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Window-opening behavior in Chinese residential buildings across different climate zones

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ABSTRACT

Window-opening behavior significantly influences indoor air quality (IAQ), energy consumption, and thermal comfort in residential buildings with natural ventilation. To understand window-opening behavior in Chinese residential buildings, this study conducted a one-year measurement in 58 apartments in 14 cities across five different climate zones in China. The influences of climate region, season, household type, and weekday/weekend pattern on the interaction between occupants and windows were analyzed and presented. The average daily "open-window" duration in Chinese bedrooms was 9.4 h. Generally, the length of time that the windows were open in cold regions was shorter than that in warm regions, even when the outdoor air temperatures among regions were similar. The open-window duration increased from winter to summer, as the outdoor air temperature increased. However, the duration decreased when the mean daily outdoor air temperature reached around 27 °C. Approximately 40% of the window-opening actions occurred in the morning from 6:00 to 9:00. During working hours (9:00–17:00) on weekdays, windows were opened more frequently if non-working persons were in the house. On weekends, residents opened windows at a later time than on weekdays. On the basis of the acquired information, a typical window-operation schedule as occupant behavior was proposed for Chinese bedrooms. It provides a more accurate boundary condition for analyses of IAQ, energy consumption, and thermal comfort in Chinese residential buildings.

1. Introduction

The action of window opening is related to energy consumption, indoor air quality, and thermal comfort in buildings [1]. Proper window-operation strategies can reduce the cooling load in buildings, as demonstrated by Wang and Greenberg [2]. They tested the effects of various window-operation control strategies on energy consumption in EnergyPlus, and achieved energy savings of 17–47%. For indoor air quality, window-opening activity affects the air exchange rate between the indoor and outdoor environments, thus influencing the indoor contaminant concentration. By means of field measurements in Copenhagen, Spilak [3] demonstrated that window-opening habits reduced the peak exposure to ultrafine particles in homes. Studies have also shown that opening windows has a large influence on concentrations of indoor particulate matter, total volatile organic compounds (TVOC), and CO_2 [4–6]. In regard to thermal comfort, a window is a common control device for the thermal environment in any building [7]. People normally open windows to cool the indoor environment, or close windows if they feel too cool. Rijal [8] showed that Japanese residents adapt to a hot and humid environment by opening windows to increase air movement.

Because of its importance, window-opening behavior has been studied in various regions in residential buildings, offices, school classrooms, and hospital wards. Andersen et al. [9] conducted long-term measurements of occupants' window-opening behavior in 15 Danish dwellings and found that indoor CO_2 concentration and outdoor air temperature were the two most important factors in window-opening and closing behavior. Rijal et al. [7] surveyed occupants' interactions with windows in 15 office buildings in the UK and used the data to develop an adaptive logistic regression model to predict window status from indoor and outdoor air temperatures. A study of window usage in school classrooms in Italy by Stazi [10] also confirmed the importance of indoor and outdoor air temperatures. Schweriker et al. [11] examined human-window interaction data obtained from three Switzerland residences and one Japanese dormitory, and concluded that the occupants' interactions with windows were strongly correlated with outdoor air temperature. D'Oca and Hong [12] analyzed window-opening behavior in 16 German offices and found that indoor air

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temperature, outdoor air temperature, time of day, and occupancy were the top drivers for window opening and closing. Heebøll [13] found that the visual feedback of CO_2 concentrations has led to greater proportion of open window in investigated Danish school classrooms.

In addition to studies in Western developed countries, studies are increasingly being conducted in China, such as those by Yao and Zhao [1] in dwellings in Beijing, Pan [14] in offices in Beijing, Shi and Zhao [15] in dwellings in Nanjing and Beijing, Li [16] in offices in Chongqing, and Shi [17] in hospital wards in Nanjing. All the above studies have provided valuable knowledge about various factors in window-opening behavior. However, the studies were conducted in a limited number of rooms in only one or two climate regions. Since climatic factors play a vital role in window-opening behavior [18], a comprehensive understanding of this behavior across different climate zones is required. In addition, household structure could affect window-opening behavior. If a family has a non-working person, such as a retiree or an adult who is unemployed, he or she may stay in the apartment during the daytime. Compared with a working person, a non-working person has a greater chance of interacting with the windows in the home. Therefore, when studying window-opening behavior in residential buildings, it is necessary to differentiate between houses with and without non-working persons. For similar reasons, the effect of variations in occupancy from weekdays to weekends should be considered.

This paper reports the findings of a year-long field measurement and evaluation of window-opening behavior in Chinese bedrooms across five different climate zones. On the basis of the acquired information, a typical window-operation schedule for Chinese bedrooms was proposed.

2. Methods

When simulating the energy consumption in buildings, many software programs, such as EnergyPlus and eQUEST, require a window-operation schedule. The schedule is determined by specifying the length of time for which a window is open (the “open duration”) and the time at which the window is opened (the “open time”), as shown in Fig. 1. Each of the components is assumed to be influenced by climate region, season, household type, and weekday/weekend pattern. We classified the families into two types: non-working families (NW families) were those with one or more non-working persons, and working families (W families) were those in which all the members of the household worked outside the home. School children were considered as working persons, while preschool children who did not go to school were considered as non-working persons. It should be pointed out that in our study, no occupant mainly does their jobs at home.

To collect data to test the proposed assumption, a large-scale field measurement of window-opening behavior was conducted, as described in the following sections.

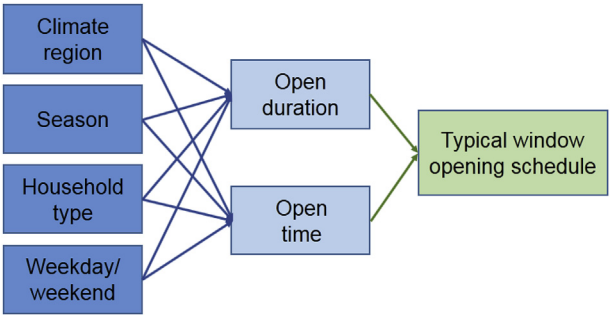

Fig. 1. Hypotheses proposed in this study to determine a typical window operation-schedule.

2.1. Monitored cities

The large-scale field measurement was conducted in residential buildings in 14 cities in China. These cities are Shenyang, Urumqi, Hami, Beijing, Tianjin, Xi'an, Shanghai, Changsha, Wuhan, Chongqing, Shenzhen, Guangzhou, Nanning, and Kunming, and they are located in different climate zones of China, as shown in Fig. 2. The climate zone classification used in this study is based on thermal design code for civil buildings in China (GB50176-2016) [19]. The code defines five climate zones, namely, severe cold (SC), cold (C), hot summer and cold winter (HSCW), mild (M), and hot summer and warm winter (HSWW), on the basis of average air temperatures in the coldest and hottest months of the year. Many studies of indoor thermal environment and building energy consumption in China have used the same climate zone classification [20–22]. As shown in Fig. 2, we conducted measurements in 58 apartments, with 10, 16, 16, 6, and 10 households for the SC, C, HSCW, M, and HSWW regions, respectively. None of the apartments had a mechanical ventilation system. The working status of each household member was obtained through questionnaires before the monitoring started. Half of the 58 apartments had one or more non-working persons, as shown in Fig. 2.

2.2. Outdoor temperature, measurement period, and seasonal division

To demonstrate the annual climatic difference among climate zones, Fig. 3 shows the historical mean, maximum, and minimum monthly air temperature in the studied cities within each zone from 1971 to 2003. Kunming is the only city in the mild climate zone, and thus Fig. 3(d) shows lines instead of ranges. Large differences can be observed among the climate regions. The lowest average monthly temperatures for SC, C, HSCW, M, and HSWW regions were −12 °C, −5 °C, 5 °C, 10 °C, and 15 °C, respectively. The differences among the lowest average monthly air temperatures were much larger than the differences among the highest monthly air temperatures, which were 24 °C, 26 °C, 28 °C, 20 °C, and 28 °C for the SC, C, HSCW, M, and HSWW regions, respectively. It is interesting to note that the ranges of the monthly mean air temperature in the M and HSWW regions were much narrower than the ranges in other climate regions.

The measurement campaign started on November 15, 2016, and lasted until November 30, 2017. In the cities of Changsha, Chongqing, Kunming, and Nanning, the campaign started slightly later than November 15. For consideration of the temperature differences in various climate zones in Fig. 3, the seasons in this study are defined on the basis of mean daily air temperature according to the Chinese national standard QX/T 152-2012: Definition of climatic season [23]. According to this standard, winter begins and ends when the five-day averaged air temperature is less than and greater than 10 °C, respectively, while summer starts and terminates when the five-day averaged air temperature is higher than and lower than 22 °C, respectively. Spring and autumn occur between winter and summer. Under this definition, the same seasons in different climate zones have similar outdoor air temperatures. Fig. 4 shows the seasonal divisions in the studied cities during the measurement timeframe. It is worth noting that the cities in the HSWW climate region did not have a winter season, while Kunming, which belongs to the M climate region, had no summer or autumn. Long winters were observed for the cities in the SC and C regions. The autumn and spring seasons in cities in the SC, C, and HSCW regions were short compared to their winters and summers.

2.3. Obtaining window-opening behavior and outdoor air temperature data

Magnetic sensors manufactured by Xiaomi Inc. were used to record window-opening and closing actions, as shown in Fig. 5 (a). Each sensor had two magnetic induction devices, which were placed on the window casement and frame. The magnetic sensor was used for both casement and sliding windows: When the distance between the two devices was