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Ventilation behavior in residential buildings with mechanical ventilation systems across different climate zones in China

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ABSTRACT

A mechanical ventilation system in a residential building provides a more reliable, controllable, and comfortable means of ventilation than natural ventilation through an open window. However, the operation of a mechanical ventilation system consumes energy and may generate noise and secondary air pollutants. Thus, it is worthwhile to study residents' actual ventilation patterns. This study investigated the usage of natural and mechanical ventilation in 46 apartments across five different climate zones in China by on-site monitoring and a questionnaire survey. On average, the daily natural and mechanical ventilation durations were 11 h and 7.2 h, respectively. Large differences existed among climate regions and seasons. From north to south, as the climate became warmer, the usage of natural ventilation increased. From a seasonal perspective, the natural ventilation duration was the longest in summer and the shortest in winter. The trend of mechanical ventilation usage was opposite to that of natural ventilation. Generally, as the outdoor air temperature increased, the duration of natural ventilation increased and the duration of mechanical ventilation decreased. This study found that occupants prioritized their thermal comfort needs over healthy indoor air quality (IAQ). However, occupants were willing to spend money on energy when the health requirement could be met by mechanical ventilation. This study provides further understanding of occupants' ventilation behavior, and the results can serve as more accurate boundary conditions for analyses of IAQ, energy consumption, and thermal comfort in Chinese residential buildings.

1. Introduction

By supplying outdoor air to buildings and removing indoor air, ventilation can create a thermally comfortable indoor environment with acceptable indoor air quality (IAQ) [1]. Ventilation can be achieved by natural forces such as wind and thermal pressures through window openings or by artificial means through mechanical ventilation systems [2]. As reviewed by Sundell [3], an insufficient ventilation rate is associated with health problems such as inflammation, communicable respiratory infections, asthma, allergies, and sick building syndrome (SBS). Occupants' ventilation behavior, such as the opening of a window or operation of a mechanical ventilation system, strongly influences the effectiveness of ventilation.

In the past decade, an increasing number of studies have been conducted in different types of buildings in various regions to understand occupants' window-opening behavior [4–13]. For example, Yao and Zhao [4] determined a typical window operation schedule in dwellings in Beijing, China, by analyzing human-window interaction data obtained in 19 residences. A number of researchers, such as Rijal [5,6], Andersen [7], and Pan [8], found that the proportion of occupants who opened windows was low under cold outdoor climate conditions, because of thermal comfort considerations [14–18]. In a cold climate, the short window-opening duration may not provide sufficient ventilation to maintain acceptable indoor air quality. A mechanical system provides a more reliable, controllable, and comfortable means of ventilation than opening windows. A mechanical fan can be operated continuously to ensure reliability, a filter can be used to provide control over outdoor pollutants, and a heat recovery unit can be used to reduce thermal discomfort. The capability of mechanical ventilation to maintain better indoor air quality than natural ventilation was demonstrated through a field measurement in fifteen apartments in South Korea [19]. In that study, Park [19] found that mechanical ventilation reduced the indoor to outdoor (I/O) ratios of particle number concentration by 26% for submicron particles and 65% for fine particles in comparison with

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natural ventilation.

Although mechanical ventilation offers several advantages over natural ventilation, it consumes energy, it may be noisy, and it can introduce secondary air pollution from the filter and duct. Therefore, it is interesting to study how people make choices between mechanical ventilation and natural ventilation when both options are available. Previous studies of ventilation behavior have focused primarily on natural ventilation via the opening of windows. Very few studies have addressed people's mechanical ventilation behavior. Andersen [7], Heebøll [20], and Gao [21] recorded window-opening behavior in rooms with mechanical ventilation, but the operation of the mechanical ventilation system was not measured. Park and Kim [22] studied mechanical ventilation behavior in apartments in South Korea in November and December of 2008 by means of a questionnaire survey. They found that 95 out of 139 respondents (68.3%) did not use mechanical ventilation at all during the heating period in winter, and the primary reason for not doing so was the associated increase in heating energy costs. Only 10 out of 139 respondents (7.2%) mechanically ventilated the space for more than 4 h a day. Park and Kim's investigation [22] provided a good example of the ways in which people actually use mechanical systems in their homes. However, the authors only conducted the measurement in winter in the cold climate of South Korea, and window-operation behavior was not recorded. In addition, the questionnaire survey method may not reflect realistic situations because the answers from respondents may be inaccurate and biased. In order to obtain a complete picture of ventilation behavior in residential buildings, comprehensive studies of both natural and mechanical ventilation behavior should be conducted in various climate regions and in different seasons by means of on-site monitoring.

This study reports the findings of a year-long field measurement of ventilation behavior in apartments with mechanical ventilation across five different climate zones in China. On the basis of the acquired information, a framework for analyzing the ventilation behavior in residential buildings was proposed, and suggestions for achieving healthy, thermally comfortable, and energy efficient ventilation were made.

2. Methods

In order to collect data for analysis of ventilation behavior, a measurement campaign was conducted in 46 apartments across five climate zones in China. This section describes the measurement campaign, the climate and season divisions within each monitored climate zone, and the data acquisition in the monitored apartments.

2.1. Measurement campaign

The one-year field campaign was carried out from January 1, 2017, to December 31, 2017, in 46 apartments equipped with mechanical ventilation systems across five climate zones in China. The classification of climate zones in this study was based on thermal design code for civil buildings in China (GB50176-2016) [23]. 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 the average air temperatures in the coldest and hottest months. As shown in Fig. 1, the monitored apartments were in the cities of Urumqi, Shenyang, and Yingkou in the SC zone, Tianjin and Xi'an in the C zone, Shanghai in the HSCW zone, Kunming in the M zone, and Guangzhou, Shenzhen, and Nanning in the HSWW zone. In the monitored apartments, ventilation could be achieved by either opening windows, i.e., natural ventilation, or by operating a mechanical ventilation system. In this study, ventilation through window openings has been defined as natural ventilation (NV), and ventilation achieved by the mechanical system has been termed mechanical ventilation (MV).

The mechanical ventilation systems installed in the 46 monitored apartments can be categorized into three types: exhaust ventilation system, supply ventilation system, and energy recovery ventilation system [24]. Fig. 2 provides schematics of the three systems. An exhaust ventilation system (Fig. 2(a)) depressurizes the building by exhausting indoor air while make-up air infiltrates into the rooms through cracks and openings in the building shell. A supply ventilation system (Fig. 2(b)) uses a fan to pressurize the building, forcing outdoor air into the building via ducts while indoor air leaks out of the building through cracks and holes in the building envelope. An energy recovery ventilation system (Fig. 2(c)) provides more control than exhaust and supply ventilation systems by introducing and exhausting approximately equal amounts of outside and inside air. In addition, the energy recovery ventilation system includes a heat exchanger that uses the exhaust indoor air to warm the cold outside air. Compared with the energy recovery ventilation system, the exhaust system and the supply system are simpler and are less expensive initially. However, the introduction of untreated air directly into the building may cause thermal discomfort and may also increase the heating load.

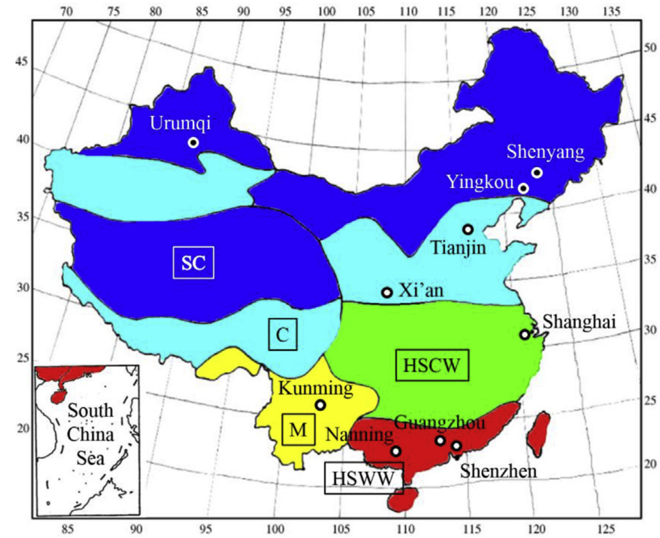

Fig. 1. Illustration of the five climate zones and the monitored cities on a map of China.

Table 1 provides a summary of the mechanical ventilation systems used in all monitored households in this study. As the table shows, the numbers of monitored households were 13, 14, 7, 7, and 5 for the SC, C, HSCW, M, and HSWW regions, respectively. All the monitored apartments in the SC and HSCW regions used energy recovery systems, and all the apartments in the HSWW regions used supply ventilation systems. Among the 14 monitored households in the C region, five used supply ventilation systems and the rest used energy recovery systems. Exhaust ventilation systems were used in the six apartments in the M region. In addition to information about the mechanical ventilation systems, Table 1 lists the outdoor air temperatures in the studied cities in 2017. Generally, from north to south, the climate became warmer and the range in air temperature became narrower. Cities in the severe cold (SC) region have the coldest climate. The lowest air temperature among the cities of the SC region was below −20 °C. The city of Kunming, in the mild (M) region, did not experience very hot weather, as its highest air temperature was only 29 °C. In contrast with Kunming, cities in the hot summer and warm winter (HSWW) region do not have a cold climate, and the temperature barely fell below 10 °C. Climate variations may lead to differences in ventilation behaviors among climate zones.

2.2. Season division

To account for the outdoor temperature differences among various climate zones, the division of seasons was based on the mean daily air