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Ventilation, indoor particle filtration, and energy consumption of an apartment in northern China

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ABSTRACT

Ventilation is commonly thought to be helpful for improving indoor air quality. However, this may not be true when the outdoor air is polluted. For example, in the event of fog or haze in developing countries, outdoor particulate matter (PM) can be drawn into rooms by ventilation systems. In such circumstances, ventilation must be accompanied by indoor particle filtration. This investigation incorporated a particulate-filtration model into the EnergyPlus software. The validated software was then used to evaluate ventilation together with indoor particle filtration in a typical Chinese residential apartment. The ventilation modes included natural, mechanical, and hybrid ventilation. Transient air change rate, indoor CO_2 and PM2.5 concentrations, air temperature, annual energy consumption, and utility costs were solved. For the mechanical systems, demand-controlled outdoor air rates and clean air delivery rates (CADRs) that ensure acceptable indoor air quality were also solved. It was found that indoor particulate filtration must be utilized in northern Chinese dwellings. A combination of natural ventilation and portable demand-controlled particulate filtration has the lowest operating cost, but the ventilation rate may occasionally be insufficient. Among the mechanical ventilation modes, decentralized systems operating only during the occupied period have great potential to minimize utility costs. Mechanical ventilation in demand-controlled operation and its hybrid with natural ventilation can further reduce energy consumption.

1. Introduction

Ventilation is commonly thought to be helpful for improving indoor air quality and reducing the incidence of sick building syndrome [1,2]. However, this may not be true when the outdoor air is polluted. For example, in the event of fog or haze in developing countries, the outdoor air can have extremely high concentrations of particulate matter (PM) [3,4]. The outdoor PM can infiltrate into rooms through building cracks [5] or be drawn into rooms by ventilation systems [6], thus posing a threat to occupational health [7]. In such circumstances, ventilation must be accompanied by air purification.

Residential buildings may use natural ventilation (NV), mechanical ventilation (MV), or hybrid ventilation (HV). NV is widely used because it does not require the operation of a fan [8] and can utilize passive cooling [9]. With an appropriate design, NV can ensure thermal comfort and indoor air quality most of the time [10], but the outdoor air may occasionally be insufficient. In contrast, MV can provide the desired outdoor air rates, but it entails an initial investment and considerable operating costs. Heat recovery and demand control are often used to reduce the energy consumption of MV systems [11]. However, the applicability of heat recovery should be carefully examined [12,13], because the recovery unit increases flow resistance and the recovered heat varies with the seasons. Demand-controlled ventilation (DCV) regulates the ventilation rate according to indoor CO_2 concentration, humidity, human occupancy, etc. [14]. As compared with conventional MV with a fixed ventilation rate, DCV can save energy in various types of buildings [15,16]. CO_2-based DCV has been studied most extensively because the CO_2 concentration is generally accepted as an indicator of indoor air quality. However, CO_2-based DCV assumes that the outdoor air has low PM concentrations. HV is a combination of NV and MV and relies on an algorithm to switch between the two modes. HV takes advantage of both NV and MV [17] and thus has the potential to minimize building energy consumption without sacrificing indoor air quality [18,19].

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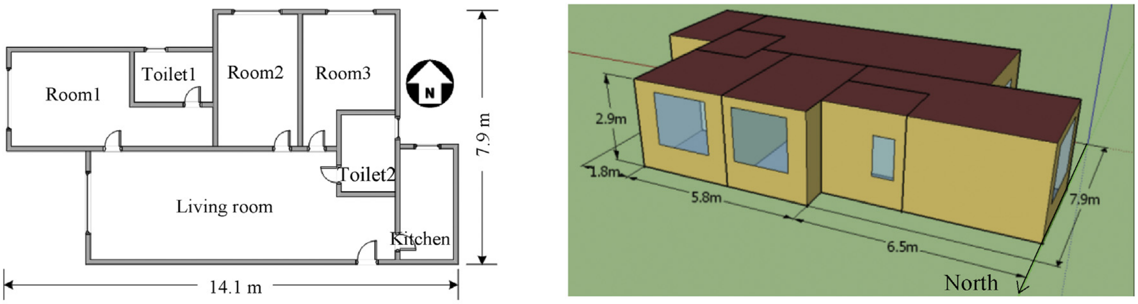

(a) (b)

Fig. 1. Apartment selected for study: (a) floor map, (b) geometric model in E+ software.

In the event of fog or haze, building ventilation on the one hand dilutes indoor gaseous pollutants, but on the other hand it brings outside PM indoors. Thus, both indoor-generated particles, such as those from smoking, cooking, and particle resuspension by human activities [20,21], and ventilation-drawn particles from the outdoor environment must be simultaneously controlled. Air cleaning, or more precisely particle filtration, has been found effective for indoor particle removal [22,23]. Appropriately positioning an air cleaner [24] and coordinating indoor flow circulations [25] could further improve the indoor air cleaning performance. However, most studies have addressed only the removal of indoor-generated air pollutants. It has been recommended that greater attention be paid to the energy consumption, initial investment and running costs associated with air cleaners [26].

A software program that is able to simulate ventilation rate, gas and particle concentrations, and energy consumption is required for evaluating different ventilation and air-cleaning strategies. Both computational fluid dynamics (CFD) and multi-zone models can be used to simulate building ventilation. CFD remains costly for simulating ventilation in a home [27]. In contrast, multi-zone model-based software programs, such as Contam and EnergyPlus, are more affordable. Contam can solve ventilation rate, airborne pollutant concentration, and even air cleaning. However, it cannot simulate building energy consumption. EnergyPlus was originally developed for building energy simulation and was recently extended the simulation of airborne pollutant concentration [28]. EnergyPlus has been validated with good accuracy for predicting ventilation rate [29], energy consumption [30], and PM2.5 concentration [31], respectively. Unfortunately, EnergyPlus lacks an air-cleaning simulation model. The above works have not validated the EnergyPlus for a comprehensive prediction of the temporal ventilation rate, air temperature, energy consumption, and PM2.5 concentration yet.

This investigation incorporated a particulate-filtration model into the EnergyPlus program. The software was validated with measurement data obtained in a test room. The extended software was then used to evaluate various strategies for residential ventilation and particulate filtration in a typical family apartment in northern China. Transient air change rate, CO_2 and PM2.5 concentrations, indoor temperature, annual energy consumption and utility costs were solved.

2. Modeling methods

2.1. Indoor particulate filtration

The PM2.5 concentration in a well-mixed room can be modified from the multi-zone model [32] as:

$$V\frac{\mathrm{d}C_i}{\mathrm{d}t} = E + \sum_j k_j F_{j\to i} C_j - \sum_j F_{i\to j} C_i - (k_g V + \mathrm{CADR}) \times C_i, \qquad (1)$$

where V is the room volume, C is the PM2.5 concentration, t is time, E is the PM2.5 source release rate, i and j are room indices, k_j is the particulate penetration ratio from zone j to zone i, F is the airflow rate between zones, k_g is the gravitational settling rate, and CADR is the clean air delivery rate of an air cleaner.

For a given CADR, the indoor PM2.5 concentration can be easily solved with Eq. (1) once the indoor airflow is available. However, in the design of demand-controlled air cleaning to ensure indoor PM2.5 concentration at a certain threshold, the CADR is unknown. One can rearrange Eq. (1) to obtain the required dynamic CADR as:

$$\mathrm{CADR} = \frac{E + \sum_j k_j F_{j\to i} C_j - \sum_j F_{i\to j} C_i}{C_i} - \frac{V}{C_i}\frac{\mathrm{d}C_i}{\mathrm{d}t} - k_g V, \qquad (2)$$

Because the CADR and the indoor PM2.5 concentration are coupled together, iterations are required to solve the dynamic demand-controlled CADR. For example, if a guessed CADR yields an indoor PM2.5 concentration greater than the specified threshold, a gradual increase in the CADR is required until the concentration is exactly equal to the threshold value. That is, when demand-controlled air cleaning is adopted, the target indoor PM2.5 concentration is the threshold value, and no less. An alternative way to solve the CADR is by specifying the indoor PM2.5 concentration as the threshold value. If a negative CADR is obtained, it means that no dedicated air cleaning is currently required, and the actual indoor PM2.5 concentration can be solved by specifying the CADR as zero in Eq. (1). However, if a positive CADR is obtained, it is the required CADR at the current time, and the indoor PM2.5 concentration is the threshold value.

2.2. An apartment and its simulation schemes

An apartment with a total floor area of $88\,\mathrm{m}^2$, as shown in Fig. 1, was chosen for this study. The apartment was located in Tianjin, approximately 113 km southeast of Beijing in northern China. The apartment was on the fourth floor of an isolated building. It was supposed that four persons lived in this apartment and that their occupancy schedules were fixed. The living room was occupied by the whole family from 18:00 to 22:00 on workdays and from 11:00 to 22:00 on weekends. Room 1 accommodated two persons from 22:00 to 7:00, while at the same time Rooms 2 and 3 each accommodated one person.

Three different ventilation schemes were considered, namely, natural ventilation (NV), mechanical ventilation (MV), and hybrid ventilation (HV). In NV, all of the windows were opened to one quarter of their maximum openable ranges when the outdoor temperature was in the range of 18–26 °C and the outdoor PM2.5 concentration was below $35\,\mu\mathrm{g/m}^3$. Otherwise, all the windows were closed with only infiltration allowed. The annual average infiltration rate was approximately 0.2 air changes per hour (ACH) if all the windows were shut. In MV, no windows were opened, and outdoor air was forced into the rooms to ensure that the indoor CO_2 concentration was less than 1000 ppm when the rooms were occupied. The HV system was equivalent to NV when both the indoor CO_2 and PM 2.5 concentrations were below the thresholds; otherwise, the system switched to the MV mode.

Table 1 presents all the simulation cases. Cases NV0 through NV2