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Diurnal and seasonal variation in air exchange rates and interzonal airflows measured by active and passive tracer gas in homes

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ABSTRACT

Outdoor air delivery to buildings is an important parameter in the assessment of pollutant exposure indoors. Detailed and well controlled measurements of air exchange rates (AER) and interzonal airflows in residential environment are scarce. We measured the outdoor AERs in up to six rooms in five dwellings across four seasons using active tracer gas. Night time AERs were also estimated in the bedrooms based on occupant-generated CO_2. Passive tracer gas measurements were performed for comparison. AERs changed frequently during the day. Differences in outdoor AERs were observed between individual rooms. Window opening behavior had a strong influence on AERs, which were highest during occupied daytime periods, lowest in the night; highest in the summer, lowest in the winter. Significant differences were found between AERs measured by the different techniques. The median nighttime AER in all bedrooms across the four seasons was 0.49 h^{-1} with the active tracer gas technique and 1.20 h^{-1} with the CO_2 method. The average winter AER in the five homes with the passive tracer (0.63 h^{-1}) differed substantially from the corresponding AER measured with the active tracer gas (0.25 h^{-1}). Additionally, we studied the pollutant distribution from one room (source room) and interzonal airflows across the dwellings. The air within a given floor was well mixed, with the average tracer gas concentration in the non-source rooms reaching approximately 70% of the source room concentration. There was less air movement between different floors. The position of the internal doors had a strong influence on the air movement.

1. Introduction

Air exchange rate (AER) is a key parameter in understanding indoor air quality, pollutant concentrations and exposure. In naturally ventilated buildings AER will depend on building characteristics, geographic location, meteorological conditions such as indoor/outdoor temperature differences and wind speed, and occupant behavior [1–5]. Performing accurate AER measurements can be challenging. Various measurement techniques can be chosen depending on the desired number of measurements, the stability of the steady-state conditions, and the experimental limitations [6,7]. Indoor environmental studies mostly rely on passive tracer gas techniques or tracer gas decay measurements, often using occupant-generated CO_2 concentrations. The accuracy of these techniques has been widely discussed [8,9]. In most cases these measurements consider the entire space as a single zone, ignoring interzonal airflows and leading to substantial uncertainties [10]. When passive tracer gas techniques are applied, a single average AER value is reported for the entire measured building zone over a certain period of time. AERs vary considerably over time [11]. AERs within a building may differ from room to room or zone to zone, depending on differences in occupant behavior (e.g. window opening) [3,12,13].

Active tracer gas measurement using the constant concentration method allows monitoring the short term changes in multizone buildings [6]. During guarded constant concentration measurements, where the tracer gas concentration in the adjacent zones is maintained at the same level as in the measured zone, airflows between the measured zone and the adjacent zones will not affect the measurements and the determined air exchange rate will be the

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outdoor air exchange rate (as opposed to total air exchange rate, obtained from e.g. occupant-generated CO_2). Due to the need of sophisticated equipment and control system, reports of continuous measurements using controlled tracer gas concentrations are scarce [7,14]. Moreover, while the various measurement techniques perform reasonably well under controlled single zone conditions [15], they have not been compared in parallel measurements under real life conditions.

Interzonal flows within buildings strongly influence spatial variation in pollutant concentrations and exposure. This is especially the case when localized pollution sources are present, such as environmental tobacco smoke (ETS). Several studies looked at the migration of ETS between rooms and concluded that considerable exposure to ETS with the source in a single room may occur throughout the home [16–19]. Few other studies on the airflows within buildings have been performed, mostly using passive tracer gas and focusing on the transport of air and pollutants between basements or garages and living areas [20–24] and between industrial zones and offices of mixed-use buildings [25]. Du et al. [12] characterized the AERs and interzonal flows between bedrooms and living areas in 126 households. The study indicated that tighter homes (lower AERs) have higher internal flows. In 26 Japanese residencies, the interzonal air exchange rates (based on interzonal airflows from other rooms as opposed to outdoor air) from bedroom to living/dining room varied between 0.54 h^{-1} in autumn to 1.6 h^{-1} in summer, and between living/dining room and bedroom it varied between 0.42 h^{-1} in autumn and 0.85 h^{-1} in summer [13]. Even in rooms with very low outdoor AER, interzonal airflows from the other rooms were substantial. These studies applied multi-compartment passive tracer measurements based on steady-state assumptions and did not consider short-term fluctuations. However, the time of occurrence and duration of interzonal airflow variations can be critical in determining pollutant concentrations indoors. Concentrations based on time-weighted average interzonal airflows could be under-predicted [26]. Short term variations in interzonal airflows can mainly arise from internal door opening patterns, but also from window opening and operation of heating and ventilation systems [17,26,27].

Outdoor air delivery to individual rooms within buildings is of interest when interpreting contaminant exposure. This paper characterizes the diurnal, seasonal and spatial variations in AERs, pollutant distribution throughout the building from a single source room and associated interzonal airflows using tracer gas concentration measurements in five homes. The effects of short-term changes in home occupancy and occupant behavior are demonstrated using real-time measurements. Room and house AERs measured simultaneously with different techniques are compared.

2. Methods

2.1. Selected residences

As part of a study conducted by the research program "Center for Indoor Air and Health in Dwellings" [28], five homes were selected for detailed investigation of their indoor environments, including chemical and microbiological parameters, during the course of one year, from summer 2010 to spring 2011 [29,30]. The homes were not selected to be representative of the Danish building stock. Because of the use of disturbing sampling equipment, the homes were chosen among colleagues and acquaintances of the project team, with the intention of reducing the risk of non-compliance or subject withdrawal from the project. However, they were selected to include both single family houses, a row house and an apartment, and dwellings of different age and means of ventilation. All homes were situated in urban areas within a 40-km radius of Copenhagen, Denmark. Characteristics of the homes are listed in Table 1. The layouts of the homes are shown in Fig. S1.

2.2. Air exchange rates

In each season of the year continuous air exchange rate (AER) measurements were performed during 2–4 days periods, which often included weekends. The measurements in the five homes were performed during five successive weeks (Table S1). An Innova 1312 Photoacoustic Multi-gas Monitor coupled with an Innova Multipoint Sampler and Dozer 1303 (Luma-Sence Technologies A/S, Ballerup, Denmark) was used. Prior to the measurements, the instrument was confirmed not to show any sign of leakage. Yet, whenever possible, the tracer gas sampler and dozer were placed behind closed doors in a room that was not directly investigated in the experiment. A constant concentration of 4 ppm of tracer gas (Freon® 134a) was maintained in up to six rooms in each dwelling, covering on average 83% of the total volume of the dwellings (Table 1). For each day of the measurement period, the occupants filled in a questionnaire. They indicated the periods when the home was occupied vs. unoccupied, the time they spent in the bedroom, the position of the windows in various rooms and the position of the bedroom door during the night (open/closed). A value was assigned to the position of the windows (closed, assigned value 0; ajar, assigned value 1; open, assigned value 2). The corresponding value was assigned to each time step for which a tracer gas concentration and AER was obtained (every 3–4 min in each room). The average window position, being a time-weighted continuous variable, was then calculated for each time period that was separately analyzed. For each measured room the AERs were determined for the entire period and separately for the periods when the home was unoccupied, occupied in the daytime and nighttime (00:00–06:00 o'clock). The average overall AER in each dwelling was calculated both as the volume-weighted average of the AERs of each room and as the sum of the obtained average airflows into the measured rooms divided by the corresponding total volume. We assumed that the average outdoor AER in the unmeasured part of the dwelling was the same as the average AER in the measured rooms. This is reasonable, given the fact that actual measurements covered the majority of the dwellings by volume (between ~60% and ~95%; Table 1). The occupants were asked not to alter their normal behavior during measurements.

The concentrations of CO_2 in the bedrooms were measured by CARBOCAP® CO_2 monitors (GMW22, Vaisala, Finland). The data were logged every 5 min by HOBO U12-012 data-loggers (Onset Computer Corp., USA). CO_2 data obtained in the time period between 00:00 and 6:00 for each measured night were extracted for calculation of the AERs. This time period was selected to represent the conditions when the occupants spent most of the time in the bedroom. The activity and occupancy were assumed to be constant during the night. AERs based on occupant-generated CO_2 were calculated according to the procedure described in detail by Bekö et al. [31].

The PerFluorocarbon Tracer (PFT) technique [32] was applied to measure the monthly average AERs during the whole year, as previously described by Frederiksen et al. [33]. In brief, two types of tracer gas were used, perfluoro-methyl-cyclopentane (PMCP) and perfluoro-methyl-cyclohexane (PMCH). Only one type was used in each dwelling. Hence, the dwellings were treated as single zones. PFT sources along with adsorption tube samplers were mounted in the dwellings. The adsorption tube samplers were changed every month, resulting in monthly average AERs. The amount of tracer adsorbed in the samplers was analyzed using thermal desorption and gas chromatography and the AER was calculated from the concentration, measured temperature, known emission rates and