Air Distribution Effectiveness for Residential Mechanical Ventilation: Simulation and Comparison of Normalized Exposures

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ABSTRACT

Even when providing the same nominal rate of outdoor air (OA), different ventilation systems distribute air in different ways, affecting the occupants differently depending on the dwelling, on source disposition and strength, on occupants' behavior, and on the cooling or heating system. This paper will report on simulations that compare ventilation systems by assessing their impact on exposure, for each system, It will examine the potential exposure variance for ordinary occupancy patterns (as opposed to extreme or ideal cases) and the influence of source emission patterns and house geometry. These simulations take into account the unsteady, occupancy-tied aspect of ventilation such as bathroom and kitchen exhaust fans. As most US homes have central HVAC systems, the results can be used to make recommendations and adjustments for distribution and mixing to residential ventilation standards such as ASHRAE Standard 62.2. This paper will then analyze the results heeded by increasing mixing of indoor air on the occupant's exposure to contaminants, showing that increasing mixing reduces the effect of the other variables that affect exposure, and vice versa.

KEYWORDS

Ventilation, Contaminant, Exposure, Simulation, IAQ, CONTAM

INTRODUCTION

Ventilation and the transport of both contaminants and clean air is becoming an increasingly important issue as we strive to improve both energy efficiency in buildings and their indoor air quality (IAQ). Existing ventilation standards for dwellings, such as ASHRAE Standard 62.2, 2007 define the amount of mechanical OA ventilation as a function of floor area and number of bedrooms. However, exposure levels within a house are strongly dependant on the ventilation system and assumptions about the pollutant source and occupant location (Sherman, 2008); moreover residential ventilation systems do not perform equally when providing the same nominal OA flow rate (Hendron, 2007). Unfortunately, the standards do not indicate how to evenly distribute ventilation or how to ensure acceptable IAQ. Our main goal in this study is to make recommendations to improve standards and provide adequate evaluation tools for residential ventilation. Towards this we simulated how occupants of a dwelling are affected by different mechanical ventilation strategies. Our simulations differ from other studies which have concentrated on best or worst case occupation scenarios and focused on a specific dwelling. We hope to prove that this reasoning is misleading, show which parameters most affect IAQ, and shed light on the debate regarding indoor air mixing and quantify its benefits to IAQ.

The measure of comparison we have chosen for this study is the relative dose (d), which defines effectiveness as a ratio of an occupant's exposure to what it would have been under the reference case of perfect mixing (Sherman, 2007). It is the integrated concentration that an occupant is exposed to over a period of time (Δt) divided by what they would have been exposed to in the perfectly-mixed case. If a(t) is the activity vector, a horizontal vector that identifies the zones occupied by an occupant at *t,* and $a_0(t)$ is a scalar equal to 1 when the occupant is indoors and 0 when outdoors, C(t) is the concentration vector and $C_0(t)$ the concentration in the perfect mixing case, then d is as shown in Eqn.1:

$$d(\Delta t) = \frac{\int_{\Delta t} \underline{a}'(t) \cdot \underline{C}(t)dt}{\int_{\Delta t} a_0(t)C_0(t)dt}$$

APPROACH

CONTAM (Walton & Dols, 2001, 2005) was the primary tool for the multizone simulation of airflows and contaminant transport in the modelled buildings. CONTAM assumes zones to be well-mixed, and after calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying mass balance equations.

Houses and occupancy patterns

Different houses lead to different OA rates, contaminant and air distribution. Because of this, we modelled three homes, chosen to represent a reasonable cross-section of a database of most common US dwellings (Persily A.K., Musser A., Leber D., 2006): a small single story detached home, a large two-story detached home, and an attached town house with a half underground basement and a tuck-under garage.

Occupation schedules were made as detailed and realistic as possible in order to study the variability of exposure for human occupants – and compare these to simple "worst or best case" scenarios. The schedules state the location in (or out of) the space of each occupant – the minimum residency in occupied zones is 15 min, and there are 30 s intervals when travelling across zones (such as hall ways and stairwells). Four profiles were simulated, with 13 occupants in total: a family with two working parents, another with an at home parent, a retired couple who spend most of their time at home, and a single occupant who spends less time at home.

Ventilation systems and contaminant generation

We simulated the two most common systems for mechanically ventilating homes. In both cases the OA rate is determined by ASHRAE Standard 62.2 (2007): 1) Central Fan Integrated Supply (CFIS). OA is periodically drawn into the return duct of the central forced air system. Every room is equipped with a supply vent and the central room of each floor with a return. In this scenario, the supply and return are balanced and the air handler (AHS) operates for 30 minutes per hour, 20 minutes of which has OA supply. 2) Exhaust with air handler (EXH + AHS). The exhaust fan in the master bathroom operates constantly. The house is equipped with the same AHS as for CFIS, which mixes air in the house one sixth of the time. 3) The exhaust case with no AHS operation (EXH ONLY) was also simulated. In each case wet rooms are equipped with intermittent fans that are occupant-activated, meaning ventilation patterns are specific to occupation profiles[1]. As for AHS operation, the initial simulations were run with the AHS capacity in cfm equal to the floor area in ft^2, which is a little higher than typical[2]. To be conservative in the amount of air exchange between zones, doors were modelled as “closed”, i.e., one-way flows. The importance of this assumption will be discussed further on.

As for generation of household contaminants, it is generally a combination of the following three profiles which we chose to simulate: OCC: Occupant-generated contaminants, representing respiration and perspiration[3]. B&K: Continuous and equal generation split between the kitchen and bathroom(s)[4]. VOL: Volume-weighted sources, where contaminants are emitted with equal intensity per unit of floor space[5].

RESULTS

After calculating d for all occupants in the various cases considered, we made a statistical analysis in which we isolated variables in the calculation of means and standard deviations. We assumed that the distribution of results is geometric and analyzed the influence of variables two at a time. The following tables combine ventilation with contamination profiles for all houses and occupancies. The other variables (occupancy and house) are averaged in the mean and their variability is captured in the standard deviation. Table 1 shows the mean with the upper and lower limit of the standard deviance interval, and table 2 gives the values of the geometric standard deviations. The tables show that each ventilation system responds better to a specific contamination profile: OCC is best diluted with CFIS and the exhaust systems are best for B&K as they directly exhaust the pollutants and mixing only serves to propagate them within the household. The EXH ONLY profile has the biggest variability and the lowest mean dose, but is dominated by the K&B results. These tables show that using extreme values (such as the mean ± 1 std dev) yield misleading results that are contrary to the geometric mean. The results also justify our choice of studying multiple houses and occupancy profiles, as these create large variations, though typically less than ventilation system and contamination profile. For example, the choice of house layout can change results up to a factor of 2, so in order to make generalizations suitable for standards; a range of house layouts and occupancies need to be taken into account.

[1] ASHRAE Standard 62.2 states 100 cfm (0.0472 m3/s) for the kitchen fan and 50 cfm (0.0236 m3/s) for the bathroom fan.

[2] Assuming an approximate cooling load of 1 ton for 500 ft^2 of conditioned space, and following California’s title 24 residential building energy efficiency standards compliance manual of 2008, which states that the central forced air system fans must maintain airflow greater than 350 cfm per nominal ton of cooling capacity, we would have a minimum flow of 0.7 cfm per ft2 of conditioned space (for heating the flows would be even lower, for example, Title 24 default is 0.5 cfm per ft2).

[3] . In accordance with previous studies (SJ Emmerich, 2008), we further assumed that the generation of an individual during sleep is 60% that of when he or she is awake. Also, since we wanted the magnitudes of emission between occupants to differ, they were attributed body weights and an equal generation rate per unit body weight.

[4] This case represents continuous emission of household contaminants kept in storage in these rooms. This case is not related to activity-based emissions, even though these are common in wet rooms (via showering, cooking, etc.).

[5] This limit represents continuous emissions from building materials such as paint, carpets, walls, etc.

TABLE 1: Geometric means for different ventilation and contamination profiles

	OCC		B&K		VOL		mean	
CFIS	1.24	+ 0.17 - 0.15	0.96	+ 0.09 - 0.08	0.99	+ 0.03 - 0.03	1.06	+ 0.17 - 0.14
EXH + AHS	1.31	+ 0.17 - 0.15	0.67	+ 0.11 - 0.10	1.01	+ 0.04 - 0.03	0.96	+ 0.33 - 0.25
EXH ONLY	1.67	+ 0.58 - 0.19	0.25	+ 0.29 - 0.04	1.01	+ 0.10 - 0.04	0.76	+ 1.16 - 0.20
mean	1.40	+ 0.38 - 0.36	0.55	+ 0.58 - 0.29	1.01	+ 0.06 - 0.09	0.92	+ 0.73 - 0.55

TABLE 2: Geometric standard deviation for different ventilation and contamination profiles

	OCC	B&K	VOL	mean
CFIS	1.139	1.094	1.026	1.158
EXH + AHS	1.130	1.169	1.035	1.347
EXH ONLY	1.344	2.142	1.095	2.530
mean	1.269	2.056	1.060	1.798

Influence of Mixing

To determine if there is an optimum operating schedule, we ran simulations with different AHS flows (the schedules remain unchanged). Figures 1 and 2 illustrate the trends in relative dose while increasing mixing. The means combine the multiple homes and occupancies and the standard deviations are shown as bars around the mean. The mechanical mixing provided by the AHS is expressed in building air changes per hour (ACH), (i.e., airflow through the AHS divided by the house volume).
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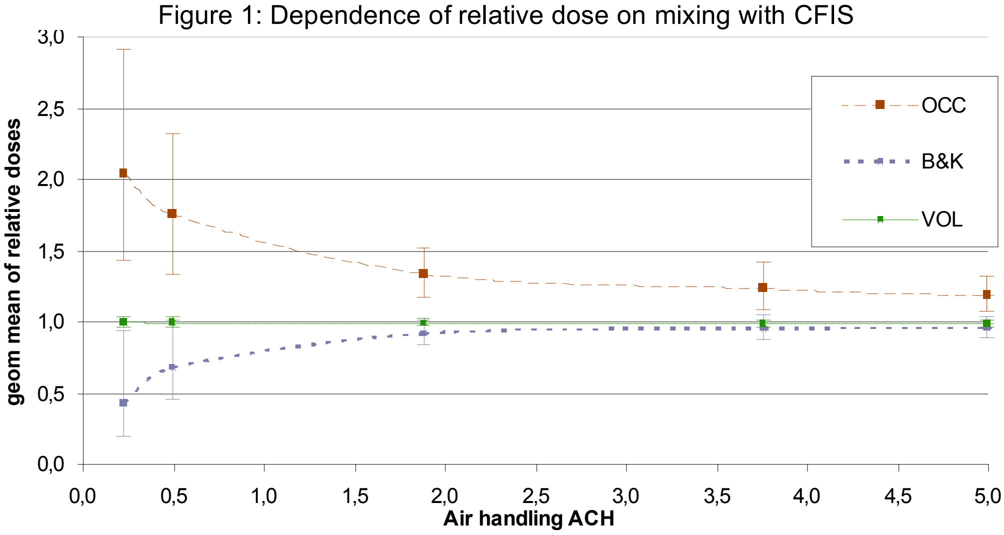
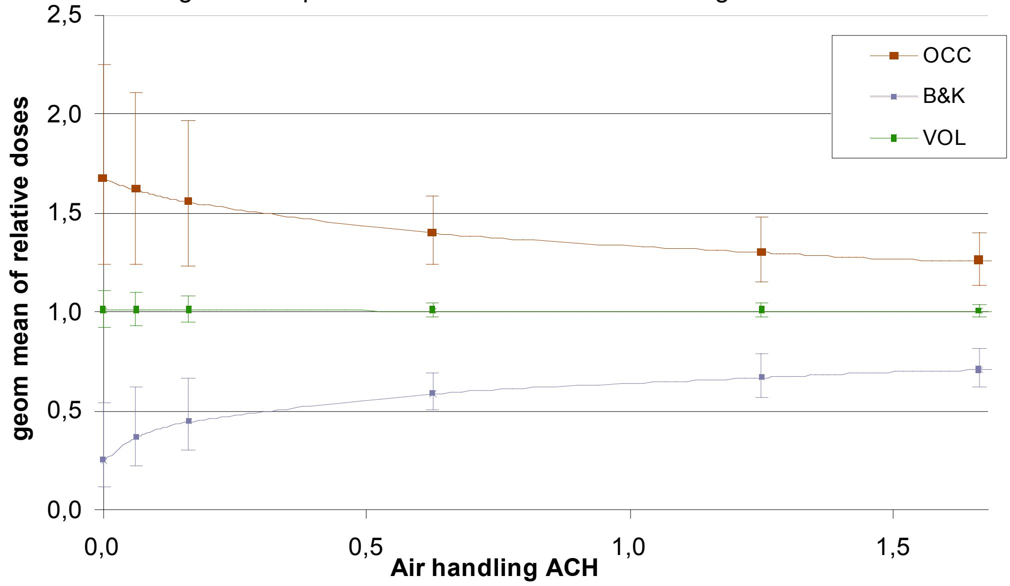
Figure 1: Dependence of relative dose on mixing with CFIS



For both CFIS and exhaust cases, increased mixing reduces the difference between means and the variability about the mean. The figures show that increased mixing above a certain rate has little effect on the results. Selection of this “cut-off” rate is fairly arbitrary, but about 0.7 ACH looks reasonable. Comparing the dose curves at equal mixing ACH values, one notices that at equal mixing rates, relative dose means and standard deviations are lower for the exhaust profile than for CFIS, meaning lower risks of extreme exposure. We attribute this benefit to two facts: 1) the exhaust tends to remove pollutants before they are mixed and 2) a central exhaust provides mixing in the house without the additional use of an AHS. To reduce relative dose, exhaust systems should exhaust from the zones of highest contaminant concentration and supply systems would provide air to occupied zones.

Figure 2: Dependence of relative dose on mixing with EXH



DISCUSSION

Doors

We ran the simulations again using the assumption that doors are “open”, modelled as large two-way flow air paths which induce very large amounts of air flow between adjacent zones[6]. Temperature differences of 1°C between the rooms were used to create natural mixing, which was extensive and easily observable: in the exhaust profile the gain in mixing is of roughly 4 ACH; and in the CFIS case, the gain is roughly 2 ACH (the difference is due to the different run-time of the AHS). Most importantly, this showed that natural mixing occurring through doors can have a noticeable effect on IAQ, and that this is a variable that should not be overlooked.

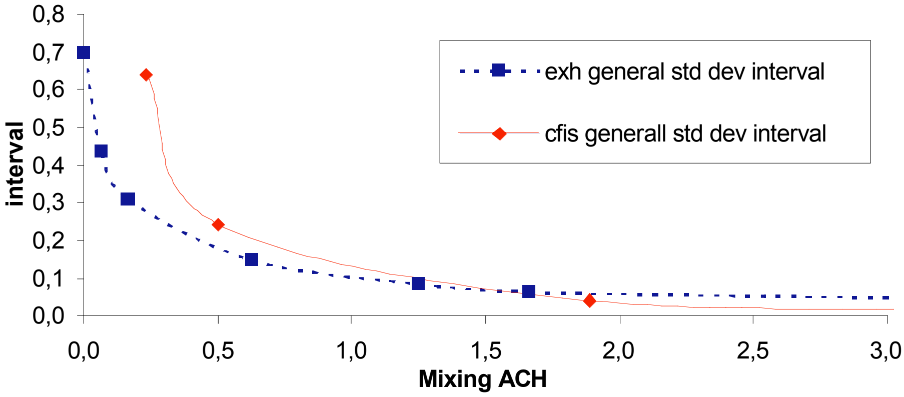
Reducing variability

In any typical house, contamination will occur in a household as a combination of OCC, B&K and VOL, for this reason, the above graphs do not help us define how much mixing provides the best IAQ. However, Exposures vary most at low mixing rates so to ensure that the worst case doesn’t occur, it is important to use mixing to reduce variability. Figure 3 summarizes the overall standard deviation per ventilation system at different mixing rates. We observe a constant shift between the two curves of 0.22 ACH, showing that in the exhaust case, the forced air infiltration throughout the envelope, travelling throughout the house to the exhaust fan, creates a certain

[6] For example, a 1°C difference typically creates an exchange of 50 cfm (0.0236 m3/s) both ways.

amount of mixing, which is attributed to the central nature of the exhaust system. We therefore encourage future studies to compare distributed and central systems. Noting that the curves have identical trends, one can attempt to make a recommendation for mechanical mixing rates on the basis of reducing risks of high exposure. A certain optimum deviation interval would have to be chosen to define the best mixing rate. Unfortunately, this is possible only subjectively. Moreover, with the choice of mixing rate comes a degree of responsibility from the occupants – with less mixing, the more their behaviour can affect their exposure. In addition, the lower mean for the exhaust case allows for a higher standard deviation for the same maximum dose. So these values could be further reduced for exhaust systems if this maximum dose metric were considered.

Figure 3: Reduction in dose variability with increasing mixing



CONCLUSIONS

The concept of relative dose was used in an unsteady model to quantify the varying impact that different ventilation systems have on IAQ, as well as the role of mixing indoor air in maintaining IAQ. The comparison of exposure to perfect mixing via d has revealed the natural mixing induced by a central exhaust system, limiting the need of an AHS, and the increase of mixing to reduce variability of exposure. The results show that mixing can be good or bad depending on the pollutant source distribution. In general, averaging shows that mixing is selectively beneficial, so no general rule can be defined as to its IAQ benefit or loss. Results also reveal that reflecting on worst-case scenarios can be misleading. Mixing of indoor air was also shown to be highly dependant on flows through doorways. As encouraged by these notions, further research should explore the scheduling of openings between zones, natural vectors of mixing in indoor space, and comparisons between central and distributed systems, in order to provide institutions that write and implement standards robust tools to take into account distribution patterns in residential ventilation.

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