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Air infiltration rate distributions of residences in Beijing

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ABSTRACT

Air change rate is a very important parameter for indoor air quality estimation as it influences the exchange of air pollutants between indoor and outdoor environments. Consequently, determining air change rate distribution is indispensable for assessment of a population's exposure to air pollutants. In this study, the annual and seasonal average infiltration rates (air change rate for window close conditions) of 180 representative residences were simulated using the multi-zone network airflow model (CONTAM) to understand the residential infiltration rate distributions in Beijing. The representative residences were selected by probability sampling based on building characteristics, including building type, floor area, number of rooms, construction year, number of floors, and building orientation. The results show that the annual average infiltration rates in Beijing range from 0.02 to 0.82 h^{-1} with a median value of 0.16 h^{-1}. The empirical distributions of the annual and seasonal average residential infiltration rates in Beijing were provided. The annual average infiltration rates were also found to well fit a two-parameter lognormal distribution, the median and standard deviation of which is −1.79 and 0.62. Infiltration rates of 34 residences in Beijing were measured via the CO_2 decay method, and the measured infiltration rates of residences matched the simulated distribution well. The differences between the simulated and measured infiltration rates are discussed.

1. Introduction

Mega cities in China, especially Beijing, the capital city, have high levels of ambient air pollution due to rapid urbanization and population explosion in the past two decades [1]. Ambient air pollutants can penetrate indoor environments through intentional and unintentional openings of building envelopes [2]. Residents' exposure to air pollution may result in adverse health risks. For example, increase in mortality has been observed due to high sulfur dioxide and total suspended particles in residential areas in Beijing [3]. Air change rate (*ACR*) is defined as the ratio of the airflow from the outdoors into a building and the volume of the corresponding enclosed space. *ACR* is a function of stack-induced airflow, which results from temperature difference between indoor and outdoor environment, and wind-induced airflow [4,5]. It is a critical aspect of air pollution exposure assessment as it influences the import of outdoor-generated air pollutants and the export of indoor-generated air pollutants. Chen et al. [6,7] showed that variance in the air change rates of different regions could partially explain the inter-regional variance in health risks to both ozone and particulate matter. Considering the fact that people spend majority of their time in residences [8,9], an evaluation of the air change rate of residences in Beijing is required to assess its population's exposure to air pollution.

For residences without mechanical ventilation system, there are two categories of *ACR*s: natural ventilation rate and infiltration rate [10]. Natural ventilation rate refers to the air change rate through the intentional openings of building envelopes (windows and doors). Infiltration rate refers to the air change rate through unintentional leakage areas of building envelopes when the doors and windows are closed. Both these categories of *ACRs* have quite different impacts on indoor air quality. Take $PM_{2.5}$ as an example. The indoor/outdoor ratio (I/O ratio) of the $PM_{2.5}$ concentration for a steady state can be expressed as:

$$\frac{C_{p,in}}{C_{p,out}} = \frac{P}{1 + K/AER} \tag{1}$$

where $C_{p,in}$ is indoor $PM_{2.5}$ concentration (μg/m^3), $C_{p,out}$ is outdoor $PM_{2.5}$ concentration (μg/m^3), P represents the fraction of $PM_{2.5}$ entering the indoor environment through the building envelope and K is the indoor $PM_{2.5}$ deposition rate (h^{-1}). When windows are

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open, P is unity and natural ventilation rate (approximately 1–10 h^{-1}) is much larger than K (approximately 0.1–0.3 h^{-1}) [11]. Thus, the indoor $PM_{2.5}$ concentration tends to be close to the outdoor level and the I/O ratio is approximately one. When windows are closed, P is approximately 0.8–1.0 [2,12] and is comparable with the infiltration rate (approximately 0.1–1.0 h^{-1}) [13], causing the I/O ratio to vary from 40% to 80%. Beijing has a typical continental monsoon climate with four distinct seasons. Most residences in Beijing are equipped with split air conditioners and central heating systems without fresh air delivery units. Inhabitants tend to close windows for a long time in the heating and cooling seasons. Therefore, the infiltration rate of residences in Beijing is important, which is evaluated in this study.

Infiltration rate of a residence is a function of the building's characteristics. Individual residences may also experience temporally different infiltration rates because of different meteorological conditions. Many researchers have attempted to conduct large-scale field measurements to study the residential ventilation rate distributions in several regions, including the United States, Norway, Sweden, and Denmark [14–21]. Some of them obtained empirical or parametric lognormal distributions of the residential ventilation rates, which have potential for use in air pollution population exposure assessment. However, almost all these measured residences were not probability samples. These residential ventilation distributions are to be used with caution due to the lack of representativeness of the measured residences. Both mechanic and empirical models were also established to evaluate residential air change rates in the United Stated based on meteorological data, housing characteristics and occupant behaviors [22]. Nevertheless, the model predicted residential air change rate is quite dependent on the cohort analysis of input parameters, which is not well collected in Beijing at present to our best knowledge. A multi-zone network airflow model (CONTAM 3.1) was developed to calculate building ventilation, which has been validated and applied in several previous studies [23–25]. Persily et al. [13] utilized this multi-zone network airflow model to simulate the infiltration rates of representative residences of the housing stock in the United States. Their results provided the infiltration rate distributions of the entire housing stock of the US. Nevertheless, the characteristics of residences and meteorological features are quite different between Beijing and the regions in these previous studies. The extrapolation of these distributions to assess the exposure to air pollution of Beijing's population is inappropriate and unreasonable.

In this study, representative residences of the housing stock in Beijing were determined based on existing official statistical reports. The infiltration rates of these representative residences were simulated via the multi-zone network airflow model (CONTAM 3.1) [26]. Both the empirical and fitted parametric distributions of the infiltration rates of residences in Beijing are presented based on the simulated infiltration rates of representative residences. In addition, the infiltration rates of 34 residential apartment units in Beijing were measured using the CO_2 decay method. The cumulative probability function of the measured results was compared with the modeled infiltration rates. The infiltration rate distributions of residences, which consider building characteristics together with the meteorological features of Beijing, are very useful in further analysis of indoor air quality, population exposure assessment to air pollution, and residential energy consumption estimation.

2. Modeled infiltration rate distributions

The majority of the buildings that have been constructed in the past two decades in China are high-rise buildings. According to the Beijing Statistical Year Book [27], the proportion of residents living in single house in Beijing is negligible. Thus, the residence type this study mainly focused on is apartment buildings. Natural infiltration of residences is composed of stack-induced airflow and wind-induced airflow [4,5]. The infiltration rate of an apartment building could be affected by the building spatial configuration, leakage area, building height and building orientation in the multi-zone network airflow model [26]. This is mainly because the building spatial configuration influence the inter airflows within different zones inside the building. The leakage area, determined by the floor area and construction year in this study [28], correlates with the amount of airflow infiltrating into the building. The leakier the apartment building is, the larger the infiltration rate would be. Building height would influence the stack-induced airflow and building orientation would influence the wind-induced airflow. Consequently, the building characteristics which may affect the infiltration rate of a residence were listed as follows: building spatial configuration, floor area, number of rooms, construction year, number of floors, and building orientation. The representative residences were selected based on these six characteristics through a probability sampling process. In this process, the whole housing stock was divided into several classifications for each influential factor. Then, the housing stock in Beijing was divided into hundreds of categories based on the classifications of the six influential factors. The "weight" of each category, which is the proportion of the category occupying the entire housing stock, was estimated based on the distribution of classifications for each influential building characteristic. A representative residence was then set up to represent each category. The representative residences, the sum of "weights" of which was larger than 90%, were chosen to simulate the infiltration rate distributions of residences in Beijing. The results showed 180 residences to be representative of the housing stock in Beijing. The details of this probability sampling process are described in the Supporting Information, in section "**Selection of representative residences**".

Annual and seasonal time-average inter-zone airflows of the representative residences were simulated using the multi-zone network airflow model (CONTAM 3.1) based on the typical meteorological parameters of Beijing. In this study, spring was set from March 16th to May 15th, summer from May 16th to September 15th, autumn from September 16th to November 15th, and winter from November 16th to March 15th according to the meteorological features of Beijing. The infiltration rate of a residence was subsequently calculated using the reported inter-zones airflows. The calculated annual and seasonal time-average infiltration rates of the representative residences were gathered and analyzed to acquire both the empirical and parametric infiltration rate distributions of residences in Beijing.

2.1. Simulation

The infiltration rate simulation of each representative residence was performed for a representative apartment building. The apartment units within the representative apartment buildings were all identical to the representative residences. The simulation of the infiltration rate of each representative apartment building was conducted as follows:

(1) Setting up the specific layout of each representative apartment building according to its building characteristics in the CONTAM sketchpad.
(2) Defining the airflow paths for each representative apartment building. It is the fact that the majority of the residences in Beijing are without mechanical ventilation system. Besides, the split air conditioners and central heating system equipped for residences in Beijing generally do not have fresh air