The influence of opening windows and doors on the natural ventilation rate of a residential building

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ABSTRACT

Increased building energy efficiency is considered important to reduce national energy use and greenhouse gas emissions due to the high energy use of buildings and relatively low energy efficiency of existing building stock. While opening windows and doors in a residential environment may increase the building ventilation rate, it may also result in an unintentional increase in energy use due to the need for heating or cooling to maintain thermal comfort. An analysis of air exchange rates due to intentional door and window openings in a research test house located in a residential environment are presented. These data inform development of strategies designed to provide a desired level of ventilation as building envelopes are tightened to improve energy efficiency of residential structures. Common physical processes in the building are evaluated for their ability to alter building air exchange rates by delivering more effective natural ventilation to desired locations. Impact on indoor air quality based on contaminant concentration is not considered. Air exchange rates were determined for door and window opens using tracer gas decay measurements. Data analysis shows a dependence of air exchange rate on door opening frequency and duration, window opened area and indoor to outdoor temperature differences.

KEYWORDS

Natural ventilation, Air exchange rate, Open windows, Open doors

INTRODUCTION

Building infiltration of outdoor air has been reduced due to the increased tightness of buildings for energy conservation. Infiltration occurs due to leakage via cracks and crevices in the building envelope and when external doors or windows are opened. Indoor to outdoor temperature differences, opening size and duration, and outdoor wind effects and window geometry (Jong and Bot, 1992), have been shown to directly affect the air exchange rate (AER) of a building (Wallace et al. 2002; Howard-Reed et al. 2002; Jordan 1963).

Of these factors, window and door openings have been shown to significantly affect AERs and can be easily controlled by residents. For example, Johnson (2004) measured a test house AER with multiple openings (windows and doors) and found the geometric mean to change from 0.76 h^{-1} for no openings to 1.51 h^{-1} for one opening, 2.30 h^{-1} for two openings and 2.75 h^{-1} for three or more openings. During wind tunnel testing for a scaled building model, Meroney (1995) found an order of magnitude increase in AER when both the door and window were open compared to window only. In 1945, Hartmann et al. published data showing an increase by a factor of four in the AER when windows were opened only a few centimetres in small apartment buildings. Howard-Reed et al. (2002) presented significant data of window and door openings in two buildings, demonstrating a maximum increase of greater than one air change per hour for the largest opening area (OA) between the houses and two to three air changes per hour for multiple window openings under a variety of different window opening combinations. Vatistas et al (2007) found a significant effect of indoor to outdoor temperature difference on AER in a building where automatic doors cycled open and closed.

Numerous other works have focused on the longer door open time frame of a commercial building. One focus of this paper is the AER in a residential property where doors are opened for shorter time frames than found in a commercial environment, such as the loading or unloading of a vehicle or independently arriving building occupants. Presented here are residential AERs for an unoccupied research test house (RTH) in the cases of a repeatedly opened door and an opened window of varying OA.

METHODS

AERs were determined by tracer gas concentration decay data acquired in the RTH located in Cary, NC, shown in Figure 1. The RTH is a single floor residential property with a floor area of approximately 121 m^2 and a volume of 292.6 m^3.

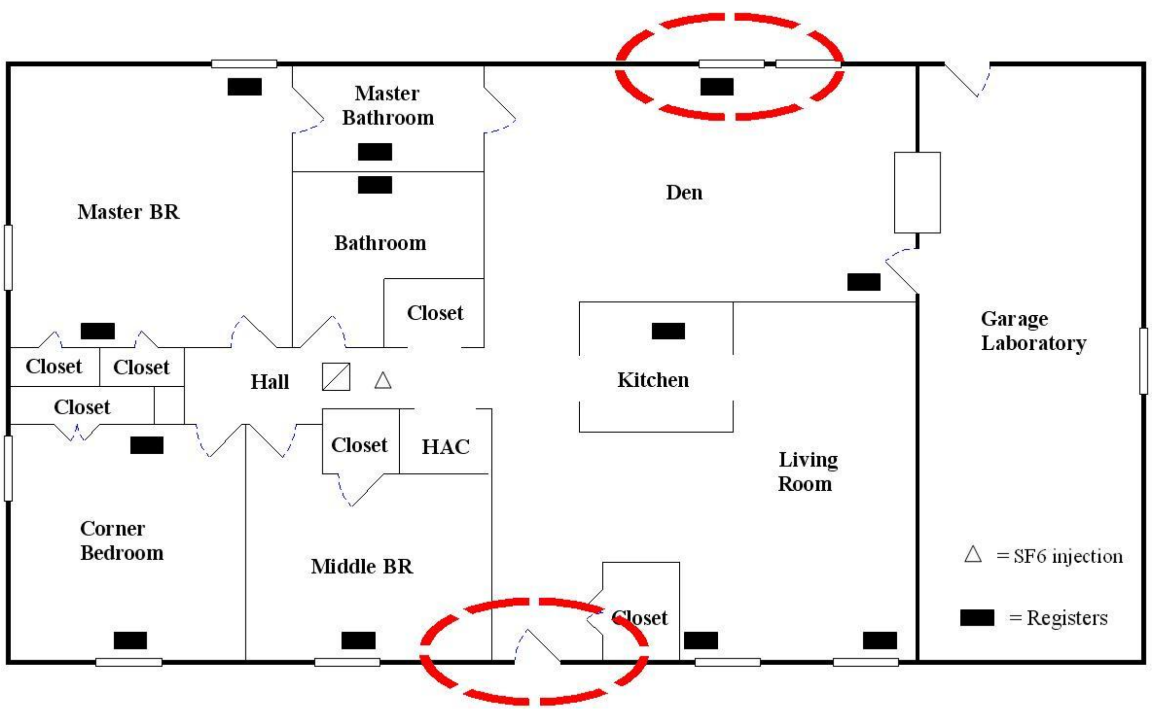

Figure 1: Layout of the single floor EPA research test house, located in Cary, NC, with circled locations of open door (bottom) and den window (top).

The tracer gas decay method with sulfur hexafluoride (SF_6) was used to measure the building AER, with injection via Teflon tubing from a tank in the attached garage. A

Bruel & Kjaer model 1302 (B&K 1302) Infrared Photo Acoustic Multigas Analyzer was used to sample the real-time air concentration of SF_6. This system has an accuracy of ± 25.0% and a precision of ± 5.0%. SF_6 was injected in the hallway near the return air grill and distributed throughout the house by the air handler, ceiling fans and auxiliary fans used for additional mixing. The heating and air conditioning (HAC) system was operated during the window AER measurements but was not used during the open door AER measurements. Window opening data was acquired during warm outdoor conditions while the door opening dataset was acquired under milder outdoor conditions that did not necessitate the use of HAC. The following sections outline the specific methods for the window and door associated AER research.

Windows

The open window scenario involved the opening of a window in the RTH den, indicated at the top of Figure 1, during June/July of 2000. For these experiments, an effort was made to seal all known or suspected leak areas in the RTH. Injection of the tracer gas occurred every six hours, for a total of 65 injection cycles. Five different window openings were used (width 89 cm, height 2.54, 5.08, 10.16, 20.32 and 40.64 cm, corresponding to 226, 452, 903, 1806 and 3613 cm^2 OAs respectively) and the closed window condition. Outdoor temperatures were measured using a local outdoor temperature sensor and indoor temperatures were maintained as necessary by the HAC system using the 'auto' setting to maintain average indoor temperature at 22 deg C (72 deg F). The RTH does not have mechanical ventilation capability. While outdoor wind velocities were recorded during this measurement period, many of the measured magnitudes were on the order of the measurement system uncertainty. For this reason, wind speed data are included as a means of correlation comparison only.

Doors

AERs were acquired for a series of door opening frequencies in late April and early May of 2005. The door in question is the main entrance of the RTH, as shown at the bottom of Figure 1. For each test, the door was opened for an average of 6.2 seconds, at a steady rate of 3, 4, 6, 12, and 60 openings per hour respectively. The time in which the door remained open was recorded by a data logger using a switch that measured when the door was fully closed. The RTH was injected with SF_6, followed by 20 to 30 minutes of HAC fan to mix the gas throughout the structure, after which point the HAC system was turned off for the remainder of the test. The tracer gas mixing was followed by two hours of door openings, two hours of closed door conditions, two more hours of door opening and another two hours of closed door conditions as shown in Figure 2. In this way, an injection of tracer gas provided four measures of AER due to an opening and closing door (based on an hourly AER analysis) and another four measures of building AER based on closed door conditions. The measurements presented are based on tracer gas decay measurements in the living room, the room closest to the open door. Indoor to outdoor temperature differential was relatively modest due to the time of year. For this reason, the HAC system was not used during these tests.

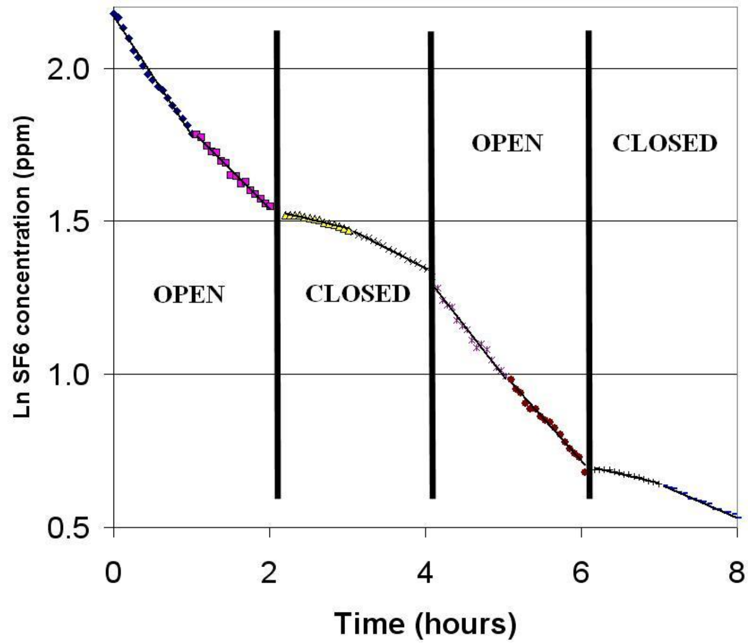

Figure 2: Example SF6 concentration data for a door open test, here opened once per minute, following tracer gas injection and mixing period.

RESULTS AND DISCUSSION

Windows

Change in AER due to an open window was also dependant on multiple other parameters. Figure 3 presents the correlation coefficient (r) between the AER and the measured parameters, including outdoor temperature (due to differences in air density), window OA, time and outdoor wind speed, determined using Equation 1.

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i - \overline{x}}{s_x}\right)\left(\frac{y_i - \overline{y}}{s_y}\right) \quad (1)$$

Where n is the number of data points, x and y are the data sets for comparison, s is standard deviation and over bar represents the mean. The AERs presented were calculated from tracer gas decay measurements in the master bedroom. The AERs for this room are, by one standard deviation, 5 percent different from those in the other rooms so it is reasonable to consider these results an indicator for the whole building AER. As shown by Howard-Reed et al. (2002), the outdoor to indoor temperature difference had the greatest effect on the AER although the other parameters were correlated to a lower degree. Cross correlations not included in this analysis, such as hour of day with outdoor temperature, also play a role in the parameter correlation determination here. The direct effect of outdoor temperature is seen in the right image of Figure 3, where AERs are presented for a series of outdoor temperature bins. As expected, the bin corresponding to the greatest deviation from indoor temperature settings (22 °C) resulted in the greatest AER value.

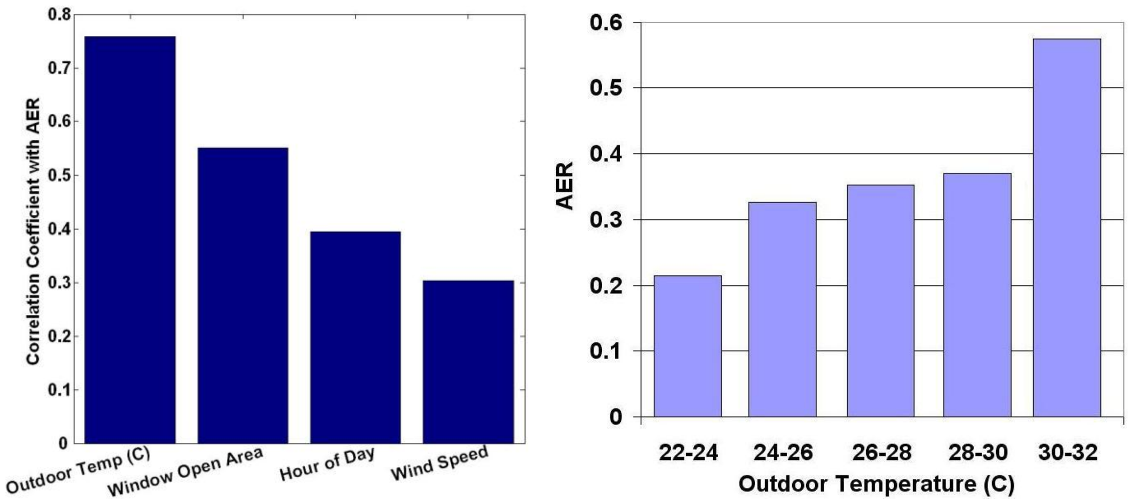

Figure 3: Correlation of measured parameters with AER for all outdoor temperatures and window OAs (left), for all outdoor temperatures over the HAC setpoint, including all window openings. On the right, AER (h^{-1}) values for specific outdoor temperature ranges including all window OA.

While window OA did affect the AER within the RTH, it was not as significant as outdoor to indoor temperature difference. Figures 3 and 4 (left) AERs were conducted using a one-hour tracer gas decay time frame. Figure 4 (right) presents the AER data set for the indoor to outdoor temperature differential by window OA in the master bedroom. Figure 4 (right) incorporates a 2.5 hour time frame, beginning one hour after peak concentrations, repeating every six hours following injection of SF_6 throughout the duration of the experiments. This allowed for a presentation of all AERs while reducing the variability associated with an hourly AER analysis. In both images of Figure 4, AERs can be seen increasing as outdoor temperatures rise above the indoor temperature setting. While an increase in AER is seen between the smallest and largest window OAs, the pattern is not consistent with each step increase in window size. This is likely due to local weather effects and the somewhat limited data set.

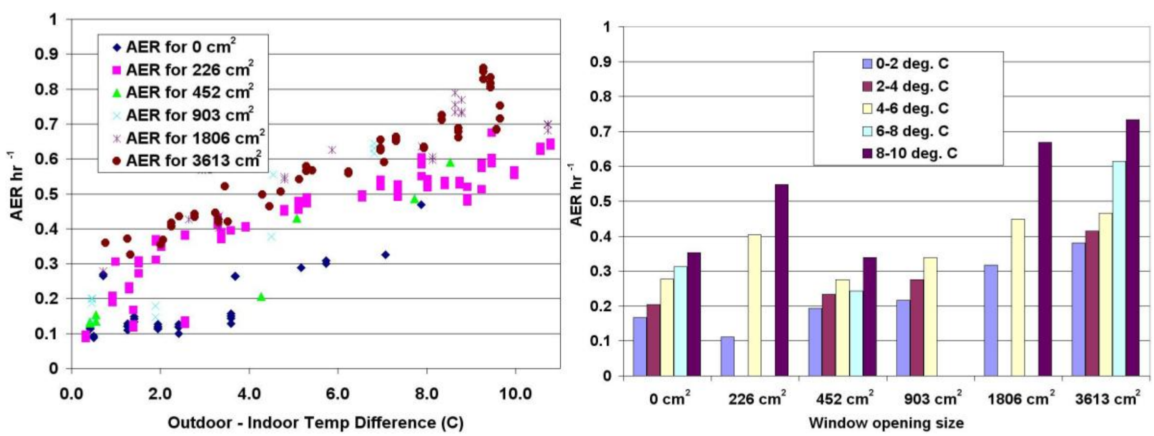

Figure 4: (Left) AER in each RTH room plotted against indoor to outdoor temperature difference for multiple window OAs. (Right) Average AER for the master bedroom plotted against window OA for multiple indoor to outdoor temperature differences.

Figure 4 (right) results are similar to those of Johnson (2004), where a near doubling of the building AER was found for a single building opening. While the actual AER values were lower, a similar percentage increase was found as the building OA value increased. Results are also of the same order as in Howard-Reed et al. (2002), who, for example, found an AER increase from 0.30 to 0.56 between a 0 cm^2 and 3822 cm^2 window OA case for a California house. For context, Offermann (2009) showed that 108 homes in California had a median window opening of 46 ft^2-hrs, equivalent to 1765 cm^2 of OA for an entire day, with a wide range and seasonal variation.

Doors

AER increased with increased door opening frequency, as shown in Figure 5. The building AER rate increase is minimal for 3, 4 and 6 door openings per hour, eventually increasing to 350% of the closed door scenario when the front door is opened every minute.

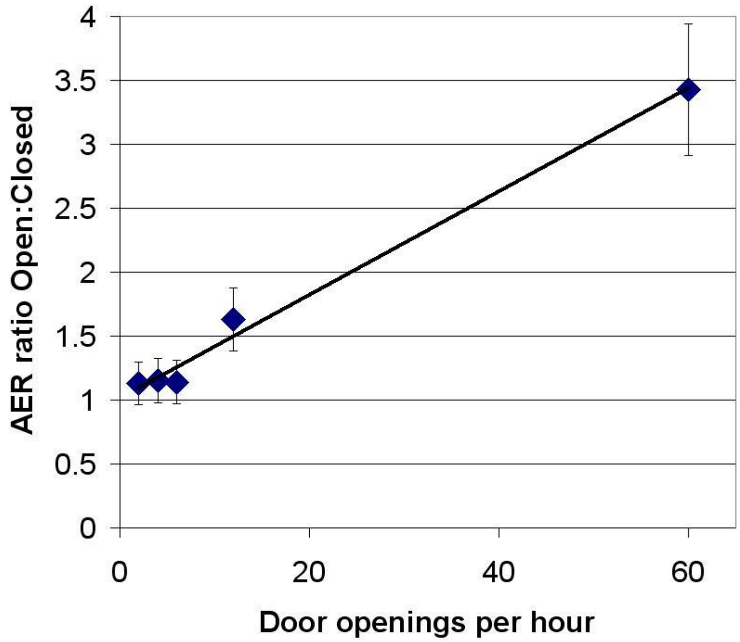

Figure 5: Increase in living room AER due to continued door openings with a given frequency, with fifteen percent uncertainty bars.

CONCLUSIONS

AERs were found to be affected by multiple parameters including open windows and doors. Several window OAs were considered, and a dependence on indoor to outdoor temperature difference was shown to have the maximum correlation with AERs of the considered parameters. Window OA, hour of day and wind speed also affected AERs to a lesser degree. The increase in AER with increased indoor to outdoor temperature difference supports the existing findings that open windows used as a means of residential ventilation can increase energy costs due to HAC use when indoor to outdoor temperature differences increase (Hartmann et al. 1945). As shown by Offermann (2009), windows are less likely to be open during increased indoor to outdoor temperature differential. This means that, during these periods, residents are choosing between reduced indoor air quality, comparatively expensive ventilation techniques (such as energy recovery ventilation), green product purchasing (to reduce indoor contaminant sources), or a combination of these techniques.

For the door opening scenario, a visible effect of door opening on the AER was not seen until the door open frequency was increased to 12 openings per hour. This door opening frequency is not often the case for the residential environment, but may be more prominent in population dense buildings such as high rise complexes. The results shown here, however, would likely differ for population dense properties as there is an increased likelihood of mechanical ventilation, stack effect or revolving doors, which are often used to attain better control of building AERs.

Where the outdoor air is known to be of higher quality than indoor air, these results show the potential of opening doors and windows to improving indoor air quality through natural ventilation. During periods of higher indoor to outdoor temperature differential, other techniques may be preferred towards improving indoor air quality while minimizing residential building energy use.

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