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Continuous measurements of air change rates in an occupied house for 1 year: The effect of temperature, wind, fans, and windows†

L.A. WALLACE,[a] S.J. EMMERICH[b] AND C. HOWARD-REED[b]

[a]*US EPA, 12201 Sunrise Valley Drive, 555 National Center, Reston, Virginia 20192, USA*
[b]*National Institute of Standards and Technology, Gaithersburg, Maryland, USA*

A year-long investigation of air change rates in an occupied house was undertaken to establish the effects of temperature, wind velocity, use of exhaust fans, and window-opening behavior. Air change rates were calculated by periodically injecting a tracer gas (SF_6) into the return air duct and measuring the concentration in 10 indoor locations sequentially every minute by a gas chromatograph equipped with an electron capture detector. Temperatures were also measured outdoors and in the 10 indoor locations. Relative humidity (RH) was measured outdoors and in five indoor locations every 5 min. Wind speed and direction in the horizontal plane were measured using a portable meteorological station mounted on the rooftop. Use of the thermostat-controlled attic fan was recorded automatically. Indoor temperatures increased from 21°C in winter to 27°C in summer. Indoor RH increased from 20% to 70% in the same time period. Windows were open only a few percent of the time in winter but more than half the time in summer. About 4600 hour-long average air change rates were calculated from the measured tracer gas decay rates. The mean (SD) rate was 0.65 (0.56) h^{-1}. Tracer gas decay rates in different rooms were very similar, ranging only from 0.62 to 0.67 h^{-1}, suggesting that conditions were well mixed throughout the year. The strongest influence on air change rates was opening windows, which could increase the rate to as much as 2 h^{-1} for extended periods, and up to 3 h^{-1} for short periods of a few hours. The use of the attic fan also increased air change rates by amounts up to 1 h^{-1}. Use of the furnace fan had no effect on air change rates. Although a clear effect of indoor–outdoor temperature difference could be discerned, its magnitude was relatively small, with a very large temperature difference of 30°C (54°F) accounting for an increase in the air change rate of about 0.6 h^{-1}. Wind speed and direction were found to have very little influence on air change rates at this house.
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Introduction

Air change rates affect energy usage and pollution characteristics in homes and buildings. Following the energy crisis of the early 1970s, homes and buildings were built more tightly to save energy, resulting in lower air change rates. Lower rates can increase indoor concentrations of pollutants produced indoors, but may decrease indoor concentrations of reactive outdoor pollutants such as ozone. In order to estimate personal exposure to various pollutants, it is desirable to understand how air change rates depend on parameters such as weather conditions and homeowner behavior.

Air change rates have been measured in several thousand homes in the US (Murray and Burmaster, 1995), 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 homeowner behavior such as window-opening habits and use of exhaust fans. Some attempts to determine temperature and wind effects have been made in unoccupied test houses (Emmerich and Nabinger, 2000), but these efforts omit homeowner behavior effects, which may be more important than the effects of temperature and wind. An early study of 28 homes in England (Dick, 1950) developed some relationships with wind speed and temperature, and also included some qualitative effects of window-opening behavior based on questionnaires of residents. One recent study has provided quantitative information on the effect in two homes of opening windows to measured widths (Howard-Reed et al., 2002), but may have lacked sufficient measurements to derive a robust relationship with temperature and wind.

1. Address all correspondence to: Dr. L.A. Wallace, US EPA, 12201 Sunrise Valley Drive, 555 National Center, Reston, VA 20192, USA. Tel.: +1-703-648-4287. Fax: +1-703-648-4290. E-mail: wallace.lance@epamail.epa.gov
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A single study capable of including all these effects was designed, and a year-long investigation was undertaken beginning January 1, 2000. A three-story townhouse in Virginia owned by one of the authors (L.A.W.) with two nonsmoking residents was selected for the study.

The main goal of the study was to document the effects on air change rates of temperature, wind, use of fans, and window-opening behavior over all four seasons of the year. A second goal was to provide a database of distributions of air change rates, indoor–outdoor temperatures and temperature differences, indoor–outdoor relative humidities (RH), use of fans, and window-opening behavior for use in indoor air quality models. The database will be publicly available.

Methods

The experimental house is a three-story, four-bedroom, four-bathroom end-unit townhouse with a floor area of approximately 50 m^2 per level and an approximate overall volume of 400 m^3. The townhouse is built on a slope such that there is a partial basement consisting of a utility room, pantry, bathroom, and den with walkout patio. The middle level consists of a kitchen, dining room, living room, and bathroom. The top level contains four bedrooms and two bathrooms. Possible leakage sites include sliding glass doors in the basement and living room, a furnace with no damper, attic fan, fireplace (flue always closed), exhaust fans, and a ducted clothes dryer. The home's HVAC system uses 100% recirculated air and its ductwork does not enter the attic, resulting in minimal exchange with outdoor air. Two blower door tests (ASTM, 1999) were performed to assess the extent of air leakage of the house. The closed house air change rates at 50 Pa were 13.4 and 15.1 h^{-1} in the two tests with estimated leakage areas of 1071 and 1170 cm^2 at 4 Pa. The first test also showed negligible influence of the townhouse that shares a wall with the Virginia house. Another test was performed to identify leakage in the ductwork. Although leakage was substantial (750 cm^2), it was considered not to affect air change rates because all ductworks were contained in the house.

The house is backed on the east and south by a 27-acre hilly wooded area with trees that were last logged in the 1930s and are much taller than the house. To the west is an inclined parking lot rising about 5 m to a road about 50 m from the house. To the north are the five other townhouses connected to the experimental house. Thus, the prevailing westerly wind strikes the townhouse "broadside," or perpendicular to the two walls with windows and doors.

An automated tracer gas injection and detection system, containing a gas chromatograph with electron capture detection (GC-ECD) was used to inject SF_6 at selected times into the central return duct and to measure concentrations at 10 locations sequentially (one location per minute). Injections were either 2 or 4 h apart. The 10 sampling locations included the central return duct itself, two locations in the basement, three on the first floor, and three on the top floor, with an additional location in the attic (Figure 1). (An outdoor location was initially included to verify no measurable tracer gas outdoors but was soon abandoned.) The range of SF_6 concentrations was 5–150 parts per billion by volume (ppbv).

The GC received multipoint calibrations at 22 SF_6 concentrations ranging from 1 to 298 ppb periodically throughout the year, although not all concentrations were employed in every calibration.

Air change rates were calculated for a 70-min time period beginning 30 min after each injection. The 30-min waiting period was based on observations that the initial inequalities of SF_6 concentrations in the various rooms were reduced by interzonal air flow to reasonable levels (approximately ±15%) after 30 min. The logarithms of the concentrations were regressed against time as described in ASTM (1995).

Temperatures were measured at the same 10 locations, also at the rate of one location per minute. RH was measured with bulk polymer resistance sensors having a claimed accuracy of 3%. RH was measured at six locations, including outdoors, the attic, and four indoor locations every 10 min. (After the first 6 months of the study, the attic sensor and one indoor sensor were removed, leaving one on each of the three floors and one outdoors.)

A portable weather station (Model 102263, Climatronics, Bohemia, NY) including an ultrasonic anemometer was mounted on the roof, about 1 m above the rooftop. Wind velocity measurements were taken every 6 s. Wind speeds were averaged over 1- and 5-min intervals. Wind

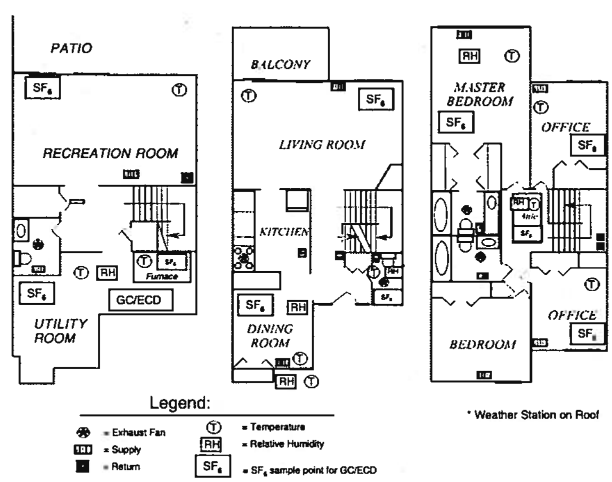

Figure 1. Floor plan of townhouse.

Table 1. Comparison of meteorology measurements at Reston house *versus* Dulles Airport.

Variable	N	Mean	SD	SE	Minimum	25th percentile	Median	75th percentile	Maximum
Reston wind speed (m/s)	8562	2.51	1.31	0.01	0.00	1.38	2.25	3.40	26.31
Dulles wind speed (m/s)[a]	8783	3.05	2.28	0.02	0.00	1.54	2.57	4.11	15.42
Reston wind direction	8488	228.28	87.59	0.95	0.20	177.15	257.37	283.74	359.82
Dulles wind direction	6477[b]	226.90	101.16	1.26	10.00	170.00	220.00	310.00	360.00
Reston temperature (°C)	8579	14.22	9.31	0.10	−11.45	6.95	15.58	21.59	39.89
Dulles temperature (°C)	8756	12.49	10.16	0.11	−15.00	3.89	13.28	20.61	33.89
Reston RH (%)	8634	68.15	22.71	0.24	3.67	51.31	71.22	87.83	99.83
Dulles RH (%)	8736	70.59	20.86	0.22	17.00	53.00	71.00	90.00	100.00

[a]Windspeeds below 3 knots (1.54 m/s) reported as zero.
[b]Wind direction not reported when wind speed was reported at zero.

direction was also averaged vectorially for 1- and 5-min periods.

Records of temperature, RH, and wind speed and direction were also obtained from Dulles Airport, 10 km northwest of the house, for comparison with the local measurements. Since the airport measures these parameters at 51 min past the hour, the corresponding times at the home were selected for comparison. The 6-s interval wind velocity measurements at the home were averaged over 1 min for these comparisons.

The attic fan was activated between April and October. Since it operates on a thermostat, it came on automatically when attic temperatures exceeded about 27°C. Sensors were installed to determine the pressure drop across the central furnace filter, the velocity of air through the supply duct, and the times when the attic fan was operating.

Two experiments involved opening multiple windows for an extended period of time (12–36 h) to establish an upper limit for the air change rate.

A daily journal was kept to record activities that might affect the air change rate. An attempt was made to keep track of when windows were open or closed, but no attempt was made to record the actual width of each opening. The normal practice was to open windows wide. An earlier study of the effect of window opening in this house had determined that opening windows wide (>30 cm) led to an increase in the air change rate on the order of 0.5 h^{-1} (Howard-Reed et al., 2002).

Results

Quality Control

Repeated calibrations of the GC resulted in error estimates on the order of 2%. Hunt (1980) provides a graph from which the estimated error in air change rates corresponding to a 2% measurement error can be made for any sampling interval from 0 to 150 min. For our interval of 70 min, the estimated error is 0.01 h^{-1}. Lagus (1980) provides another estimate of the error, which for our integrating time of 70 min results in an error estimate on the order of 2%. For a typical air change rate of 0.5 h^{-1}, the absolute error from the Lagus estimate is again 0.01 h^{-1}. Also, the Excel function used to calculate the air change rate provides an estimate of the standard error of the slope. These estimates were again on the order of 0.01 h^{-1}.

All the above estimates assume a constant air change rate over the integrating period. A more realistic approach to estimating the error associated with the regression is to use slightly different integrating intervals (60 or 80 min). This approach led to somewhat larger estimates of the error, on the order of 0.03 h^{-1}. Since this approach allows for variable air change rates, it is a more realistic estimate of the likely error. It is understood that much larger errors could occur in the case of imperfect mixing. However, since the furnace fan was operating so much of the time, mixing was probably better than normal.

The Climatronics weather station was tested before installation (using a portable fan) to be sure that zero wind speed produced the expected response and that wind direction was recorded correctly. Although the manufacturer stated that the device had a positive offset, a number of zero wind speed measurements were noted. These zeros were retained for the instantaneous measurements of wind speed, but removed for 1- and 5-min averages.

Comparison with Dulles Airport

Measurements of temperature, RH, and wind speed and direction at the Reston house are compared with those at Dulles Airport in Table 1. Outdoor temperatures at Dulles Airport showed high correlations (Spearman r=0.97) with temperatures measured at the house. A simple linear regression indicated that outdoor temperatures at the house were related to temperatures at the airport as follows:

$$\text{Reston temp} = 3.0 + 0.89 * \text{ airport temp. } (°\text{C}) \quad (r = 0.97,\ N = 8552)$$

Measurements of RH were also reasonably well correlated:

$$\text{Reston RH} = 6.7 + 0.87 * \text{ airport RH } (\%) \quad (r = 0.80,\ N = 8633)$$

Wind directions at Dulles Airport were compared with those at the house for several month-long periods. R^2 values ranged between 60% and 80%. For the entire year, the Spearman correlation coefficient for wind direction was 0.68 (N=6250, t=73.8, P<0.0000001).

Wind speeds were also compared for the same months. Correlations were significant but not high, with R^2 values on the order of 10–15%. For the entire year, the Spearman correlation coefficient was 0.30 (N=8000, t=28, P<0.0000001).

Summary Statistics

Approximately 5.1 million (97%) of the possible 5.3 million wind speed and direction measurements were successfully recorded. Since the measurements were averaged over 5-min time periods, only about 100,000 values are retained in the database (Table 2). About 46,400 (95%) of the possible approximately 49,000 temperature measurements were collected at each of nine indoor sites and one outdoor site. About 103,700 (98%) of the 105,408 possible RH measurements were collected at each of three indoor sites (one on each floor of the house) and one outdoor site, and an additional approximately 50,000 measurements at two other sites (a bathroom and the attic) that were operated only part of the year.

Monthly mean outdoor temperatures ranged from −1°C in January to 23°C in June, while indoor temperatures ranged from 21°C in January to 27°C in July (Figure 2).

Table 2. Summary statistics.

	N	Mean	SD	Minimum	Maximum
Wind speed (m/s)	102,705	2.47	1.15	0.0	40.9
Wind direction (° clockwise from north)	101,876	226.0	87.8	0.0	360.0
Temperatures (°C)					
Utility (basement west)	46,385	25.2	2.6	17.3	33.8
Recreation room (basement east)	46,385	24.7	3.1	15.9	31.5
Central return	46,385	23.7	2.6	16.0	30.4
Kitchen (first floor west)	46,385	22.8	3.0	12.1	36.5
Living room (first floor east)	46,385	23.0	2.8	13.1	30.3
Bathroom (first floor west)	46,383	23.2	2.8	14.9	29.5
Master bedroom (second floor east)	46,385	24.0	2.3	17.5	30.7
Front office (second floor west)	46,385	23.7	2.6	16.0	31.7
Rear office (second floor east)	46,385	24.4	2.8	16.8	32.3
Attic	46,385	18.5	7.9	1.4	45.1
Outdoor	46,385	14.1	9.3	−12.8	39.9
Average indoor (not including attic)	46,385	23.8	2.6	15.9	30.6
Indoor–outdoor temperature difference	46,385	10.0	7.0	0.0	33.9
RH (%)					
Utility (basement west)	103,677	41.2	12.6	13.0	84.4
Kitchen (first floor west)	103,676	45.2	15.5	10.2	86.8
Bathroom (first floor west)	50,277	41.1	11.5	15.5	72.4
Master bedroom (second floor east)	103,676	44.4	15.5	12.0	94.9
Attic	50,279	52.7	10.3	19.6	83.2
Outdoor	103,669	67.7	22.7	3.2	99.8
Average indoor (not including attic)	103,682	44.4	14.7	13.2	87.1
Air change rates (h^{-1})					
Utility (basement west)	4639	0.63	0.52	−0.07	3.95
Recreation room (basement east)	4668	0.66	0.57	−0.05	5.55
Central return	4670	0.65	0.59	−0.08	6.46
Kitchen (first floor west)	4628	0.67	0.62	−0.86	6.56
Living room (first floor east)	4654	0.66	0.59	−0.68	5.43
Bathroom (first floor west)	4671	0.65	0.59	−0.11	5.66
Master bedroom (second floor east)	4705	0.64	0.60	−0.34	4.94
Front office (second floor west)	4708	0.64	0.59	−0.06	4.70
Rear office (second floor east)	4687	0.62	0.59	−0.04	5.24
Attic	4716	0.34	0.54	−3.81	3.94
Average indoor (not including attic)	4656	0.65	0.56	0.04	4.10
SD	4656	0.09	0.15	0.00	2.14
RSD	4656	0.15	0.15	0.01	1.24

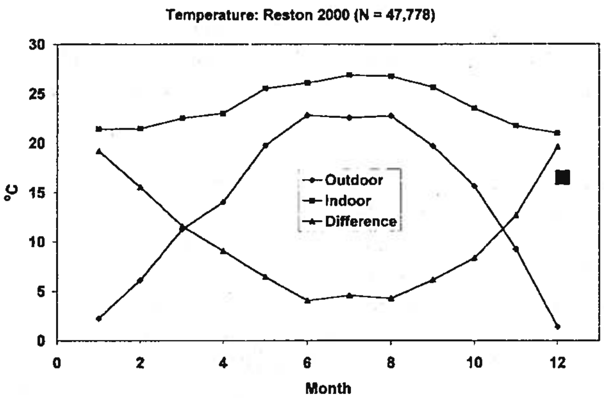

Figure 2. Monthly variation of indoor and outdoor temperatures and the absolute indoor–outdoor difference ($N = 47{,}778$).

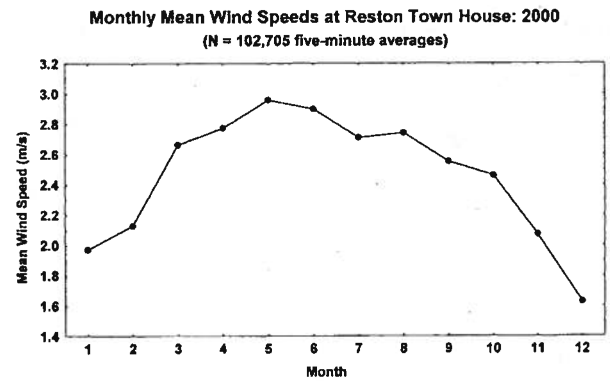

Figure 4. Monthly wind speeds measured at rooftop level ($N = 102{,}705$ five-minute averages).

The monthly mean absolute indoor–outdoor temperature difference varied smoothly from about 20–22°C in December and January to 4–5°C in June, July, and August.

Outdoor monthly average RH varied from 53% in March to 84% in August, and monthly average indoor RH from 25% in December to 63% in July (Figure 3). The outdoor–indoor difference was close to 20% for 9 months of the year, and close to 30% for the winter months of December, January, and February. Diurnal RH averaged over the year varied from 80% at 6 a.m. to 48% at 1 p.m.

Rooftop wind speeds were right-skewed, but showed considerable departures from log normality. Wind speeds averaged 2.5 m/s for the year, compared to 3.0 m/s at Dulles Airport. Monthly average speeds were highest at 2.6–3.0 m/s in spring and summer, but fell to 1.6–2.2 m/s in the winter (Figure 4). Hourly averages increased from a minimum of 2.0 m/s at midnight to a maximum of 3.1 m/s at 1 p.m. (Figure 5).

Air change rate percentiles are provided in Table 3. Air change rates were skewed to the right, so the logarithms are plotted in Figure 6. Monthly average air change rates varied from 0.44 h^{-1} in October and November to 1.30 h^{-1} in July (Figure 7). The mean overnight (midnight to noon) air change rate was 0.56 h^{-1} (0.42 SD, N=2439); mean daytime (noon to midnight) value was 0.73 h^{-1} (0.65 SD, N=2012). Yearly mean tracer gas decay rates were nearly identical in all rooms of the house, varying only from 0.63 to 0.68 h^{-1}. The mean relative SD of the hourly average air change rates across all rooms (not including the attic) was 15% (SE=0.2%). The air change rate fell below 0.35 h^{-1} on 1087 occasions out of 4451 measurements; thus, the home fell below the recommended value (ASHRAE Standard 62) about 24% of the time.

The attic fan was operating for nearly 20% of the summer months, and 11% of the time during the year. When the attic fan was on, air change rates increased by approximately 0.8 h^{-1}. The average air change rate when the attic fan was operating was 1.53 h^{-1} (SE=0.04 h^{-1}, N=440).

The central furnace fan was on for approximately 90% of the year. However, the central furnace fan had no apparent

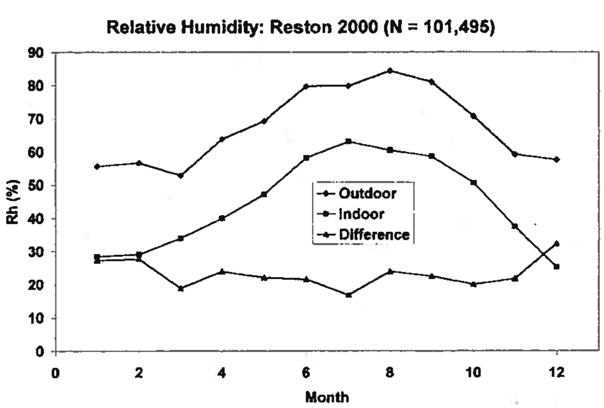

Figure 3. Monthly variation of indoor and outdoor RH and the absolute indoor–outdoor difference ($N = 101{,}495$).

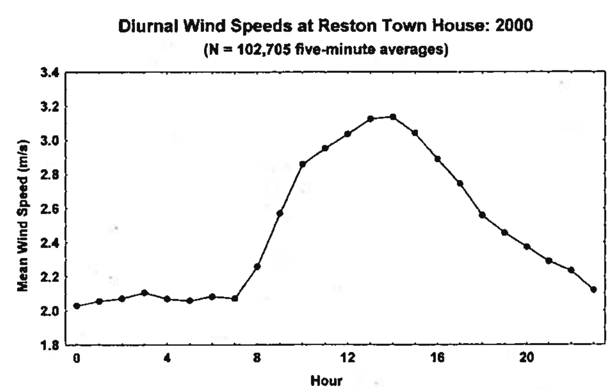

Figure 5. Diurnal wind speeds averaged over 1 year ($N = 102{,}705$ five-minute averages).

Table 3. Air change rate percentiles.

Percentile ($N = 4656$)	Air changes per hour (h^{-1})
Minimum (0.01)	0.039
0.1	0.063
0.5	0.083
1	0.11
2	0.14
5	0.19
10	0.25
25	0.35
50	0.49
75	0.65
90	1.29
95	1.94
98	2.61
99	3.04
99.5	3.32
99.9	3.69
Maximum (99.99)	4.10

effect on air change rates. The ductwork for the fan was found to have leaks; however, no part of the ductwork was external to the house, so the leaks had no effect on air change rates.

Two day-long experiments with keeping multiple windows open resulted in an estimated upper limit for the experimental house of about two air changes per hour over an extended period of time. Although higher rates of 3–4 h^{-1} were achieved for a brief time, the average over 12–36 h was never more than 2 h^{-1}. One likely reason for this is that no matter the initial indoor–outdoor temperature difference, that difference will quickly fall toward zero due to the large amount of outdoor air coming in. In one case, the indoor temperature fell from 23°C to 9°C in 1 h following the opening of several windows on a cold day. This means that windows are likely to be opened for extended periods of time only when outdoor temperatures are moderate, so the temperature difference ceases to be an important driving force under these conditions.

Differences by Floor Level

Tracer gas concentrations were examined by floor level to determine the extent of the stack effect, which would lead to a gradient with increased concentrations in the upper levels, at least during the colder months. In fact, concentrations on the second floor averaged 8% higher than those on the first floor, and the first floor concentrations averaged 4% higher than those in the basement during 10 of 12 months. During the two hottest summer months, however, the first floor had up to 15% *lower* concentrations than the basement, due presumably to the greatly increased frequency of open windows on that floor, whereas the basement window was rarely open.

Temperatures were consistently highest in the basement (mean of 24.9°C) and lowest (22.9°C) on the first floor, perhaps due to heat from the pumps driving the monitoring equipment. RH values were highest on the first floor (45%) and lowest in the basement (41%). Air change rates were not significantly different by floor level, but tended to be higher (0.66 h^{-1}) on the first floor, where doors and windows were open more often, and lower (0.62 h^{-1}) on the second floor (Figure 7).

Because of these tracer gas concentration differences and temperature differences by floor, the house is probably more nearly represented as a three-zone system than as a well-mixed single zone. Under such conditions, it is no longer precisely true that the absolute magnitude of the slope of the tracer gas concentration decline can be interpreted as an air change rate. Instead, the observed slope will have a positive bias with respect to the air change rate, the magnitude of the bias being dependent on the amount of

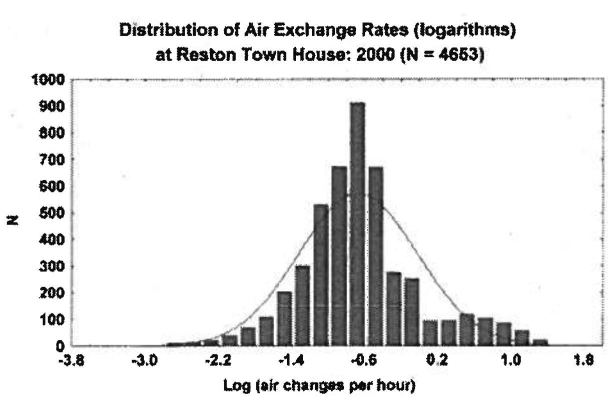

Figure 6. Distribution of logarithms of air change rates over the year ($N = 4653$ seventy-minute averages).

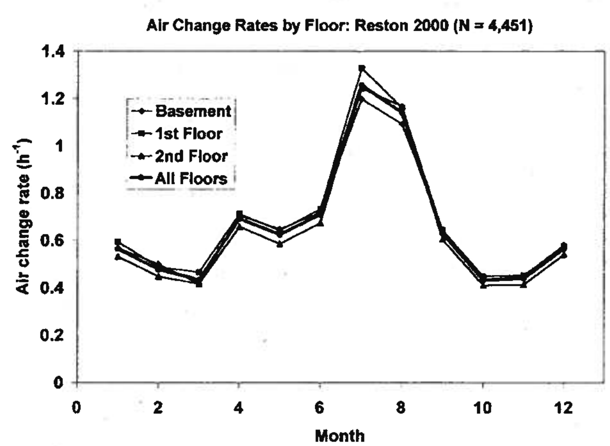

Figure 7. Monthly air change rates by floor ($N = 4451$ seventy-minute averages).

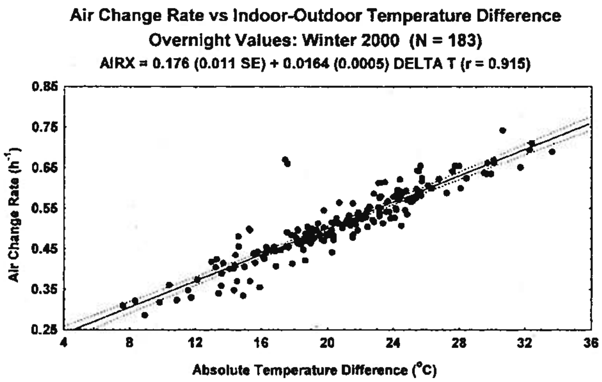

Figure 8. Regression of air change rate on absolute indoor–outdoor temperature difference. Overnight values (midnight–8 a.m.) in winter (January–March 2000). I (h^{-1}) = 0.176(0.011 SE) + 0.0164(0.0005) ΔT (°C) (N = 183, R^2 = 0.82).

interzonal flow (Etheridge and Sandberg, 1996). Because of the relatively small interfloor differences of less than 10%, we expect that the overestimate of the air change rate is also of this magnitude.

Correlations

Pearson correlation coefficients for temperatures were generally above 0.9 for all indoor locations except the kitchen, where values ranged from 0.82 to 0.88 (N=46,385). For RH, Pearson correlation coefficients ranged from 0.94 to 0.95 for three of four indoor locations, but were slightly lower (0.87–0.91) for the bathroom (N=59,850). For air change rates, Pearson correlation coefficients ranged from 0.86 to 0.97 (N=4429). Spearman rank-order correlation coefficients were in close agreement with the Pearson values for the air change rates.

Cross-correlations of RH and temperature with air change rates were consistently low, with Spearman correlation coefficients varying from −0.07 to 0.18.

Regressions

A question of great interest concerns the influence of meteorological factors on air change rates. Therefore, a multiple regression of air change rate on wind speed, wind direction, and indoor–outdoor temperature difference was performed. In order to limit the scope to times when the windows were likely to be closed, only the overnight hours from midnight to 8 a.m. during the six coldest months (October through March) were included in the regression. Also, air change rates greater than 0.8 h^{-1}, which are likely to have been due either to windows open or the attic fan being on, were excluded. For this overnight period, only the temperature difference had a substantial effect, increasing the air change rate by 0.0156 h^{-1}/°C (SE=0.0005 h^{-1}, N=778). For the observed range of indoor–outdoor temperature differences of 0–34°C, this corresponds to an effect of up to 0.5 h^{-1} on the air change rate. Wind speed had no effect and wind direction only a tiny effect, increasing the air change rate by 0.016 h^{-1} (SE=0.003 h^{-1}) when the wind included an easterly component. The adjusted R^2 for the multiple regression was 0.62 [N=778, $F(4,773)$=324, P<0.0000001]. A multiple regression for the daylight hours confirmed the strength of the temperature difference and the weakness of wind effects, although the R^2 value was reduced due to the increased frequency of window and door openings during the day.

Since the indoor–outdoor temperature difference dominated all other variables, a simple regression of air change rate *versus* indoor–outdoor temperature difference was carried out. The regression was limited to overnight hours (midnight to 9 a.m.) during the winter months to reduce the likelihood of windows being open. Also, air change rates >0.8 h^{-1} were censored, since such values were considered to be possible only if a window were open or an exhaust fan were operating. (There were four such values, ranging between 0.9 and 1.1 h^{-1}.) Only times when the duct fan was operating were included, since air change measurements are more uncertain when mixing is inefficient. Finally, the relative SD of the air change measurements in the 10 indoor locations was required to be <10%. The result (Figure 8) shows a strong (R^2=83%, N=183) effect of the indoor–outdoor temperature difference on the infiltration I:

$$I\ (h^{-1}) = 0.176(0.011\ SE) + 0.0162(0.0005)\Delta T\ (^{\circ}\mathrm{C}).$$

Discussion

The dependence of infiltration I on indoor–outdoor temperature difference ΔT and wind speed W remains poorly understood. Different investigators (Bahnfleth et al., 1957; Burch and Hunt, 1978) have found linear dependence on both variables, while some (Dick and Thomas, 1951) have found a dependence on the square root of the temperature difference, and others (Goldschmidt et al., 1980; Wang and Sepsy, 1980) have found a dependence on the square of the wind speed. Some have found that the function is additive, while others have found empirically (Dick, 1950; Dick and Thomas, 1951; Persily, 1986) or theoretically (Sinden, 1978) that it is subadditive. Many find no effect of wind direction, but others (Malik, 1978) find that direction is important. Two ASTM publications (Hunt et al., 1980; Trechsel and Lagus, 1986) provide convenient collections of papers on air leakage measurements.

An early paper by Warner (1940) describes early investigations of air infiltration. Warner quotes a result by Pettenkofer (1858) finding a strong effect of temperature difference on air change, but no mention of an effect of concurrent wind speed. On the other hand, Warner quotes Haldane (1899) who found a strong effect of wind but does not mention temperature difference. Warner's own experiments on a block of London flats showed a strong effect of opening windows.

Sinden (1978) provided a theoretical proof that air flow is subadditive with respect to temperature and wind. The proof depends on the generally accepted assumption that air flow through an opening is proportional to the pressure difference across the opening raised to some power:

$$Q = K(\Delta p)^n.$$

The exponent n is considered to lie between 0.5 and 1, depending on the shape and size of the opening and the type of flow, with only laminar flow having an exponent equal to 1. (A number of studies suggest that, empirically, the coefficient is around 0.65.) The pressure difference due to wind and temperature effects is simply the algebraic sum of the pressure differences due to each separately:

$$\Delta p = \Delta p_W + \Delta p_{\Delta T}$$

Since this sum is raised to a power less than one, then the flow due to both variables together must be less than the sum of the flows due to each one separately:

$$Q(W, \Delta T) \leq Q(W, 0) + Q(, \Delta T)$$

This proof is quite general and holds no matter what the exponents on the temperature and wind variables may be.

Sinden also presented thought experiments showing how, under some conditions, wind speed and temperature differences can act in opposition, such that an increase in either one can lead to a decrease in the infiltration rate.

Dick (1950) and Dick and Thomas (1951) studied air change rates in 28 occupied houses during the winters of 1948 and 1949 in England. Dick developed equations relating air change rates to the first power of wind velocity and also to the square root of the indoor–outdoor temperature difference.

Bahnfleth et al. (1957) measured infiltration rates in two test houses at the University of Illinois.

Coblentz and Achenbach (1963) measured infiltration in 10 electrically heated houses in the midwest.

Laschober and Healy (1964) measured air change rates in a test house during the winter of 1960–1961. They tested models including linear and quadratic terms for both wind and temperature difference. The best-fit model considering the degrees of freedom was linear in both terms.

Wang and Sepsy (1980) measured air change rates in four specially built test houses. They found the best relationship to be linear with temperature and quadratic with respect to wind speed.

Goldschmidt et al. (1980) measured wintertime air change rates in two mobile homes. One was caulked in a normal fashion and the other was sheathed to reduce air change. The authors found the best relationship to be linear with temperature difference and to include both a linear and quadratic term including wind speed.

Malik (1978) measured air change, wind, and temperature in two interior townhouses. Regression analyses indicated effects not only of wind speed and temperature but also of wind direction, with the direction normal (or within 20° of normal) to the long axis of the townhouses having, as expected, a stronger effect on air change than other directions. A linear effect of temperature and wind velocity or the perpendicular component of wind velocity was noted.

Nazaroff et al. (1985) studied a single house in Chicago, measuring indoor and outdoor temperature, pressure, and air change rates over 15 consecutive weeks. Weekly average rates were well correlated with both pressure and temperature differences (Spearman r=0.74–0.75, P<0.001), but not with wind speeds (r=0.25, P=0.36) (our calculations from their Table 2).

Lagus and King (1986) measured air change rates in a number of Naval duplexes and apartments. They noted in a single anecdotal observation that use of a kitchen fan and two bathroom fans in one unit increased air change rates by 0.75 h^{-1}. This value was higher than any air change rate measured for the next 9 months.

Persily (1986) carried out pressurization tests and air change measurements in 82 homes with passive solar energy collectors throughout the US. Six empirical models were developed using linear and quadratic combinations of wind speed and temperature. All six models performed about equally well, with R^2 values of about 0.7.

Palmiter et al. (1991) measured infiltration rates using perfluorotracers (PFTs) and blower door tests in five different studies including 472 all-electric homes in the Pacific northwest. Since the PFT tests took place in occupied homes over an average of 17 days, occupant behavior was an important source of variation in air change rates.

Effect of Temperature and Wind

In this home, indoor–outdoor temperature differences had a clear effect on air change rate. The temperature difference alone was sufficient to explain 60–70% of the variation in air change rates measured when all windows were closed. The magnitude of the effect was approximately 0.16–0.20 air changes per hour per 10°C increase in the indoor–outdoor temperature difference. By contrast, multiple regressions, including wind speed and direction, consistently showed no or little effect of these variables on air change rates. A simple regression on wind speed while keeping the indoor–outdoor temperature difference <2°C

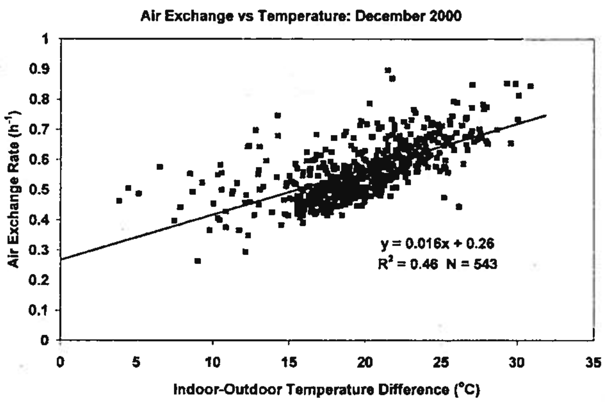

Figure 9. Regression of air change rate on absolute indoor–outdoor temperature difference. All values during December 2000. $I\ (h^{-1}) = 0.26(0.02\ SE) + 0.016(0.004)\Delta T\ (^{\circ}C)\ (N = 543,\ R^2 = 0.46)$.

(with attic fan off and windows closed) resulted in a very small coefficient of 0.03 h^{-1}/m/s with only marginal significance (P=0.06). The finding of little or no effect of wind was also recently reported (Howard-Reed et al., 2002) for both this Virginia house and also a house in California. It may be that the generally tighter construction of homes and the use of vapor barriers have reduced the effect of wind speed and direction on residential air change rates compared to earlier studies.

Because of the strong effect of the temperature difference and the weak effect of the wind, several graphs comparing air change rates to indoor–outdoor temperature differences by month were prepared (Figure 9). These generally showed an apparent lower boundary that was roughly linear with the temperature difference. Very few points strayed into the apparent "forbidden region" below and to the right of the boundary. This phenomenon suggests that a given temperature difference produces a certain minimum air change rate governed mainly by the building construction characteristics, and that observed higher air change rates at that temperature difference are due to open doors, windows, use of fans, or other activities that increase air change rates for a time.

A simplified two-opening model of natural ventilation suggests that the air change rate should be proportional to the square root of the temperature difference. Therefore, separate simple regressions were performed of air change rate on the temperature difference and on the square root of the temperature difference, using only overnight values during the winter months of December through March. The correlations were 0.785 and 0.784, respectively, providing no clear evidence of the superiority of either the linear or the square root model.

All regressions resulted in a positive intercept on the order of 0.12–0.18 h^{-1}, suggesting that some air change occurs when neither wind nor temperature differences exist. In the absence of such differences, natural fluctuations of temperature and pressure due to outdoor air turbulence would still exist, causing some minimal but nonzero air exchange to occur. A portion of the observed positive intercept could also be due simply to measurement error causing a regression toward the mean, but the absence of values very close to zero suggests that measurement error could not account for the entire amount. A positive intercept of similar magnitude (0.13–0.16 h^{-1}) for a multiple regression including wind speed and either pressure or temperature difference was also noted in the study of Nazaroff et al. (1985) (our calculations based on their Table 2).

Effect of Attic Fan

Several experiments established that turning the attic fan on while all windows were closed resulted in a consistent air change rate increase of about 0.8 h^{-1}. The attic fan was on about 20% of the time during the spring and summer. During the time it was operating, the air change rate averaged 1.55 h^{-1} (SE=0.04 h^{-1}, N=454), compared to 0.55 h^{-1} (SE=0.01 h^{-1}, N=4179) when the fan was off. Of course, windows were also open during these months, so the observed difference of 1.00 h^{-1} is not entirely due to the fan. The attic temperature averaged 27.8°C when the fan was on *versus* 17.3°C when it was off.

Effect of Opening the Windows

Based on the observation that temperature differences could not account for air change rates >0.8 h^{-1}, it is possible to estimate that windows were open or the attic fan was on or both during approximately 856 of 4656 measurements of air change rates, or about 20% of the time. A strong seasonal effect was noted (Figure 10), with windows open and/or attic fan on more than half the time during the summer months of July and August. The windows were closed more than 90% of the time during the fall and winter months of October through March.

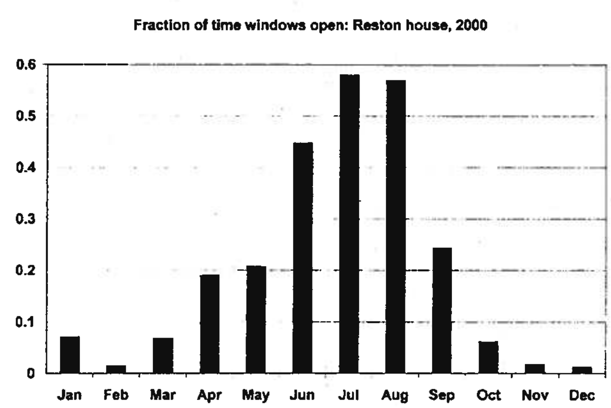

Figure 10. Estimated fraction of time windows wide open.

The mean air change rate in the home when windows were closed was 0.44 (SD=0.15) h^{-1}. With windows open or the attic fan on, the mean rate was 1.57 (SD=0.73) h^{-1}. Thus, the effect of opening one or more windows or having the attic fan on was to increase the average air change rate by about 1.1 air changes per hour. Since the mean indoor–outdoor temperature difference was 10°C, corresponding to an increase in the air change rate on the order of 0.4 h^{-1}, one may conclude that opening windows or using the attic fan produced, on average, about two to three times the effect on air change rates of typical indoor–outdoor temperature differences.

Limitations

A limitation of this study is that an adequate record of window-opening behavior was not kept, due to the difficulty in keeping track of two adults and various relatives and visitors staying in the home. However, based on an earlier study (Howard-Reed et al., 2002) that concluded that opening a single window as little as 10–15 cm produced an air change rate of >0.5 h^{-1}, and the finding from this study that meteorological conditions alone could not account for air change rates >0.8 h^{-1}, it is possible to attribute air change values >0.8 h^{-1} either to open windows or use of exhaust fans. Also, since a record of the attic fan use was kept, it is possible to differentiate between high air change rates caused by the attic fan and those caused by open windows. Using this rough approach to determining when windows were open, we find that air change rates exceeded 0.8 h^{-1} on 393 occasions (9% of the time) when the attic fan was not operating, and an additional 417 times (9% of the time) when the attic fan was operating. Since windows were likely to be open in this house when the attic fan was operating (use of the air conditioner was limited to a few very hot days), a reasonable estimate of the time that windows were open would be 15–20%. This estimate is likely to be lower-bound, since windows could have been open during times of minimal indoor–outdoor temperature difference such that the air exchange rate was <0.8 h^{-1}.

A second limitation is that the central fan was kept on nearly continuously due to the need to distribute the tracer gas after its injection into the return duct to the rest of the house. Compared to homes in which the central fan is turned on automatically only when the furnace or air conditioner is on, this would lead to greater similarities of temperature, RH, and air change rate among the different rooms and levels than would normally occur.

Database Description

The raw data from the various instruments were all transformed into Excel files. Since the instruments had differing collection intervals, ranging from 6 s to 10 min, these files were further transformed into monthly files with a 5-min interval format. A series of macros was developed to partially automate the process. The monthly Excel files were then transformed into monthly Statistica files, and collected together to form a yearly Statistica file. All of the statistical tests in this paper were performed using Quick Statistica (mathsoft.com). The database will be available from the corresponding author.

Conclusions

This study was an attempt to collect detailed year-long data on indoor–outdoor temperatures, RH, window-opening behavior, and the effects of these parameters on air change rates in an occupied house. About 95% of the possible data points was collected.

Opening windows had the largest effect on air change rates, causing increases ranging from a few tenths of an air change per hour to approximately two air changes per hour. (Higher rates of three to four air changes per hour could be attained but only for short periods of time.)

Indoor–outdoor temperature differences had a clear effect on air change rates, with extreme temperature differences of 30°C resulting in an increase of about 0.5–0.6 air changes per hour. No clear evidence favored either a linear or square root dependence.

For this home, the typical effect of opening windows or having the attic fan on was to increase air change rates by about 1 h^{-1}, whereas the typical temperature difference of 10°C produced an increase of 0.2 h^{-1}. By this measure, opening windows may be considered to be several times as effective in producing air change rate increases as temperature difference.

No attempt was made to determine the effect of temperature differences on air change when windows were open. Part of the problem in determining this relationship is that air change rates must be integrated over a certain period on the order of an hour, but an extreme temperature difference cannot be maintained for long with open windows.

Very little effect of either wind speed or wind direction was noted in this study. Wind speeds measured at the roof of the house were similar to wind speeds measured at the nearby airport, so the reason for the lack of effect cannot be attributed to an unusually sheltered condition. On the other hand, since the wind speed was not measured at the first or second floor level, it is not possible to say what the actual speed affecting the air change rate was. This question requires further study.

Room-to-room variations in temperature, RH, and air change rates were generally small. When large variations were noted, it was often easy to identify the reasons, including washing clothes and taking showers, opening windows, and cooking.

Seasonal variations in indoor temperatures, RH, and air change rates were well delineated. Indoor temperatures increased from about 21°C to about 27°C between winter and summer. RH increased from about 20% to about 70% in the same period. Windows were open only a few percent of the time in winter, but about half the time in summer. Air change rates increased greatly in the summer due to open windows, but also increased (compared to spring or fall) in the winter due to greater indoor–outdoor temperature differences.

Diurnal variations in indoor temperatures, RH, and air change rates were also recorded, with higher temperatures and air change rates in the daytime hours.

The data from the study, subject to the limitations of being a single house of a certain type of construction in a single climatic region of the country, may prove useful to modelers dealing with indoor air quality, and thus are available to all researchers.

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