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Seasonal variation of window opening behaviors in two naturally ventilated hospital wards

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ABSTRACT

Natural ventilation enables personal control, and occupant behaviors in window opening play a decisive role on natural ventilation performance, indoor air quality (IAQ), and/or airborne infection risk in a hospital setting. The occupant behaviors differ significantly from different building types with different functions and living habits. Based on a one-year field measurement in two general hospital wards in Nanjing, China, the effects of air quality (i.e. indoor CO_2 concentration and outdoor $PM_{2.5}$ concentration) and the climatic parameters (i.e. indoor/outdoor temperature, relative humidity, and outdoor wind speed, wind direction and rainfall) on window opening/closing behaviors are analyzed. Indoor air temperature or relative humidity is found to be a dominant factor for window opening behaviors. Seasonal differences are observed for the different influences of physical factors. The outdoor temperature is found to be associated with the window opening probability negatively during the cooling season, but positively during the transition and heating seasons. The indoor relative humidity positively affects the window opening probability during the transition season while a negative impact appears during the cooling and heating seasons. Based on the seasonal variation of window opening behaviors, Logistic regression models in different seasons (cooling, transition and heating seasons) are developed to predict the window opening/closing state and are verified to be promisingly adaptable with results of accuracy bigger than 70%.

1. Introduction

In hospitals, a high ventilation rate has proven to be effective for reducing the cross-infection risk [1–3]. Natural ventilation can provide a much higher ventilation rate with proper utilization than mechanical ventilation, showing a great potential for controlling airborne infection [4–6]. Large ventilation openings were found to help reduce the infection risk of Severe Acute Respiratory Syndromes (SARS) among healthcare workers (HCWs) during the 2003 epidemics in Guangdong Province [7]. The occupants' window opening behaviors play a decisive role on the natural ventilation performance and significantly influence the airborne infection risk and indoor air quality (IAQ) [8], as well as the energy consumption for air-conditioning systems [9–11]. Many factors are known to influence the window opening behaviors, including thermal-driven factors, time-related factors, environment-driven factors, psychological factors and other uncertain factors [12–25,34,35]. Thermal-driven factors, including outdoor climate conditions, indoor air temperature and relative humidity, occupants' number, clothing condition, gender, etc., are recognized as the most important driving factors in many previous studies [12–17]. Warren and Perkin [12] found that the outdoor air temperature accounted for 76% of the observed variance of window opening status in office buildings, with sunshine for 8% and wind speed for 4%. Fritch et al. [13] developed a stochastic model with outdoor temperature as the only variable based on data of four office rooms from October to May. No significant variations of window opening behaviors were found with wind speeds lower than 5–6 m/s, and its correlation with sunshine was only observed for the south-facing vertical openings [13]. A study in occupied buildings in the UK, Pakistan and throughout Europe suggested that the indoor temperature was a more coherent predictor for window-opening behaviors rather than the outdoor temperature [14]. Huang et al. [15] found that higher indoor temperature in residential buildings promoted people open windows more frequently in winter. Stazi et al. [16] suggested that the need of thermal comfort was a stronger driving factor for undertaking adaptive actions on windows than the need of improving air quality in classrooms. Time-related

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factors vary significantly among buildings with different functions. Haldi and Robinson [18] analyzed the window opening behaviors in office buildings and found the interactions with window opening had a significant correlation with occupants' commuter time because window opening or closing behaviors commonly occurred when occupants arrived at or leaved their offices. Besides, an attempt to take seasonal effects into consideration by adding a factor with 12 levels corresponding to each month of a year did not bring any significant improvement to the model. Barthelmes et al. [19] used K-S test to rank the influencing variables in residential apartment, and results turned out that the time of the day was the most important variable. Windows were opened and closed at certain times of the day (morning and late afternoon hours) regardless of the different day in a week. Jones et al. [20] investigated the impact of season on residential buildings for window opening/closing behaviors, finding that seasonality affected both frequency and drivers of window operation in bedrooms. Same simulation models to predict window operation behavior could be used in spring and autumn. Environment-driven factors, related to the indoor and outdoor environment quality, occupant's perceived illumination, awareness of environmental concern, cognitive resources, building structure and insulation, even geographic areas, are also important driven factors on occupants' interaction with windows [15,16,21–25]. Andersen and Fabi [24] measured 15 Danish residential buildings of window opening behaviors and corresponding environmental conditions during winter, spring and summer. Results indicated that the indoor CO_2 concentration and outdoor temperature were the two single most important variables for window opening prediction. The indoor CO_2 concentration is regarded as a direct indicator for IAQ and ventilation performance since it is a good surrogate for bioeffuents, even for airborne infection risks [26–29]. It is suggested that $PM_{2.5}$ is more hazardous than PM_{10} as it is more likely to penetrate and deposit deeper in the tracheobronchial and alveolar regions [30]. In recent years, $PM_{2.5}$ pollution has been a predominant problem and caused great health burden in China [31,32]. Previous study showed that the outdoor $PM_{2.5}$ concentration has become a highly concerned factor on residents' interaction with windows in China [25]. Therefore, outdoor $PM_{2.5}$ concentration can be taken as a representative parameter for outdoor air quality in China. Different geographic areas were also supposed to affect occupants' interactions with windows in office buildings [22,25]. Shi and Zhao [25] conducted a field study in 8 naturally ventilated residential apartments in Beijing and Nanjing, and found that the window opening probability had different correlation strengths for the same variable in different cities, especially accounted for the outdoor $PM_{2.5}$ concentration. Besides, household size, disposable income and ethnicity are all found to be influential factors in residential buildings [33].

The characteristics of window opening behavior vary significantly from buildings with different functions. In office buildings, the window opening and closing behaviors are not only driven by thermal comfort needs but also driven by daily routine (time of the day) and habits (arriving and leaving time) [34]. In residential buildings, occupants' daily activities play an important role on window opening and closing behavior. Cooking, cleaning and getting fresh air accounted for 27%, 40% and 33% of the total openings respectively [35]. The day of week does not influence the window opening behavior in residential buildings [19], which is different from that in office buildings. In classroom buildings, the daily routine is also an essential factor and students' interaction frequency with windows is higher during breaks [17]. Few researches are available on the window opening behaviors in hospitals, although many studies focusing on occupants' window opening behaviors have been carried out in residential, office and classroom buildings, etc. [12–14,24–26,36–38]. Studies on window opening behaviors are significantly important in hospital buildings compared to those in other buildings, as ventilation performance is crucial for infection control in hospitals. The interactions with windows in hospitals have the following different characteristics from that in other buildings. Firstly, the patient group is not fixed and each person has different living habitat, which makes the interactions with windows in hospital buildings a collective behavior. Secondly, patients may have different thermal comfort due to both health and clothing conditions. Nematchoua et al. [39] conducted an experimental study in 5 big hospitals and 50 shopping centers in Northern Madagascar and confirmed that the comfort temperature was slightly higher in shopping centers than that in hospitals due to the difference of subjects' activity and clothing conditions. Thirdly, the occupation period is mostly 24 h in hospital buildings, which makes the time-related factors differ from other buildings. Besides, the maximum window opening size is limited in many hospital wards for occupants' safety and security. Moreover, the IAQ requirement is generally higher in hospitals than those non-hospital environments. Finally but importantly, inpatients and HCWs would open windows sometimes to cater for their physical or psychological needs even when air-conditioning is on, although windows are usually advocated to be closed to save energy.

This paper aims to investigate occupants' window opening behaviors in hospital wards. Both of the indoor thermal factors (indoor temperature and relative humidity) and outdoor climatic factors (outdoor temperature, relative humidity, wind speed and direction, rainfall, solar radiation, etc.) are analyzed. In terms of the crucial influence of air-conditioning status on the indoor thermal comfort, the window opening behaviors are analyzed by seasons, including the cooling (summer), transition (spring and autumn) and heating seasons (winter). Seasonal statistical models are developed and verified to help evaluating IAQ and energy consumption.

2. Methods

2.1. Field measurement

A one-year field measurement was designed and carried out in a general hospital building in the Jiangsu Province Hospital, Nanjing, China, which holds up to 42,000 inpatients annually. The investigated building is of central corridor type, one of the most common design for general hospitals in China, as shown in Fig. 1. Semi-centralized (with

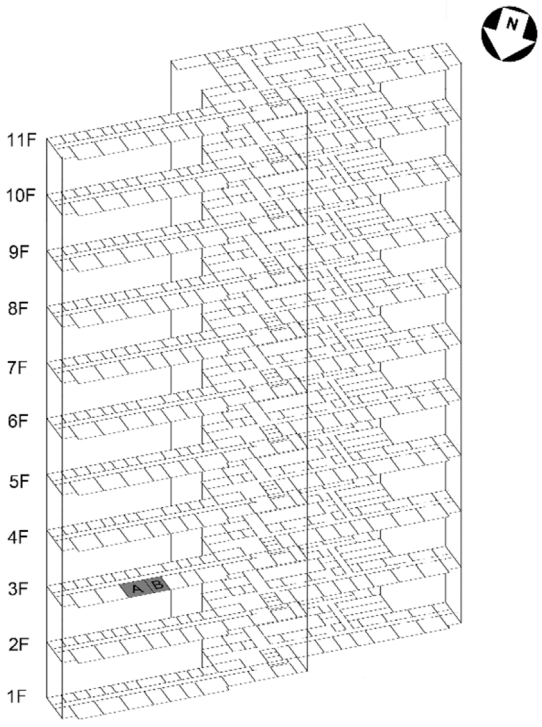

Fig. 1. The spatial distribution of measured wards (grey shaded areas).