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Published in:
Building and Environment

Link to article, DOI:
[10.1016/j.buildenv.2016.05.016](https://doi.org/10.1016/j.buildenv.2016.05.016)

Publication date:
2016

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Bekö, G., Gustavsen, S., Frederiksen, M., Bergsøe, N. C., Kolarik, B., Gunnarsen, L., Toftum, J., & Clausen, G. (2016). Diurnal and seasonal variation in air exchange rates and interzonal airflows measured by active and passive tracer gas in homes. *Building and Environment*, 104, 178-187.
<https://doi.org/10.1016/j.buildenv.2016.05.016>

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

Gabriel Bekö^{1*}, Sine Gustavsen¹, Marie Frederiksen², Niels Christian Bergsøe², Barbara Kolarik², Lars Gunnarsen², Jørn Toftum¹, Geo Clausen¹

¹ International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé 402, 2800-Lyngby, Denmark

² Danish Building Research Institute, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen, Denmark

**Contact email: gab@byg.dtu.dk, phone: (+45) 45 25 40 18, fax: (+45) 45 93 21 66*

Highlights

- Air exchange rates and internal airflows were measured in 5 homes during 4 seasons
- Large diurnal, spatial and seasonal variations in AER were observed
- Window opening was a key factor influencing AER
- Large differences were found between AERs measured by the different techniques
- With open doors the air was well mixed within the same floor, not so between floors

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 CO₂. 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 CO₂ 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.

41

42 **Keywords:** Ventilation, Spatial variation, Measurement technique, CO₂, Occupant influence

43

44 **1. Introduction**

45 Air exchange rate (AER) is a key parameter in understanding indoor air quality, pollutant
46 concentrations and exposure. In naturally ventilated buildings AER will depend on building
47 characteristics, geographic location, meteorological conditions such as indoor/outdoor temperature
48 differences and wind speed, and occupant behavior [1][2][3][4][5]. Performing accurate AER
49 measurements can be challenging. Various measurement techniques can be chosen depending on
50 the desired number of measurements, the stability of the steady-state conditions, and the
51 experimental limitations [6][7]. Indoor environmental studies mostly rely on passive tracer gas
52 techniques or tracer gas decay measurements, often using occupant-generated CO₂ concentrations.
53 The accuracy of these techniques has been widely discussed [8][9]. In most cases these
54 measurements consider the entire space as a single zone, ignoring interzonal airflows and leading to
55 substantial uncertainties [10]. When passive tracer gas techniques are applied, a single average AER
56 value is reported for the entire measured building zone over a certain period of time. AERs vary
57 considerably over time [11]. AERs within a building may differ from room to room or zone to zone,
58 depending on differences in occupant behavior (e.g. window opening) [3][12][13].

59

60 Active tracer gas measurement using the constant concentration method allows monitoring the short
61 term changes in multizone buildings [6]. During guarded constant concentration measurements,
62 where the tracer gas concentration in the adjacent zones is maintained at the same level as in the
63 measured zone, airflows between the measured zone and the adjacent zones will not affect the
64 measurements and the determined air exchange rate will be the outdoor air exchange rate (as
65 opposed to total air exchange rate, obtained from e.g. occupant-generated CO₂). Due to the need of
66 sophisticated equipment and control system, reports of continuous measurements using controlled
67 tracer gas concentrations are scarce [14][7]. Moreover, while the various measurement techniques
68 perform reasonably well under controlled single zone conditions [15], they have not been compared
69 in parallel measurements under real life conditions.

70

71 Interzonal flows within buildings strongly influence spatial variation in pollutant concentrations and
72 exposure. This is especially the case when localized pollution sources are present, such as
73 environmental tobacco smoke (ETS). Several studies looked at the migration of ETS between
74 rooms and concluded that considerable exposure to ETS with the source in a single room may occur
75 throughout the home [16][17][18][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][21][22][23][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 residences, 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,

111 Denmark. Characteristics of the homes are listed in Table 1. The layouts of the homes are shown in
112 Figure S1.

113
114 *2.2 Air exchange rates*

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

140
141 The concentrations of CO₂ in the bedrooms were measured by CARBOCAP[®] CO₂ monitors
142 (GMW22, Vaisala, Finland). The data were logged every 5 minutes by HOBO U12-012 data-
143 loggers (Onset Computer Corp., USA). CO₂ data obtained in the time period between 00:00 and
144 6:00 for each measured night were extracted for calculation of the AERs. This time period was
145 selected to represent the conditions when the occupants spent most of the time in the bedroom. The

146 activity and occupancy were assumed to be constant during the night. AERs based on occupant-
147 generated CO₂ were calculated according to the procedure described in detail by Bekö et al. [31].
148

149 The PerFluorocarbon Tracer (PFT) technique [32] was applied to measure the monthly average
150 AERs during the whole year, as previously described by Frederiksen et al. [33]. In brief, two types
151 of tracer gas were used, perfluoro-methyl-cyclopentane (PMCP) and perfluoro-methyl-cyclohexane
152 (PMCH). Only one type was used in each dwelling. Hence, the dwellings were treated as single
153 zones. PFT sources along with adsorption tube samplers were mounted in the dwellings. The
154 adsorption tube samplers were changed every month, resulting in monthly average AERs. The
155 amount of tracer adsorbed in the samplers was analyzed using thermal desorption and gas
156 chromatography and the AER was calculated from the concentration, measured temperature, known
157 emission rates and the volume of the dwelling. Details of the PFT technique, including analysis of
158 tracer gases and estimation of tracer gas emissions have been described by Leaderer et al. [34]. For
159 comparison with the AERs from the other measurement techniques, the monthly AERs obtained by
160 the PFT technique during the months corresponding to the other measurements were used. For more
161 direct comparison of the air exchange rate measurement techniques, the PFT technique was also
162 applied for a 5-day period overlapping with the active tracer gas measurements in each home during
163 winter.
164

165 *2.3 Pollutant distribution and interzonal flows*

166 Before each AER measurement the distribution of a simulated pollutant from a source point across
167 the dwelling was measured over a period of about 26 hours. Constant concentration of tracer gas (4
168 ppm) was maintained in a selected room and its concentration was monitored in the rest of the
169 rooms (identical to the AER measurements). The selected source rooms are listed in Table S1.
170 Steady-state concentrations in the source rooms were reached in less than an hour after the
171 measurements began. The data obtained after this point were used for analyses. The average tracer
172 gas concentration was calculated in each source room and each measured non-source room. 30-
173 minute running average tracer gas concentrations were used to calculate the fractions of source
174 room concentrations in each non-source room for each measurement time-step (approximately
175 every four minutes). These fractions were then averaged over the total measurement period. Since
176 two of the homes had two floors where measurements were performed, we also present the results
177 separately for the source floors and non-source floors. The results were additionally stratified over
178 home occupancy and distance from the source room (in case of single-floor houses). The source
179 room was considered Zone 1. Zone 2 consisted of rooms immediately adjacent to the source room,
180 while other rooms belonged to Zone 3. The airflows between adjacent rooms, between the source

181 room and the rest of the dwelling and between two different floors were calculated from the
182 obtained data. Additionally, the fraction of the total airflow entering a given space that arises from
183 another space (interzonal flow proportions) was calculated. Details of these calculations can be
184 found in the Supplementary Material.

185

186 *2.4 Statistical analyses*

187 Statistical analyses were made in STATA software, release 12.1 for Windows (StataCorp LP,
188 College Station, Texas, USA). Differences in AERs and concentration fractions by season were
189 tested using Kruskal-Wallis test. Differences in tracer gas concentrations, AERs and window
190 opening between various occupancy periods, as well as differences between AERs measured by the
191 different techniques were tested using Wilcoxon matched-pairs signed-rank test. Two-sample
192 Wilcoxon rank-sum test and two-sample t-test were used to look for differences in tracer gas
193 concentrations and concentration fractions between different floors or zones. We used linear
194 regression to examine the association between AER and outdoor temperature or average window
195 position and between AERs obtained by different techniques.

196

197 **3. Results and Discussion**

198

199 *3.1 Diurnal and seasonal variation in air exchange rates*

200 Large differences in AERs were observed between the five dwellings (Table 2). The highest AER
201 was consistently measured in home E, which was a relatively new apartment building with
202 mechanical exhaust ventilation. This is consistent with earlier results from Scandinavia [35][36].
203 The differences among the single family homes were likely caused by the different construction and
204 age of the buildings, weather conditions during the measurements and occupant behavior [37][38].
205 The AER in each room fluctuated during the day. An example of the diurnal changes in room AERs
206 is shown on Figure S2. The diurnal trends in AER of the entire homes averaged across all
207 measurement days are shown for each home and season in Figure 1. The highest average AERs
208 were measured during the day. The strong influence of occupant behavior on the AER is supported
209 by the fact that significantly higher AERs were measured during daytime periods when the homes
210 were occupied, compared to nights and unoccupied periods. The windows were open significantly
211 more during the occupied daytime periods (Table 3). Airing by periodic opening of windows is
212 common in Scandinavia throughout the year. A linear relationship between the median AER and the
213 average window position in Table 3 had a coefficient of determination $R^2=0.66$.

214

215 In dwellings, the Danish building code requires a minimum outdoor air supply rate of 0.3 L/s/m²
216 heated floor area to remove moisture from the indoor air. However, moisture generation will
217 typically not be constant, but will vary during the day with the occupants' activities. Allowing
218 variation of the outdoor air supply rather than specifying a constant minimum may be a more
219 efficient means of ventilating dwellings. Currently, it is not clear how the criteria for a minimum
220 outdoor air supply rate that accounts for the variation in moisture generation should be specified.
221 Some guidance may be found in Table 3, which shows how the outdoor air supply rate was lower at
222 night or unoccupied day periods than when the occupants were present in the dwelling. In particular
223 during the winter and spring, the area specific outdoor air supply rate was lower than what's
224 specified in the building code, when the occupants were sleeping or not present. When the
225 occupants were present and awake, their activities in the dwelling resulted in increased supply of
226 outdoor air. Thus, in the five dwellings investigated in this study, the outdoor air supply seemed to
227 trace the expected variation in moisture generation.

229 Significant seasonal variation in AER was observed (Tables 2 and 3). In all homes, the lowest
230 AERs, mostly below 0.5 h⁻¹, were measured in the winter and autumn, highest in the summer. This
231 is typical for buildings in moderate climate that use primarily natural ventilation [1][13][20][39]. In
232 dwellings that have no balanced mechanical ventilation, the actual AER is strongly influenced by
233 changing occupant behavior, especially window opening [4][40][41], which tends to be more
234 extensive in the summer [13][42]. We observed more window opening during warmer seasons
235 (Table 3). A moderate positive linear relationship between outdoor temperature and AER was
236 obtained, with the coefficient of determination R²=0.65 (p<0.001; n=19; using AERs in Table 2 for
237 each season and home, excluding one data point – an unusually high summer AER in home E. R²
238 with this data point included was 0.41).

240 The large effect of window opening on AER has been documented in a number of studies
241 [3][31][43]. Howard-Reed et al. [5] found that window opening increased the air exchange rate by
242 0.10 to 2.8 h⁻¹. Wallace et al. [3] observed that temperature differences could not account for AERs
243 above 0.8 h⁻¹. A strong seasonal effect was noted with windows open more than half the time during
244 the summer months and closed more than 90% of the time during the autumn and winter months.
245 Wilson et al. [44] noted that in the Los Angeles area, AER increased with the ambient temperature
246 between 11 and 24 °C, then decreased as the temperature increased above 24 °C. The authors argued
247 that people open doors and windows more often when the outside temperature is between 19-24 °C,
248 and they keep their homes tighter at colder and hotter outdoor conditions.

250 There were substantial differences in AERs between rooms within the dwellings (Figure S2; see
251 also the relatively large standard deviations in Table 2). In the study by Wallace et al. [3], the mean
252 relative standard deviation of the hourly average AERs across all rooms in a single dwelling was
253 15%. Du et al. [12] reported bedroom AERs approximately twice as high as whole-house AERs,
254 suggesting that windows were frequently open in bedrooms and that they may have large exterior
255 wall-to-volume ratio, increasing air infiltration. Shinohara et al. [13] reported slightly higher AERs
256 in the bedrooms in the summer, compared to living rooms and kitchens, while the opposite trend
257 was observed in the other seasons. Bekö et al. [41] found significantly lower AERs in bedrooms
258 located on the ground floor of the dwelling, in comparison with bedrooms located on the first floor
259 or higher. Du et al. [20] compared AER measurements in basements and in corresponding
260 residencies in 170 houses. AERs in basements were consistently higher than in the living areas. On
261 the other hand, the differences between weekly mean AERs measured in 390 entire homes and in
262 the children's bedrooms within these houses were very small [35].

263

264 *3.2 Comparison of AER measurement techniques*

265 The seasonal trends were similar for AERs determined from the constant tracer gas concentration
266 and from occupant-generated CO₂ (Table 4). However, at the median level, the AERs in the
267 bedrooms during night determined from CO₂ were more than twice as high as the corresponding
268 AERs measured by tracer gas. The median nighttime AER in all bedrooms across the four seasons
269 was 0.49 h⁻¹ with the tracer gas technique and 1.20 h⁻¹ with the CO₂ method (Table S2). The
270 relatively strong linear relationship between the AERs measured by the two techniques is indicated
271 on Figure 2.

272

273 The PFT measurements captured the differences between the dwellings, but did not show the same
274 variation across the seasons as the other techniques (Tables 4 and 5; see also Figure 2 in
275 Frederiksen et al. [33] for monthly AER in the five homes across seven months). It is therefore not
276 surprising that the 5-day average AERs were very similar to the average AERs for the
277 corresponding months in each home (Table 5). These values differed substantially from the AERs
278 measured with the active tracer gas technique. The correlation between the average AERs in the
279 five homes during the four seasons obtained by the two techniques was weak ($R^2=0.22$; $p>0.05$).

280

281 All of the techniques use certain assumptions and have their limitations. They rely on steady-state
282 and well mixed conditions. The CO₂ method assumes uniform CO₂ concentration throughout the
283 space and it assumes that the CO₂ generation, outdoor CO₂ concentration and ventilation rate
284 remain constant during the measurement period. Interzonal flows constitute a problem, and

285 therefore this technique often provides an estimate of the total airflow into the bedroom, including
286 airflows from adjacent spaces. Bekö et al. [31] estimated that AERs from a single-zone mass
287 balance of CO₂ can have a relative error as high as 120%. The error depends on the occupancy in
288 the adjacent rooms, the true air exchange rate and the amount of air flowing from the adjacent room
289 to the measured room.

290

291 The accuracy of AER measurements using passive tracer has received considerable attention. A
292 potential problem with this technique is that for accurate measurements it requires a relatively long
293 measurement time and it assumes that ventilation is constant over that time [6]. This assumption is
294 difficult to satisfy in naturally ventilated dwellings, where occupant behavior can cause frequent
295 changes in AER. Mathematical models indicated that, when applying only one tracer (single-zone),
296 this technique may underestimate the average AER by up to 30% [8]. This negative bias is due to
297 the fact that the reciprocal of the average tracer concentration, which is the item measured by the
298 passive sampler, is not identical to the average reciprocal tracer concentration, which is the item
299 needed to calculate ventilation rates [34]. Under typical uncontrolled field conditions (e.g., open
300 windows), the error can be on the order of a factor of two [9]. The use of multiple tracers (multi-
301 zone measurement) eliminates some of the limitations associated with the single passive tracer
302 technique [8][10]. In our case, however, the PFT technique often overestimated the AERs obtained
303 with the active tracer gas measurements. This may occur if the tracer gas adsorbs not only on the
304 sorption material in the samplers, but also on surfaces within the measured space. Dorer et al. [45]
305 concluded that the PFT technique may overestimate airflow rates due to such sink effects by a
306 factor of 1.2 to 2.2. While this is usually assumed not to be the case in typical dwellings, some
307 adsorption has been indicated to occur in dwellings with fleecy surfaces [33]. Moreover, limited
308 number and imperfect positioning of the PFT sources and samplers may have led to non-uniform
309 tracer concentrations. This may have especially been the case in home B, a three-floor home where
310 PFT sources were not placed in the entrance/staircase between the living area and the sleeping area,
311 a room with relatively large volume, in order to avoid the direct effect of the main entrance on the
312 source. Indeed, the PFT technique overestimated the AER from the active tracer gas measurements
313 the most in this home. It is also noteworthy, that the PFT technique and the active tracer technique
314 treated the volume of the measured space differently when determining AERs. The overall AER
315 from the active tracer technique in each dwelling was based on the total volume of the rooms where
316 measurements took place. The PFT technique relied on the total volume of the entire dwellings,
317 although PFT sources and samplers were not placed in all rooms.

318

Active tracer gas measurement using the constant concentration method is believed to be the most accurate ventilation measurement technique available in buildings where multizone effects are important [6]. Its error depends on the measurement duration and it assumes that there is no difference between the mean concentration during the measurement period and the target concentration. In case of guarded measurements, it is also assumed that the tracer gas in all surrounding rooms is at the target concentration. These conditions often cannot be met in a dynamic environment with frequent changes in AERs of the various rooms/zones. In most of the dwellings in our study, the six sampling/dosing channels were sufficient to cover nearly all major rooms (guarded measurements). We therefore assert that our measurements reasonably reflect outdoor AERs. However, in dwellings where we could not place a sampling and dosing point in all of the rooms, a constant tracer gas concentration could not be guaranteed throughout the entire dwelling. Interzonal flows between the measured rooms and spaces with lower tracer gas concentration would then lead to overestimated outdoor AER in the measured rooms. Another source of uncertainty in home E (apartment) may be the potential leakage between adjacent zones (neighboring apartment and staircase) [46]. Additionally, the ideal positions of the sampling and dosing points may have been restricted by the occupants and room functionality [47]. However, air mixing in most rooms was likely satisfactory, especially during occupied periods (see following section).

336

337 *3.3 Pollutant distribution and interzonal flows*

The average tracer gas concentrations in all dwellings reached about 60% of the source room concentration (Table 6). The average tracer gas concentration in the non-source rooms, relative to the source room was somewhat lower in the summer, when outdoor AERs were highest. In the two houses that had two floors (homes B and D), the average tracer gas concentration over the four seasons on the source floors (without the source room) was 3.0 ppm. Similar average concentration on the source floors was obtained in the single-floor homes. Significantly lower average concentration was achieved on the non-source floors of homes B and D (1.2 ppm). Together with the lowest interzonal flow proportions between the two floors compared to the rest of the values in Table S3, these results indicate that the air within a given floor is reasonably well mixed, while there is limited air movement between different floors. Van Ryswyk et al. [10] calculated the ratios of perfluorocarbon tracer concentrations in the source floor and the adjacent floor. Median values for these ratios were 2.0 and 2.3, depending on whether the source floor was the main floor or the basement/second floor, respectively. However, we observed episodes when the difference in concentrations on the two floors was small (e.g. Figure 3, afternoon of 13.1.2011). This can occur under certain conditions that may influence airflow directions, such as favorable temperature differences, combination of open windows and doors and occupant movement (e.g. early morning

354 of 14.1.2011). Generally, periods of active presence of occupants disrupted the steady state
355 conditions compared to night or unoccupied periods, reflecting more air movement in the dwellings.
356 Du et al. [20] measured the highest portion of air entering the living zone from basement in the
357 winter, lowest in the summer. The authors concluded that these results reflect enhanced stack effect
358 in the winter and increased natural ventilation in the summer. Similar conclusion was drawn by
359 Dodson et al. [23].

360

361 The position of the internal doors can influence the air movement between rooms [17][26][27]. An
362 open door between two adjacent rooms or zones can make multiple rooms behave as a single
363 compartment [19]. For example, the bedroom door in house C was ajar in the night but was most
364 likely fully open during daytime (data on door opening was only available for night time). Indeed,
365 the average ratio of bedroom to source room concentration during night was 41%, while during
366 daytime it was 80%. During the measurements in the five homes there were altogether five episodes
367 when the door to a *non-source bedroom* was closed. All these rooms had closed windows during
368 these periods. In most cases the tracer gas concentration was decreasing during this time, after it had
369 built up prior to closing the door (e.g. Figure S3 B). There were four episodes when the door of the
370 *source room* was closed (e.g. Figure 4). The average concentration in the rest of the rooms was
371 lower during these periods compared to the concentration during the entire measurement period.
372 Since extensive airing often resulted in lower concentrations in the non-source rooms (Figures S3
373 and S4), it's important to note that all these closed-door episodes occurred in the autumn and
374 winter, when the windows were mostly closed and the ventilation rates were low.

375

376 The present results have limitations. Our calculations assume uniform concentrations within the
377 measured rooms. Furthermore, the measurements of interzonal airflows were performed over
378 relatively short periods of time. When rapid changes in the conditions occurred, the calculated
379 average concentrations may not represent the steady state conditions well. Information on the
380 position of the internal doors was only available for the bedrooms during night. Diaries about
381 occupant activities such as window opening are often inaccurate compared to data supported by
382 measurements. Studies conducted in a larger number of homes among the general population, using
383 a second active tracer gas (two-zone approach) and collecting more reliable information about
384 activities that affect AER and interzonal airflows, are warranted. It should also be noted that
385 somewhat different results may be obtained in a different climate and in buildings with different
386 characteristics than those included in this study (e.g. with balanced mechanical ventilation).

387

388

4. Conclusion

Air exchange rates were measured to be highest in summer, lowest in winter. They were highest during occupied daytime periods. Airflows from outdoors into the rooms as well as airflows between rooms within a dwelling can be dynamic, leading to frequently changing air exchange rates during the day and even differences in AERs between rooms. Occupant behavior, especially window and door opening, is a major driver of these changes and to a certain degree of the differences in outdoor AER between seasons as well as between dwellings. However, the limitations of the different measurement techniques should be born in mind, when reporting outdoor AERs and comparing them between studies. Large differences between AERs measured by three different techniques were observed. Bedroom AERs determined from occupant-generated CO₂ (total AER) were more than twice as high as the corresponding AERs from the active tracer gas measurements using the constant concentration method (outdoor AER).

Measurements of pollutant distribution throughout the dwelling from a single source revealed that the air within a given floor was well mixed, while there was limited air movement between different floors. The average tracer gas concentration in the non-source rooms was about 70% of the source room concentration on the same floor, but below 30% on a floor different from that of the source room. The average tracer gas concentration in the non-source rooms, relative to the source room, was lower in the summer, when extensive airing took place and AERs were high. At the same time, the airflow rates between adjacent rooms were highest in the summer. The position of the internal doors had a strong influence on the air movements within the dwelling. These are some of the most comprehensive measurements of AER and airflows in residencies under real life conditions. The results may help in the evaluation of the spatial and temporal factors affecting occupant exposure to indoor pollutants in residential environments.

Acknowledgments

This work was part of the Centre for Indoor Air and Health in Dwellings (CISBO) study, supported by the Realdania foundation. We thank the participating families for their cooperation.

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543 **Figure captions**

544 **Figure 1.** Diurnal variation in outdoor AER in the five homes during four seasons: a. summer, b.
545 autumn, c. winter, d. spring. Note the different range of the vertical axes. Each 4-hour interval is an
546 average of the corresponding time intervals over several days. The overall AER in each dwelling
547 was calculated from the total outdoor airflow into the measured rooms (sum of average flows for
548 each room during the given 4-hour period) and the total volume of these rooms.

549
550 **Figure 2.** Relationship between bedroom air exchange rates during night determined by active
551 tracer gas measurement and from occupant generated CO₂. Each data point represents the average
552 AER over several nights in a given bedroom within a season ($p < 0.001$; $n = 39$; 10 bedrooms over 4
553 seasons, one bedroom was excluded in the autumn due to no occupants).

554
555 **Figure 3.** Results of the interzonal flow measurements in home B during winter. The house has two
556 floors. The door between the lower floor and the staircase leading upstairs was closed overnight and
557 presumably during the unoccupied daytime. Bedroom doors were open during the night. The source
558 room was the kitchen, which was on the same floor as the living room.

559
560 **Figure 4.** Results of the interzonal flow measurements in home A in winter. Note that the door of
561 the source room (child room) was closed overnight.

562

563 **Figures – Color figures for online only. B&W Figures for print provided below.**

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Figure 1

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Figure 2

Figure 3

Figure 4

577 **Tables**

578 **Table 1.** Characteristics of the five homes.

Home	Type / No. of floors	Construction year	Occupants Adults + children	Floor area (m ²) ^a	Volume (m ³)	% of volume measured	Basement	Ventilation
A	Detached / 1	1964	2 + 1	117	314	79.1	No	Natural ^c
B	Detached / 2 ^b	1921	2 + 2	122 ^b	294 ^b	96.5	Yes	Natural ^c
C	Row house / 1	2007	2 + 0	87	242	87.5	No	Natural
D	Detached / 2	1947	2 + 0	170	398	58.5	Yes	Natural
E	Apartment / 1	2004	1 + 0	66	172	93.0	No	Bath. exhaust

579 ^a Based on the measured area of each room in the dwelling

580 ^b Values without basement. With basement 177m² and 398m³. No measurements were made in the basement and the
581 door to the stairs leading to the basement were always closed during the measurements.

582 ^c Exhaust fan with manual control present in the bathroom

583

584

585 **Table 2.** Air exchange rates in the five homes during four seasons measured by active tracer gas.
586 Each home AER is the volume-weighted average of the AERs of the measured rooms (except last
587 row ^a).

Home	Average AER ± SD (h ⁻¹)					Grand Average (h ⁻¹)
	A	B	C	D	E	
Summer	1.38±0.8	1.60±0.8	2.36±0.7	1.91±1.1	5.40±1.4	2.53
Autumn	0.14±0.5	0.98±0.9	0.16±0.2	0.05±0.04	1.11±0.4	0.49
Winter	0.24±0.4	0.29±0.2	0.04±0.01	0.10±0.2	0.62±0.7	0.26
Spring	0.68±0.3	1.93±0.8	0.32±0.2	0.20±0.1	1.22±0.6	0.87
All seasons ^a	0.52	1.17	0.63	0.36	1.97	-

588 ^a based on overall AERs in each house within each season, calculated from the total airflow into the measured rooms
589 (sum of average flows for each room) and the total volume of these rooms.

590 p<0.001 for differences between AERs for all measured rooms (n=24) by season; Kruskal-Wallis test

591

592

Table 3. Air exchange and ventilation rates in *all measured rooms* during periods when the homes were actively occupied (excluding nights), during night periods (00:00-06:00) and unoccupied periods.

	N	Average AER $\pm$ SD (h ⁻¹)	Median AER (h ⁻¹)	Average vent. rate (L/s/m ²)	Average window pos. ^a
<i>All seasons</i>					
Occupied - day	96	1.20 $\pm$ 1.44	0.59	0.84	0.37
Night	96	0.48 $\pm$ 0.72	0.17	0.33	0.24
Unoccupied	66	0.93 $\pm$ 2.48	0.27	0.66	0.07
<i>Summer</i>					
Occupied - day	24	2.82 $\pm$ 1.68	2.70	2.01	0.91
Night	24	0.93 $\pm$ 1.07	0.47	0.65	0.67
Unoccupied	19	2.42 $\pm$ 4.31	0.87	1.73	0.18
<i>Autumn</i>					
Occupied - day	24	0.53 $\pm$ 0.82	0.20	0.36	0.16
Night	24	0.37 $\pm$ 0.49	0.10	0.26	0.12
Unoccupied	9	0.48 $\pm$ 0.32	0.36	0.33	0.00
<i>Winter</i>					
Occupied - day	24	0.39 $\pm$ 0.44	0.24	0.26	0.10
Night	24	0.24 $\pm$ 0.36	0.13	0.16	0.02
Unoccupied	14	0.32 $\pm$ 0.42	0.17	0.21	0.00
<i>Spring</i>					
Occupied - day	24	1.07 $\pm$ 0.98	0.67	0.74	0.33
Night	24	0.40 $\pm$ 0.56	0.14	0.26	0.20
Unoccupied	24	0.28 $\pm$ 0.27	0.18	0.20	0.05

^a Values assigned to the position of the windows for each time step of AER measurement: 0=closed, 1=ajar, 2=open. The average window position is a time-weighted continuous variable.
 $p < 0.001$ for difference in AER between occupied and night periods ($n=96$) and between occupied and unoccupied periods ($n=66$). No significant difference was observed between night and unoccupied periods ($n=66$); Window opening was significantly different between all three periods (Wilcoxon matched-pairs signed-rank test; all seasons combined)

Table 4. Bedroom air exchange rates measured by active tracer gas (constant concentration in the entire home) and by occupant generated CO₂ during identical night periods. Whole-house monthly AERs from passive tracer gas during the months corresponding to the other measurements are shown for comparison.

	AER-Tracer gas (h ⁻¹)				AER-CO ₂ (h ⁻¹)			AER-CO ₂ /AER- Tracer gas ratio		PFT (n=5 per season, 17 for All s.) ^c (h ⁻¹)
	N	Average	SD	Median	Average	SD	Median	Average	Median	Average
Summer ^a	10	1.22	0.92	1.12	2.88	2.35	2.25	4.7	2.11	1.02
Autumn ^a	9	0.44	0.64	0.14	1.07	1.14	0.62	4.9	4.41	0.64
Winter ^a	10	0.22	0.29	0.10	0.48	0.41	0.50	10.5	3.16	0.68
Spring ^a	10	0.65	0.75	0.24	1.12	1.22	0.80	5.26	2.14	0.36
All seasons ^a	39	0.64	0.76	0.25	1.40	1.68	0.65	6.38	2.42	0.73
All seasons ^b	98	0.67	0.94	0.20	1.45	2.01	0.64	11.02	2.93	-

^a based on average AERs in each bedroom across all measured nights ($n=39$ bedroom measurements in total; 10 bedrooms over 4 seasons, one bedroom was excluded in the autumn due to no occupants)
^b based on raw AERs obtained for each night in each bedroom ($n=98$ measured nights)
^c Missing 3 values for spring
 $p < 0.001$ for differences between AER measured by tracer gas and CO₂; Wilcoxon matched-pairs signed-rank test; all seasons ($n=39$)

613 **Table 5.** Air exchange rates in the five homes during winter measured by active tracer gas and
614 passive tracer gas applied during the same days. Monthly AER from PFT are indicated for
615 comparison.

Home	AER (h ⁻¹)					Average (h ⁻¹)
	A	B	C	D	E	
Tracer gas (by rooms) ^a	0.24	0.29	0.04	0.10	0.62	0.26
Tracer gas (by home) ^b	0.19	0.28	0.03	0.13	0.62	0.25
PFT (5 days) ^c	0.20	1.41	0.25	0.30	0.99	0.63
PFT (entire month) ^c	0.32	1.39	0.29	0.34	1.07	0.68

616 ^a Volume-weighted average AERs from all measured rooms
617 ^b Overall AERs in the house, calculated from the total airflow into the measured rooms (sum of average flows for each
618 room) and the total volume of these rooms
619 ^c Based on the total volume of the entire dwellings

620

621 **Table 6.** Average tracer gas concentrations and fractions of source room concentrations in all
622 measured non-source rooms in the five homes. Results stratified by house floor, occupancy and
623 distance from source room (single-floor houses only) are also presented.

	Source room conc. (ppm)			Non-source room conc. (ppm)			% of source room conc.	
	N	Average (SD)	Median	N	Average (SD)	Median	Average (SD)	Median
All seasons	20	4.0 (0.6)	4.1	92	2.3 (1.1)	2.5	58 (26)	62
Summer	5	3.5 (0.9)	4.0	24	1.5 (0.9)	1.2	46 (23)	48
Autumn	5	4.1 (0.1)	4.1	23	2.6 (1.0)	3.1	64 (25)	78
Winter	5	4.3 (0.2)	4.4	23	2.8 (1.0)	2.7	65 (22)	66
Spring	5	4.1 (0.1)	4.1	22	2.4 (1.2)	2.8	59 (29)	68
Source floors: 1- floor homes ^a	-	-	-	52	2.6 (1.0)	2.9	67 (20)	68
Source floors: 2- floor homes ^a	-	-	-	16	3.0 (0.6)	3.0	72 (16)	74
Non-source floors	-	-	-	24	1.2 (0.8)	1.1	31 (21)	27
Zone 2 ^{a,b}	-	-	-	15	3.1 (0.9)	3.3	77 (11)	82
Zone 3 ^{a,b}	-	-	-	24	2.9 (0.8)	3.2	73 (14)	77
Occupied	16 ^c	4.1 (0.3)	4.1	72	2.5 (1.1)	2.7	61 (24)	65
Unoccupied	16 ^c	4.2 (0.5)	4.2	72	2.5 (1.3)	3.0	61 (29)	69

624 ^a Does not include source room (considered as zone 1); ^b Data from two single-floor houses; ^c During four
625 measurements the occupants didn't provide occupancy data
626 p<0.05 for differences between fractions by season; Kruskal-Wallis test
627 p<0.001 for differences in both concentrations and fractions between source floor (all homes combined, n=68) and non-
628 source floor; Two-sample Wilcoxon rank-sum test and two-sample t-test
629 No significant difference between occupied and unoccupied periods, or between zone 2 and zone 3.

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631 B&W versions of the color figures for print

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635 **Figure 1 - B&W for print**

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638 **Figure 3 – B&W for print**

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641 **Figure 4 – B&W for print**

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