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Airflow utilization in buildings in hot and humid areas of China

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ABSTRACT

Airflow utilization is a traditional and effective way for people to improve their thermal comfort in summer in the areas of China that are hot and humid. We conducted a summer-long field study on nine naturally ventilated buildings in Guangzhou and collected airflow-related behaviors, motivations, and perceptions from 32 college students. The results show that the behaviors of opening windows and doors were driven by both indoor air quality and thermal comfort motivations. The proportions of open windows and doors increased linearly and slowly with the indoor ET*, and the acceptable range for opening windows and doors was an indoor ET* $\leq$30.3 °C with the condition that a maximum of 0.25 m/s indoor air speed needs to be achieved. The behaviors of using fans were driven by thermal comfort motivations. The proportions of use of fans increased strongly with the indoor ET*, and the acceptable range for using fans was an indoor ET* $\leq$31.0 °C with the condition that a maximum of 0.87 m/s indoor air speed needs to be achieved. A strategy for airflow utilization was proposed. Our study is believed to provide a better understanding of airflow-related behaviors, motivations, and perceptions as well as better designs of natural ventilation and fans and better simulations of performance for buildings in the hot and humid areas of China.

1. Introduction

In the areas of China that are hot and humid, people are familiar with and fond of airflows due to their cooling effects in summer, and opening windows and using fans are two common ways for people to utilize indoor airflows. Taking Guangdong and Guangxi provinces as examples, the popularity of electric fans can be seen by the fact that families on average have 2.93 of these and this level of ownership has exceeded that of air conditioners and mobile phones since 2006 [1]. It is important to study the airflow utilization in the buildings in the hot and humid areas of China to facilitate better architectural designs and energy conservation in these areas. The literature on this subject has focused on airflow-related behavior, perceptions, and acceptable ranges and these are briefly reviewed below.

The behavior related to opening windows and using fans has been studied in Pakistan [2], Singapore [3], Indonesia [4], India [5,6], the United Kingdom [7,8], mainland Europe [8], and China [9–13]. Higher frequencies and preferences for fan usage and window operation were found in naturally ventilated houses in hot climates like Singapore and Indonesia [3,4]. Thermal factors like indoor and outdoor temperatures have been widely studied as drivers for this behaviors and their relationships with the proportions of opening windows and using fans were established as linear, polynomial, or logistic equations. The changes in window use were found to be more relevant to indoor temperatures than outdoor temperatures [8]. A comparison between the United Kingdom, mainland Europe and Pakistan [8] shows that a significant increase in the proportion of open windows occurs at an indoor temperature of about 22 °C for all countries and at a given temperature the proportion is higher in the United Kingdom, then mainland Europe, and lastly Pakistan. The comparison also shows that if fans are provided, the use of fans will follow the pattern given by the Pakistan/Greece probit curves that 20% of building occupants use fans at outdoor temperatures of 18 °C, 50% at 23 °C, and 80% at 28 °C. Another comparison by Rijal et al. [14] shows that mixed-mode buildings are generally controlled as naturally ventilated buildings rather than air-conditioned buildings.

Studies on airflow-related behavior started in 1999 in China [9] and some results have been obtained that relate to the hot and humid areas of China. Zhang et al. [10,13] established the probit

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relationships between the proportion of open windows and fan usage and the indoor ET* for both naturally ventilated buildings and buildings with split air conditioners in Guangzhou. Hwang et al. [11,15] found that window-opening was the most popular adaptive strategy for both elderly people and others, and the average percentage was as high as 87% for the simultaneous utilization of air-conditioning and electric fans in workplaces and residences in Taiwan. It is noteworthy that non-thermal factors, including contextual, psychological, and social factors, were recently studied, together with thermal factors, as potential drivers [16].

Perceptions on airflow include the factors of draft, intensity, and expectations. Draft was the first factor to attract researchers' attention due to its strong negative impact on thermal comfort in cold environments, and restrictions on indoor air speed are widely provided in thermal comfort standards to accommodate this problem [17–20]. Draft was later studied in terms of warm environments as well and this work provided new issues in relation to the unpleasant perceptions from too much skin and mucous membrane evaporation or too much airflow impulsion [21]. The perceived airflow intensity was found to be proportional to the square of the air speed [22]. The expectation on air movement was usually used to judge the sufficiency of the indoor airflow. The study on the ASHRAE RP 884 database [23] did this and discovered that many people in air-conditioned buildings want more airflow.

The acceptable ranges of indoor airflows have been extensively studied in climate chambers in view of the well-known compensation effects of air speed on air temperature and humidity. The first study was conducted in the 1970s in the United States [24], and then similar studies were also conducted in the United States [25–28], Japan [29], and China [30]. The compensation effects are widely adopted in thermal comfort standards [17–20] to guide indoor airflow utilization. It should be noted that the acceptable ranges obtained in climate chambers may not be directly used in real buildings due to the big differences in the adaptive opportunities of the occupants. Candido et al. [31] obtained the acceptable ranges directly by field study in naturally ventilated buildings in Brazil, and their results show that the minimum air velocity is 0.4 m/s for an indoor operative temperature range of 24–27 °C, 0.41–0.8 m/s for 27–29 °C, and >0.81 m/s for 29–31 °C.

The purpose of the present study is to provide a better understanding and reasonable strategies for airflow utilization in buildings in the hot and humid areas of China. We specifically aim to: 1) collect airflow-related behaviors, motivations, and perceptions in real buildings; 2) analyze the impacts of the indoor environment on behaviors, motivations, and perceptions; 3) obtain acceptable ranges and conditions of indoor airflows; and 4) recommend strategies for airflow utilization in buildings in the hot and humid areas of China.

2. Research methods

2.1. Climate, buildings, and people

Guangzhou is located at latitude 23°08′N and longitude 113°19′E and is a typical example of a city in the hot and humid areas of China. The long summers are hot and humid with plentiful rainfall and the winters are warm and short. The monthly mean temperature is 28.4 °C and the humidity is 83% in July and 13.3 °C and 74%, respectively, in January.

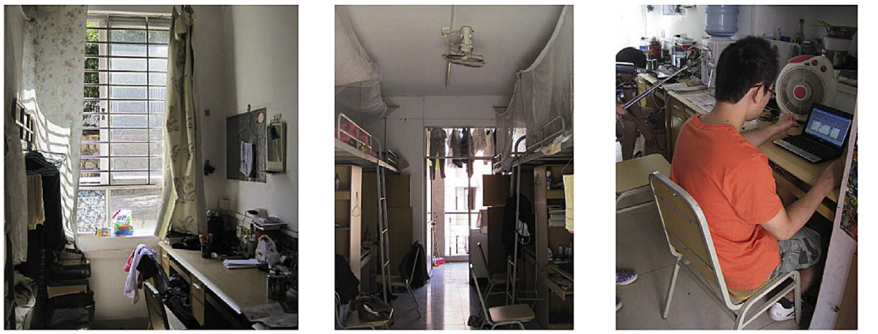
We focused on naturally ventilated buildings where people utilize indoor airflows most actively. Based on a preliminary survey of the buildings at the South China University of Technology, nine dormitory buildings were selected to be the objects of our study. They had the following features: 1) there is no air-conditioning; 2) the windows and doors are freely and easily opened or closed by the occupants (Fig. 1a); 3) both public and personal fans are commonly used, where the public fans are fixed on ceilings and controlled by anybody in the room and the personal fans are used individually (Fig. 1b and c).

Thirty-two students, who have been living in the investigated buildings for more than one year, were recruited as the subjects. Their basic information is shown in Table 1.

2.2. Conduct of field study

The field study was conducted continuously for a whole summer during which each subject was surveyed twice a week, on workdays and weekends. Each survey took about 15 min during which the subjects completed a well-designed questionnaire and the investigators measured their ambient thermal environments. The measuring positions were chosen to be within 0.3 m of the subjects and at three heights (0.1, 0.6, and 1.1 m) above the floor (see Fig. 2). All four parameters, that is, air temperature, relative humidity, globe temperature, and air speed, were measured using lab-grade instruments (see Table 2) according to ISO 7726 [32].

The questionnaire started with an activity report and clothing checklist followed by an airflow section and ended with the thermal acceptability ratings of the thermal environment (see Fig. 3a). The airflow section contained three parts: behaviors, motivations, and perceptions. The usage of operable windows, doors, public fans, and personal fans were collected by questions on behavior. All potential answers were provided to the subjects in the questions on motivations and the real motivations were obtained from multiple



a Open windows b Use of public fans c Use of personal fans

Fig. 1. Conditions of the investigated dormitory buildings.