iButton was discretely placed within the occupied zone of the room (bedroom and living room for each home) to monitor ambient air temperature. The sample interval was set at 15-min for all temperature measurements.

During the monitoring period, online "*right-here-right-now*" questionnaires [14] were periodically sent out to householders' smartphones with a frequency of two or three times for each week of the study period. The questionnaire (Table 1) was completed only when the participating householders were at home. If the householders were not at home when they received the questionnaire, they were allowed to either terminate the questionnaire or complete it when they arrived at home later. During the first home visit householders also completed a background questionnaire covering demographic and basic household information.

A total of 4157 AC events and 1697 online comfort questionnaires were collected. These specific points of interest (AC events and online survey responses) were paired with concurrent indoor air temperatures (recorded by iButtons) and outdoor air temperatures acquired from nearby weather stations. This paper specifically analyzes AC usage patterns, thermal environment and occupant thermal sensations in these homes.

Table 2
Average, maximum and minimum outdoor temperature (°C) in Tianjin, China.

Months	5	6	7	8	9	10	11	Average
Average	22	26.1	28.2	27.9	23.7	15	6.2	21.3
Maximum	36.1	37	36.6	36.2	34	27.4	14.8	31.7
Minimum	9.7	16.4	20.8	20	11	2.1	−5.2	10.7

3. Results

3.1. Local climate and household information

Most of the municipality of Tianjin is considered a *Humid Continental Dwa* climate within the revised Köppen–Geiger climate classification system, and just *Cold* in China's five-zone classification. Being located on the eastern seaboard of the Asian landmass Tianjin experiences hot and very humid weather during the warmer months of the year when this study was conducted. The autumn season is short. Monthly minimum, average, and maximum outdoor air temperature during the monitoring period (from May to November 2016) are described in Table 2.

Daily average outdoor air temperatures were used to calculate the prevailing mean outdoor air temperature using the weighted 7-day running mean, as per the adaptive comfort model guidelines in ASHRAE Standard 55 [1]. The moving average outdoor temperature, called the prevailing mean outdoor air temperature was calculated as follow:

$$t_{pma(out)} = (1-\alpha)[t_{e(d-1)} + \alpha t_{e(d-2)} + \alpha^2 t_{e(d-3)} + \alpha^3 t_{e(d-4)} + \ldots] \quad (1)$$

where $t_{(pmaout)}$- the prevailing mean outdoor air temperature (°C).

α- coefficient of the equation ranging from 0.6~0.9 (0.8 in this study).

$t_{e(d\text{-}1)}$- the mean daily outdoor air temperature for the previous day (°C).

Background information on the sample of 43 householders such as gender, household size, level of education and the gross income are summarized in Table 3. There were more female participants (69.7%) than male participants (30.3%). Most households comprised at least three people.

3.2. AC usage patterns

Air-conditioning usage patterns by the householders in this study were characterized by analyzing time-series measurements of the air temperature. As an example, the changing trend in air temperatures measured in the AC supply air vent in the living room of one sample house is shown in Fig. 2. In Fig. 2 five typical AC operation events can be observed from 20th August 2016 to 23rd August 2016. In all five AC events, air temperatures of the supply air vent were consistently 10–15 °C lower than the condition when AC was not in use. So this temperature gradient can be used to diagnose when AC was in use and when not.

For AC operation events 1 and 4 in Fig. 2, air temperatures recorded in the supply air vent tended to remain stable at about 15 °C without noticeable fluctuations after AC was switched on. In contrast, for AC events 2, 3 and 5, the supply air temperature fluctuated as the compressor cycled. Before the householder switched on the AC, air temperatures of the supply air vent remained stable