

STUDY ON THE DYNAMIC NATURAL VENTILATION RATES OF OCCUPIED RESIDENCE

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Abstract. The residential natural ventilation rates have a significant impact on indoor thermal comfort and air quality and building energy consumption. The characteristics of the indoor-outdoor temperature difference and wind pressure change over time, as well as the occupants' window opening behavior and the use of HVAC systems, resulting in the residential air change rate being dynamic with time. Many previous studies of residential ventilation measured the steady-state air change rates, which does not reflect the actual dynamic characteristics. In this study, a field measurement was conducted in a bedroom of one natural ventilation residential building in Beijing with continuously monitoring the CO₂ concentration, indoor air temperature, and outdoor meteorological parameters for one year. Using the CO₂ released by occupants as a tracer gas, the extended Kalman filter based on the Transient Mass Balance Equation (TMBE) was adopted to calculate the dynamic air change rate. This method can effectively filter the CO₂ concentration measurement noise. The trend of air change rate with each influencing factor was analyzed. This study is expected to lay the foundation for future studies of dynamic air change rates in residential buildings.

1 Introduction

Ventilation rates have significant impacts on building energy consumption and indoor air quality. Natural ventilation driven by wind and heat pressure is the main form of ventilation in residential buildings. Factors influencing the air change rate include weather (indoor-outdoor temperature difference, wind speed) and the leakiness of the building envelope. Occupancy-associated factors are also important, including window opening and the use of HVAC systems. Many previous studies have found that the immediate consequence of window opening behavior is the significant variability of air change rates. In a Japanese study [1], 87% of the total air change rates were accounted for by occupants' opening window behavior. Another study in Denmark found that the air change rates in bedrooms with windows half-open or ajar were approximately twice as high as those in rooms with closed windows [2]. Due to the dynamic characteristics of the above-mentioned influencing factors, the air change rates vary with time. Determining air change rates in residential buildings is always a challenging issue. Tracer gas methods are widely used to characterize natural ventilation by assuming steady airflows [3]. An interesting method derived from tracer gas methods is the occupant-generated CO₂ method. Taking advantage of the CO₂ gas directly produced by occupants, no injection of any tracer gas is required and interference with the daily life of occupants is avoided, especially for prolonged exposures in this method. Up to

date, occupant-generated CO₂ tracer gas methods have been widely employed to estimate ventilation rates in residential buildings, school buildings, and office buildings and the accuracy of these methods has been widely discussed [3]. The vast majority of the research related to the occupant-generated CO₂ method to date has involved measuring the constant airflow rate under certain circumstances, such as constant air infiltration, specific period and stable CO₂ emission rate, to investigate whether the occupied space could fulfill the minimum requirements of 0.5h⁻¹ or the relationship between air change rates and building style [4,5]. The fact is that the airflow rates usually change greatly during natural ventilation with window airing, depending on weather conditions, building characteristics, and occupants' behavior of opening windows. To the best knowledge of our authors, a few studies have accounted for the dynamic ventilation rate for the actual in-use conditions of windows in occupied rooms, but most of these were one-time measurements made over short periods of 12 h to several weeks, making it impossible to determine the effects on air change rates of weather conditions and occupants' behavior. In this respect, some attempts have been made to determine continuous ventilation rates over a period of time. Wallace et al. [6] conducted a single study capable of including all these factors to investigate the effects on air change rates of temperature, wind, use of fans, and window-opening behavior. Duarte et al. [7] proposed a new method for estimating dynamic ventilation rates in a window-aired room considering "in-

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use” conditions and uncertainty in occupancy and measurements of indoor air CO₂ concentration. However, they did not study the relationship between calculation results and environmental parameters and occupants’ window opening behavior.

Therefore, a field study was conducted in a bedroom of one residential building in Beijing by continuously monitoring the window status, the indoor CO₂ concentration, indoor air temperature, and meteorological parameters for one year. The TMBE method associated with the extended Kalman filter (EFK) was adopted to calculate the dynamic air change rate (ACR). This study aims to obtain dynamic ACR for a normally occupied residential room and detect its correlation with environmental parameters and occupants’ window-opening behavior and provide a database for building energy simulation.

2 Methods

2.1 Field measurements

This study conducted a one-year field measurement of a bedroom in Beijing from March 2017 to March 2018. The measured residence has a floor area of 80 m² and is located on the eighth floor of a twelve-story residential building. None of the occupants smoke, which means that no additional pollution will be caused to the indoor environment, thereby affecting the occupants’ window-opening behavior. The residence uses waterborne radiators for heating in winter and split air-conditioners for cooling in summer. In the transitional season, mainly relies on natural ventilation to adjust the indoor heat and humidity environment. The whole dwelling is naturally ventilated, except for the exhaust hood in the kitchen and the exhaust fan in the bathroom. We conducted a questionnaire survey to obtain specific information, including the daily occupancy and the weight and height of each occupant. We also surveyed the daily schedule and living habits of the occupants.

The window switch status was recorded by magnetic induction devices (TJHY-CKJM-1). Magnet-to-magnetic induction devices were placed on the window casement and frame. For horizontal sliding windows, when the distance between the two devices exceeded 3 cm, the window was considered to be open, and the magnetic induction device would record “1”. Conversely, the device would record “0” when the window was closed. The environment monitoring instruments (TJHY-WEZY-1 and Testo174H) recorded the indoor parameters, which included indoor CO₂ concentration and indoor air temperature. Meteorological parameters obtained from the outdoor weather station closest to the residence being measured include outdoor PM2.5 concentration, outdoor air temperature and wind speed.

2.2 Air change rate calculation method

The derivation process of the calculation method will be briefly presented in the following section, and the more detailed introduction can refer to Reference [7]. Based on

the conservation equation of tracer gas CO₂ released by occupants in the room, the air change rate can be formulated as:

$$dC/dt = -n(C - C_{out}) + S/V \quad (1)$$

where C is the indoor CO₂ concentration(ppm); C_{out} is the outdoor CO₂ concentration(ppm); n is the air change rate (h^{-1}); t represents time; V is the effective volume of the room(m³) (subtracting the volume of major cabinets and furniture); S is the production rate of CO₂ (cm³/s).

In residential buildings, n and S vary with time, the quasi-instantaneous approach is used by dividing the time series into small intervals Δ , in which C , n and S are treated as constants. The uncertainty caused by CO₂ concentration measurement and the estimation of the emission rate, which depend on measurement noise, each occupant, occupancy, activity and gender, need to be considered. Equation (1) is converted into the form applicable to the Kalman filter as follows:

$$\begin{cases} \begin{bmatrix} c_{k+1} \\ S_{k+1} \\ n_{k+1} \end{bmatrix} = \begin{bmatrix} e^{-n_k \Delta} c_k + (1 - e^{-n_k \Delta}) S_k / (n_k V) \\ S_k \\ n_k \end{bmatrix} + \begin{bmatrix} r_k^c \\ r_k^S \\ r_k^n \end{bmatrix} \\ \begin{bmatrix} c_k' \\ S_k' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} c_k \\ S_k \\ n_k \end{bmatrix} + \begin{bmatrix} v_k^c \\ v_k^S \end{bmatrix} \end{cases} \quad (2)$$

where k represents the number of time step; c represents relative CO₂ concentration $c = C - C_{out}$; the state vector $x_k = [c_k; S_k; n_k]$;

$F_k(x_k) = [e^{-n_k \Delta} c_k + (1 - e^{-n_k \Delta}) S_k / (n_k V); S_k; n_k]$, the

transition matrix $A_k = dF_k / dx_k|_{x_k}$; the process noise

vector r_k is normally distributed white noise with zero mean and its variance-covariance matrix is R ; the

measurement vector $z_k = [c_k'; S_k']$; the observation

matrix $H = [1, 0, 0; 0, 1, 0]$; the measurement noise vector

v_k is normally distributed white noise with zero mean and its variance-covariance matrix is V . The Kalman filter

contains two distinct stages, namely the predicting stage, and the updating stage. The predicting stage uses the

estimation of the state vector parameters ($\hat{c}_{k-1}$, $\hat{S}_{k-1}$ and $\hat{n}_{k-1}$) at the preceding time step to predict the current state

vector parameters($\hat{c}_{k|k-1}$, $\hat{S}_{k|k-1}$ and $\hat{n}_{k|k-1}$). Then, predicted

state vector parameters are compared to measurement vector parameters (c_k' and S_k'), and the filter corrects the

state vector parameters knowing the measurement covariance matrix, and the process noise covariance matrix. The estimation of the state vector parameters at

the current time step ($\hat{c}_k$, $\hat{S}_k$ and $\hat{n}_k$) can be obtained. The

two-stage calculation of the Kalman filter provides instantaneous results of the dynamic ACR. The

calculation process of Kalman filter program was realized by MATLAB.

3 Results and discussion

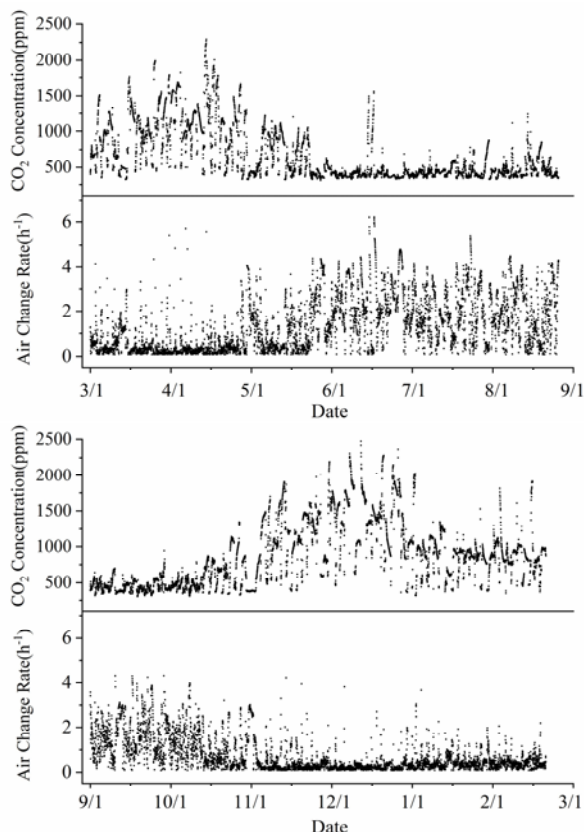


Fig. 1. Time-series of measured indoor CO₂ concentration and calculated ACR values

Fig.1 presents time-series of measured indoor CO₂ concentration and the calculated ACR values. The dynamic ACR calculated by the Kalman filter in Fig.1 provides an important data base for the influence factor analysis in the subsequent sections.

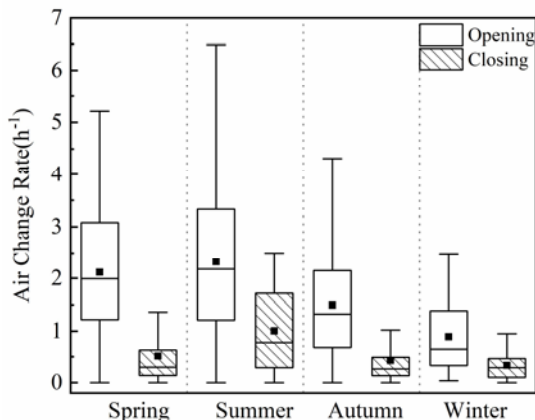


Fig. 2. ACR values in different seasons.

Fig.2 shows the distribution of ACR in each season. The mean value of ACR during the window opening period in each season is 2.11 h⁻¹, 2.31 h⁻¹, 1.48 h⁻¹ and 0.89 h⁻¹ respectively. The ACR values in spring and summer is significantly higher than that in autumn and winter. The mean value of ACR during the window closing period in each season is 0.51 h⁻¹, 0.38 h⁻¹, 0.42 h⁻¹ and 0.33 h⁻¹ respectively, which is much lower than the ACR values during the window opening period. It shows that the window-opening behavior has a significant impact on the ventilation rate of the room.

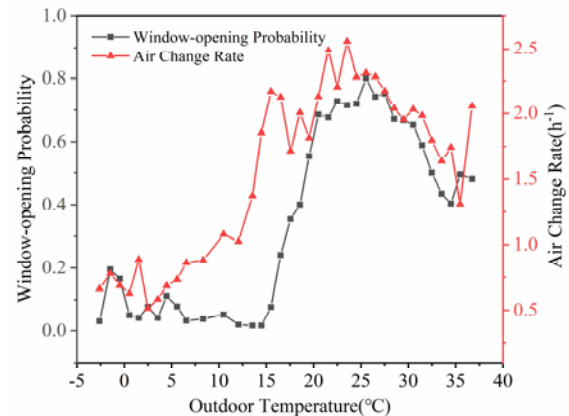


Fig. 3. Window-opening probability and ACR in different outdoor temperature

Fig.3 shows the variation of window-opening probability and ACR varying with an increase in outdoor air temperature (T_o). When T_o was lower than 5 °C, there was no noticeable variation in window-opening probability and ACR. When T_o was in the range of 5°C~15°C, the window-opening probability remained stable, while the ACR increased sharply, their trends showed differences. One possible reason was that the window opening degree was different. The window-opening probability raised sharply when T_o was in the range of 16°C~26°C, at a temperature of 26°C, the highest value was reached. When T_o was higher than 26°C, the ACR and window-opening probability decreased as the T_o increased, and their trends were similar. In this study, on the one hand, occupants turned on the air conditioner, which reduced the window-opening probability. On the other hand, occupants adjusted the window opening degree to ensure a comfortable indoor thermal environment, which leads to a reduction in ACR values.

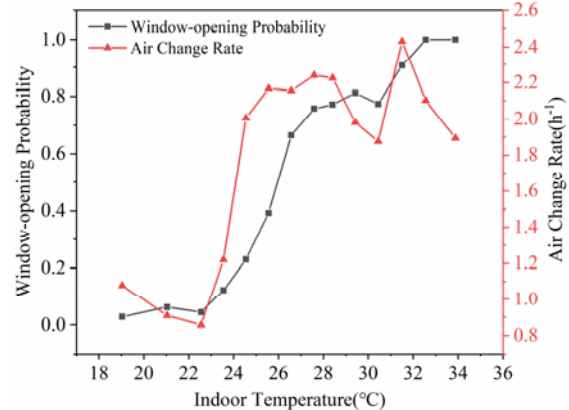


Fig. 4. Window-opening probability and ACR in different indoor temperature

Fig.4 illustrates the variation of window-opening probability and ACR varying with an increase in indoor air temperature (T_{in}). When T_{in} was in the range of 18~22°C, the window-opening probability remained stable and ACR decreased slightly. The window-opening probability and ACR increased sharply when T_{in} was in the range of 22~26°C. The window-opening probability reached 100% when T_{in} was higher than 33°C. One possible reason was that the room was unoccupied and the windows were opened during this period. The window-opening probability would be extremely high because this period was short.

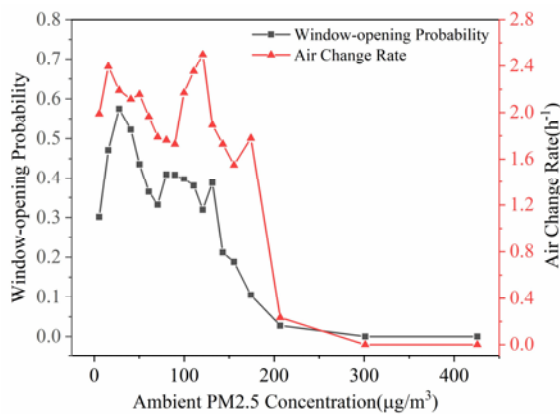


Fig. 5. Window-opening probability and ACR in different outdoor PM2.5 concentration

Fig.5 illustrates the variation of window-opening probability and ACR varying with an increase in ambient PM2.5 concentration. PM2.5 is the primary pollutant in China, so the ambient PM2.5 concentration can be used as a representative parameter of outdoor air quality. In the present study, when the PM2.5 concentration was higher than 120 µg/m³, the window-opening probability and ACR decreased sharply, when the concentration was higher than 200 µg/m³, the window-opening probability approached 0, which means the window was always closed. This trend of change indicates that outdoor air quality has a great impact on occupants' window-opening behavior.

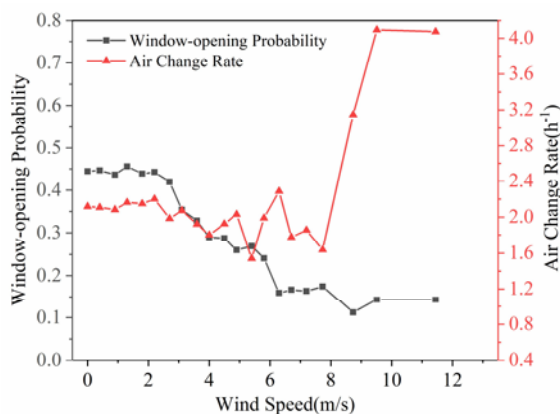


Fig. 6. Window-opening probability and ACR in different wind speed

Fig.6 illustrates the variation of window-opening probability and ACR varying with an increase in wind speed. No significant variations of window-opening probability and ACR were found with wind speeds lower than 3 m/s. It is observed that the window-opening probability decreased when the wind speed was higher than 3 m/s. The ACR remained stable, until when the wind speed was higher than 8 m/s, the ACR increased abruptly, with a maximum value of 4.0 h⁻¹. The window-opening probability had dropped to about 0.1, which means that the windows were closed most of the time. In the case of such high wind speed, when the window was opened, the sharp rise of ACR was caused by large wind pressure.

4 Conclusions

The window opening behavior of occupants has a significant effect on the ACR of the residence. An in-

depth study of the natural ventilation demand of residential buildings needs to take the window opening behavior of occupants into account.

The transient mass balance equation method associated with the extended Kalman filter can be used to calculate the time-varying ventilation rates of residential buildings with CO₂ concentration and room occupancy recorded.

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