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ABSTRACT

The software CONTAM was used to create a calibrated multi-zone model to replicate in-field tracer gas decay measurements of a new 2-story, 2600 ft^2 (240 m^2), single-family house in Sacramento, CA under different whole-house dilution ventilation scenarios. The model incorporated measured values of ventilation system airflow rate, building enclosure leakage, fan-forced mixing between floor levels, indoor and outdoor temperature, and wind speed and direction. The enclosure leakage distribution was adjusted to tune the model to the measured tracer gas concentration data. The calibrated model was then used to compare different ventilation systems under identical outdoor conditions over a one-day period. Zones that received more ventilation air had faster concentration decay rates compared to zones that received less ventilation air. Results showed that ventilation systems that delivered air to all zones, either by a dedicated duct system or by incorporation of the central forced-air space conditioning system, had more uniform ventilation air distribution.

INTRODUCTION

This paper describes the creation of a calibrated computer model for residential ventilation systems and the use of the calibrated model to extend the results obtained in previous field testing. The model calibration process used test data from tracer gas testing of residential ventilation systems in a new single-family house near Sacramento, California. Hendron (2007) detailed the tracer gas testing and conclusions. The work described in this paper was performed in order to evaluate ventilation systems that were not present in the houses tested by Hendron and to provide the capability to extend the results of field testing in one location under one set of environmental conditions to many locations under many sets of environmental conditions.

DESCRIPTION OF HOUSE

This work concentrates on one of the two houses tested by Hendron (2007). The house is two-story, approximately 2600 ft^2 (240 m^2), with four bedrooms and three bathrooms. The first floor consists of one bedroom, one bathroom, a laundry room, the living room area, and a kitchen and dining room. The second floor consists of the master bedroom and bathroom, two additional bedrooms, an additional bathroom, and a small common area at the top of the stairway which overlooks the living room below. Figure 1 contains a drawing of the floor plan of the house.

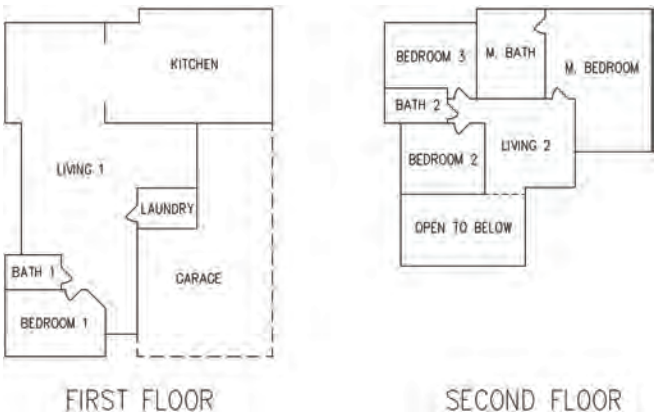

Figure 1 *House floor plan.*

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DESCRIPTION OF PREVIOUS TRACER GAS TESTING

Hendron (2007) describes the tracer gas testing in detail. In total, seventeen ventilation tests were performed on the house using tracer gas decay methods. Table 1 lists the tracer gas tests performed. For each test, the house was first brought to a well-mixed state with uniform tracer gas concentration in all zones by running the central air handler (AHU) and auxiliary mixing fans. The test was initiated by deactivating the mixing systems and activating the ventilation system as appropriate for the test, and leaving the house in that state for a period of 2 to 14 hours. Three ventilation systems were tested. The first ventilation system tested was the central-fan-integrated supply (CFIS) ventilation system, which consists of an outside-air duct to the return side of the AHU and a controller that operates the AHU on a minimum duty cycle. The outside-air duct contains a damper that remains closed except when the CFIS system is activated. The duty cycle of the AHU and CFIS system varied from test to test. This ventilation system was operated at different ventilation rates using a variable-speed fan installed inline with the outside air duct, as described in Table 1. The second and third ventilation systems were upgraded exhaust fans located in the laundry room and master bedroom, respectively. The exhaust fans were tested only at 100% of the ASHRAE Standard 62.2-2003 (ASHRAE 2003) (referred to elsewhere in this paper simply as 62.2) ventilation rate, and were tested with and without simultaneous operation of the AHU for mixing. In addition to the ventilation tests, natural infiltration and air handler bump (natural infiltration with the AHU running) tests were also conducted. During the tracer gas tests, the bedroom doors were either open or closed. The house was built with transfer grills, which are passive openings above the doorways that allow a return air path when the bedroom doors are closed. The transfer grills were also either open or closed (taped over) during the tracer gas tests. The doors to the bathrooms and laundry room were always open. All exterior doors and windows were always closed.

Table 1. Tracer Gas Tests

Test Number	Description
CFIS Tests With Mixing (All have AHU 20 min off/10 min on)	
1	Doors Closed, Transfer Grills Open, 95% of the 62.2 Ventilation Rate*
2	Doors Closed, Transfer Grills Open, 60% of the 62.2 Ventilation Rate
3	Doors Closed, Transfer Grills Open, 33% of the 62.2 Ventilation Rate
4	Doors Closed, Transfer Grills Closed, 60% of the 62.2 Ventilation Rate
Laundry Exhaust Tests With Mixing (All at 100% of the 62.2 ventilation rate)	
5	Doors Closed, Transfer Grills Open, AHU 20 min off/10 min on
6	Doors Closed, Transfer Grills Open, AHU 25 min off/5 min on
7	Doors Closed, Transfer Grills Closed, AHU 25 min off/5 min on
Laundry Exhaust Tests Without Mixing (All at 100% of the 62.2 ventilation rate)	
8	Doors Open, Transfer Grills Open
9	Doors Closed, Transfer Grills Open
10	Doors Closed, Transfer Grills Closed
Master Bathroom Exhaust Tests With Mixing (All at 100% of the 62.2 ventilation rate)	
11	Doors Closed, Transfer Grills Open, AHU 25 min off/5 min on
Master Bathroom Exhaust Tests Without Mixing (All at 100% of the 62.2 ventilation rate)	
12	Doors Closed, Transfer Grills Open
13	Doors Closed, Transfer Grills Closed
Natural Infiltration Tests (No ventilation or AHU operation)	
14	Doors Open, Transfer Grills Open
Air Handler Bump Tests (No ventilation, AHU on)	
15	Doors Open, Transfer Grills Open
16	Doors Closed, Transfer Grills Open
17	Doors Closed, Transfer Grills Closed

*Test 1 was 95% instead of 100% of the 62.2 ventilation rate due to hardware limitations.

DESCRIPTION OF MODELING SOFTWARE

CONTAM is a multi-zone air flow network modeling software developed by the National Institute of Standards and Technology (Walton 2005; Emmerich 2003; Emmerich 2001). It is commonly used in ventilation research to model buildings, ventilation systems, and contaminants in indoor and outdoor air (Emmerich 1995; Persily 1998). In CONTAM, the user specifies attributes of the building's zones, air flow pathways between zones (such as leaks or fans and ducts), contaminant sources and sinks, and other relevant inputs. The software performs the simulation and the results are available for visualization or export.

TESTING OF SUBSTITUTE HOUSE

At the time of the work described in Hendron (2007), an enclosure air leakage test was performed with a blower door (ASTM 2003), but no further diagnostics were performed on the house enclosure or interior demising walls as further work was not planned at the time. Later, when the decision was made to create a calibrated computer model, much more detailed information about the enclosure and interior airflow paths was needed in order to provide a reasonable starting point for the calibration process. The original house was no longer available for testing, so another house of the same floor plan was tested instead. While two houses of the same floor plan can certainly have different leakage characteristics, these

two houses were built within a few months of each other, by the same builder and likely the same subcontractors, and the overall enclosure leakage testing results were similar. The original house had a leakage rate of 1346 cfm (635 L/s) at 50 Pascals (0.2 in. of water) pressure difference across the enclosure (CFM50), and the substitute house had 1608 CFM50 (759 L/s at 50 Pa). The substitute house was slightly larger due to an option that added two additional bedrooms and an additional bathroom; after subtracting the leakage in the additional bedrooms, the substitute house was 1411 CFM50 (666 L/s at 50 Pa). As the substitute house was simply a starting point for calibrating the model, differences between the houses were of minor consequence and were remedied during the calibration process.

Air leakage characterization on the substitute house was performed to quantify both house-to-exterior and room-to-room leakage characteristics. The testing also included tests of zone pressures and central forced-air system airflow to each room. The testing procedure was able to quantify the leakage characteristics of each room to the exterior and to neighboring zones, but no attempt was made to identify the specific locations of leakage within each room. Further details of the testing at the substitute house are included in the appendix.

MODELING PROCEDURE

The goal of the modeling was to produce a set of inputs for the house enclosure and zone-to-zone leakage pathways that, when simulated with CONTAM, would produce the same results as the tracer gas tests when the ventilation systems were operated in the same manner as each of the tracer gas tests.

As a starting condition, leakage values calculated from the leakage testing in the substitute house were used for the exterior enclosure and the interior partition walls. Because the actual leakage locations within each room were not determined by the testing, leakage within each room was initially distributed proportional to the wall and ceiling area. Wall leakage was broken into leakage for each wall orientation and into five vertical locations on each wall, with equal vertical separation between the locations. Each leakage location on a wall had the same leakage coefficient and exponent. Initial test runs with simplified models showed the vertical spacing chosen (5 leaks per wall, equally spaced on a 9 ft (2.7 m) wall) approximated diffuse wall leakage, while still maintaining a manageable number of leakage elements in the model. The temperature in each room and the outdoor temperature and wind speed had been recorded during the tracer gas testing, and were used as inputs to the model. Wind direction was not recorded during the tracer gas testing, so meteorological data from the nearest airport (Auburn, CA, approximately 10 miles (16 km) away) was obtained and the wind direction data was used as an input to the model. Drawings and specifications for the AHU and duct system were obtained from the subcontractor, which were used to create a full duct and AHU model. The AHU and all ductwork in this house are located within conditioned space, greatly simplifying the need to characterize duct leakage. For each test simulated, a schedule was created that controlled the ventilation systems, AHU operation, and transfer grill and bedroom door status to replicate operation as performed in the tracer gas tests. Results from the model were compared to the tracer gas data and the leakage inputs were modified via trial-and-error to decrease the error between the model output and the tested data. No formal method was used to obtain a minimized error function, only visual comparison of the measured and simulated tracer gas decay curves, so there is no reason to assume that the final inputs represent a unique or optimized solution.

During the initial comparisons of measured and simulated data, it became clear that the most difficult tests to replicate were the tests with large differences in tracer gas decay rates between the different rooms. Stated differently, it is easier to replicate the decay rate in a well-mixed house (which might be approximated as a single well-mixed zone) than it is to replicate the decay rates of six interconnected zones. Consequently, a single test was used for the calibration, and the remaining tests were used after the calibration was complete in order to evaluate the results. The test used to calibrate the model was test 9, which utilized the continuously-operating laundry room exhaust fan as the ventilation system, did not have mixing via the AHU, and had the bedroom doors closed and the transfer grills open. Test 9 was selected as the calibration test because it was a long test (14 hours) without mixing, there were substantial differences in the tracer gas concentrations, and it had an interesting change in tracer gas decay rate during the test due to a temperature change in two of the zones.

Figure 2 shows the tracer gas decay curves from the initial simulation of test 9 using the enclosure leakage values calculated from the substitute house. The results are not unreasonable, yet clearly there is room for improvement. Figure 3 shows the results of the final simulation of test 9, which were deemed to agree with the measured data sufficiently to cease further trial and revision of the model.

STATISTICAL METHOD FOR EVALUATION OF MODELING RESULTS

Results were evaluated statistically using ASTM D5157-97 Standard Guide for Statistical Evaluation of Indoor Air Quality Models (ASTM 2008). ASTM D5157 has three criteria relevant to evaluating the results of this work. The first criterion is that the data used for the evaluation should be independent from the data used to develop the model. All of the test results with the exception of test 9 meet this criterion, as they were not used to calibrate the model. The second criterion consists of a set of quantitative parameters related to the agreement between the predicted (modeled) and observed (measured) data sets. These parameters are:

1. Correlation coefficient, r, between the predicted and observed data sets. r ranges from -1 to +1, with -1 indicating an inverse relationship, 0 indicating no relationship, and +1 indicating a strong relationship between the

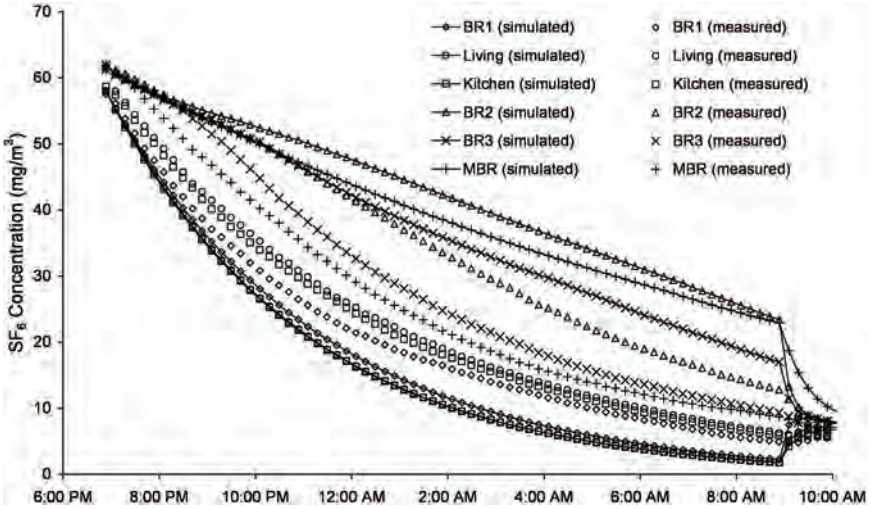

Figure 2 *Results of simulation of test 9 using initial data from the substitute house.*

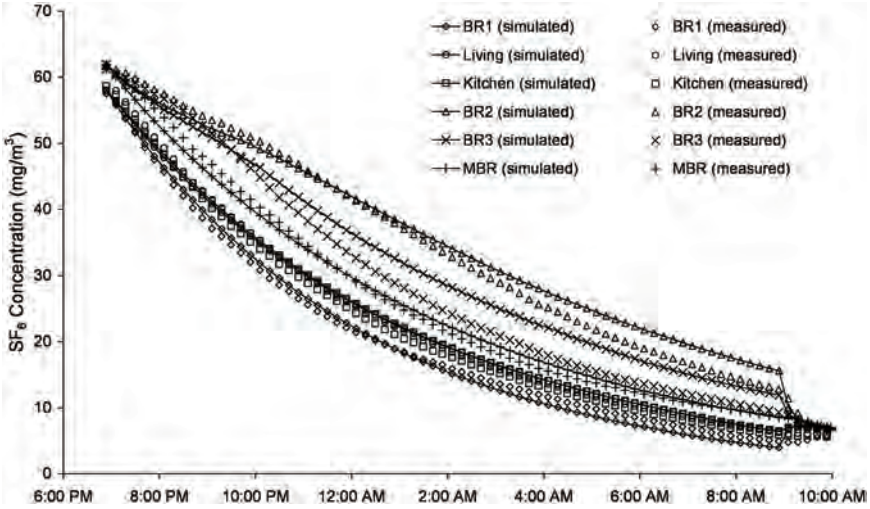

Figure 3 *Results of simulation of test 9 after trial and error calibration of the model.*

two data sets. D5157 suggests that r values greater than 0.9 generally indicate adequate model performance with respect to correlation coefficient.

2. Best-fit line of regression between the predicted and observed data sets. Regression of perfectly-matched data sets would have a slope, m, of 1.0 and an intercept, b, of 0.0. D5157 suggests that an a slope of 0.75 to 1.25 and an intercept less than 25% of the mean value of the observed data set (thus $b/\overline{C}_o < 0.25$, where $\overline{C}_o$ is the mean value of the observed data set) generally indicate adequate model performance with respect to regression.
3. Normalized mean square error (NMSE), a measure of the magnitude of the error between the predicted and observed data sets. NMSE is calculated as in Equation 1:

$$\text{NMSE} = \Sigma[(C_{pi} - C_{oi})^2/n]/[(\overline{C}_p)(\overline{C}_o)] \quad (1)$$

where the C is the concentration of pollutant in the air, the subscripts p and o indicate predicted and observed, respectively, the summation index i is over the entire data set, and the overbars represent the average for the entire predicted or observed data set. NMSE will have a value of 0 if all pairs in the data sets are equal. D5157 suggests that a value for NMSE of less than 0.25 generally indicates adequate model performance with respect to NMSE.

4. Fractional bias (FB), a measure of the bias of the mean concentration of the predicted data set. FB is calculated as in Equation 2:

$$FB = 2 \bullet (\bar{C}_p - \bar{C}_o)/(\bar{C}_p + \bar{C}_o) \quad (2)$$

FB will have a value of 0 when $\bar{C}_p$ and $\bar{C}_o$ are equal. D5157 suggests that a value of less than 0.25 generally indicates adequate model performance with respect to FB.

5. Index of variance bias (FS), calculated as in Equation 3:

$$FS = 2 \bullet (\bar{\sigma}_p^2 - \bar{\sigma}_o^2)/(\bar{\sigma}_p^2 + \bar{\sigma}_o^2) \quad (3)$$

Where $\bar{\sigma}_p$ and $\bar{\sigma}_o$ are the variance of the predicted and observed data sets, respectively. D5157 suggests that a value of less than 0.5 generally indicates adequate model performance.

Finally, the third criterion suggested by D5157 is the qualitative tool of plotting the predicted and observed concentrations versus time, to allow visual comparison and indicate the areas of agreement and disagreement between the predicted and observed data sets.

MODELING RESULTS

Overall, good agreement between the modeling and tracer gas results was obtained. As described above, greatest agreement was obtained for cases with mixing and the least agreement was obtained for the natural infiltration case. Tracer gas concentration decay plots and statistical parameters are examined below for one test in each of the ventilation system categories from Table 1. The full set of statistical parameters from all of the tests is presented later.

Figure 4 shows the measured and simulated tracer gas decay curves for test 1, a 12-hour test of the CFIS system at 95% of the 62.2 rate. Test 1 was not run at 100% of the 62.2 rate due to hardware limitations at the test site. Figure 4 shows good agreement between the measured and simulated data sets. This agreement is quantified via the ASTM D5157 parameters in Table 2. All of the parameters are within the

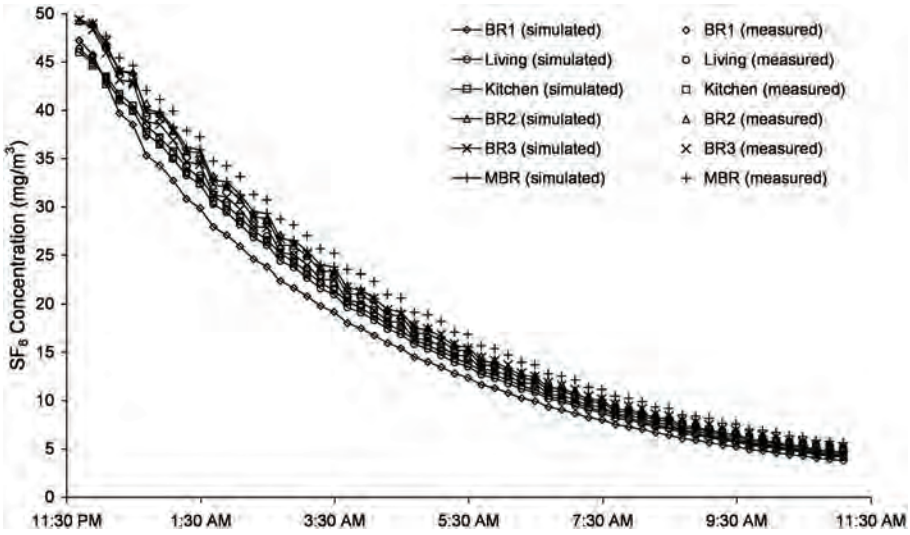

Figure 4 *Comparison of testing and modeling results for test 1 (CFIS with mixing).*

Table 2. ASTM D5157 Parameters for Test 1

ASTM D5157 Parameter	r	m	$b/\bar{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test Zone						
BR1	1.00	0.99	-0.09	0.01	-0.10	-0.01
Living	1.00	1.01	-0.07	0.00	-0.05	0.01
Kitchen	1.00	1.04	-0.05	0.00	-0.01	0.04
BR2	1.00	1.02	-0.05	0.00	-0.02	0.02
BR3	1.00	1.01	-0.06	0.00	-0.05	0.01
MBR	1.00	1.00	-0.06	0.00	-0.07	0.00

ranges suggested by D5157 as adequate, and Figure 4 shows visually that the agreement between the measured and simulated data sets is good.

Figure 5 shows the measured and simulated tracer gas decay curves for test 6, a 14-hour test of the laundry exhaust ventilation system with the AHU operating for mixing 5 minutes out of every 30 minutes. Figure 5 again shows good agreement between the measured and simulated data sets. Table 3 contains the ASTM D5157 parameters for test 6. All of the parameters are within the ranges suggested by D5157 as adequate.

Figure 6 shows the measured and simulated tracer gas decay curves for test 10, a 12-hour test of the laundry exhaust ventilation system without the AHU operating for mixing. Figure 6 shows that the tracer gas concentrations matched well for the rooms on the first floor (BR1, Living, and Kitchen) but significantly over-predicted the decay rate for the MBR zone on the second floor. Table 4 contains the ASTM D5157 parameters for test 10. The values for m and $b/\overline{C}_o$ are further from ideal than the previous tests, as are the NMSE and FB for the MBR zone, yet all are still well within the D5157 adequate range.

Figure 7 shows the measured and simulated tracer gas decay curves for test 11, a short 4-hour test of the master bedroom exhaust ventilation system with the AHU operating for mixing 5 minutes out of every 30 minutes. Table 5 contains the ASTM D5157 parameters for test 11. Again in this test the model over-predicts the decay rate of the tracer gas concentration in the master bedroom. This is shown graphically in the figure and quantitatively in the table as higher absolute values for $b/\overline{C}_o$ and FB for the MBR zone. All of the values are still within the D5157 recommended ranges.

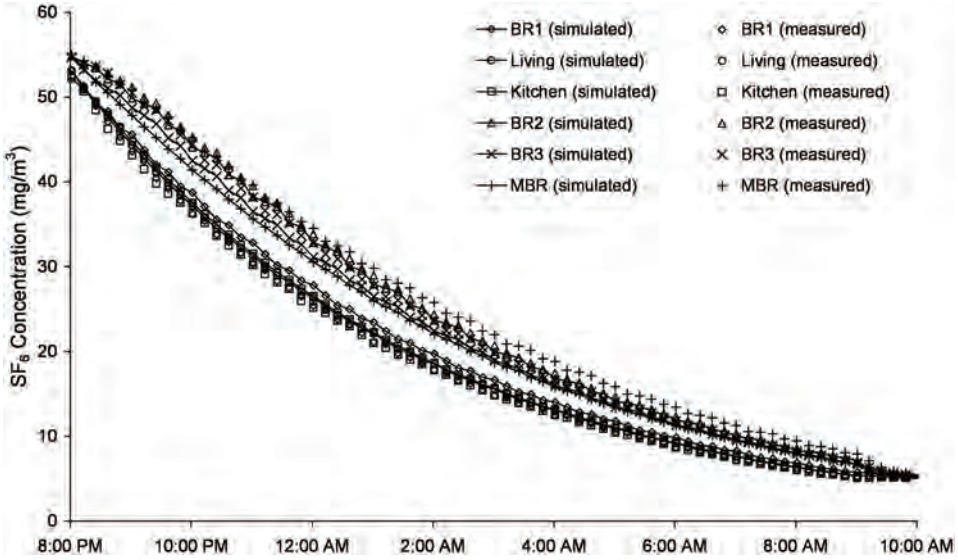

Figure 5 *Comparison of testing and modeling results for test 6 (laundry exhaust with mixing).*

Table 3. ASTM D5157 Parameters for Test 6

ASTM D5157 Parameter	r	m	$b/\overline{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test Zone						
BR1	1.00	1.02	0.05	0.00	0.06	0.02
Living	1.00	1.00	0.00	0.00	0.00	0.00
Kitchen	1.00	1.03	0.01	0.00	0.04	0.03
BR2	1.00	0.99	0.00	0.00	-0.02	-0.01
BR3	1.00	0.97	0.00	0.00	-0.03	-0.03
MBR	1.00	0.96	-0.06	0.01	-0.11	-0.04

Figure 8 shows the measured and simulated tracer gas decay curves for test 12, a 12-hour test of the master bedroom exhaust ventilation system without the AHU operating for mixing. Table 6 contains the ASTM D5157 parameters for test 12. For this test the model over-predicts the decay rate of the tracer gas concentration in the MBR zone and under-predicts the decay rate in the BR3 zone. This is shown graphically in the figure and quantitatively in the table as higher absolute values for $b/\overline{C}_o$ and FB for the MBR and BR3 zones. All of the values are still within the D5157 recommended ranges.

Figure 9 shows the measured and simulated tracer gas decay curves for test 14, a short 2-hour natural infiltration test with neither ventilation fan nor AHU operation. Table 7 contains the ASTM D5157 parameters for test 14. For this test the model under-predicts the decay rate of the tracer gas concentration in the BR2, BR3, and MBR zones. This is difficult to see in the figure due to the short test, but is shown quantitatively in m, $b/\overline{C}_o$, and FS parameters for these three zones. This test contains the first parameters that fall outside of D5157's adequate range.

Figure 10 shows the measured and simulated tracer gas decay curves for test 17, a 2.5-hour test with no ventilation fan operation but with the AHU running continuously. Table 8 contains the ASTM D5157 parameters for test 14. For this test the model slightly under-predicts the decay rate in all six zones in the house. This is shown quantitatively in the table as poorer values for the m and $b/\overline{C}_o$ parameters for these three zones. These values do fall within D5157's adequate range.

Table 9 contains the statistical evaluation parameters for all seventeen tests. In general the parameters fell well within the bounds suggested by D5157 as adequate. The first exception is test 3. In test 3, the Living, Kitchen, BR2, and BR3

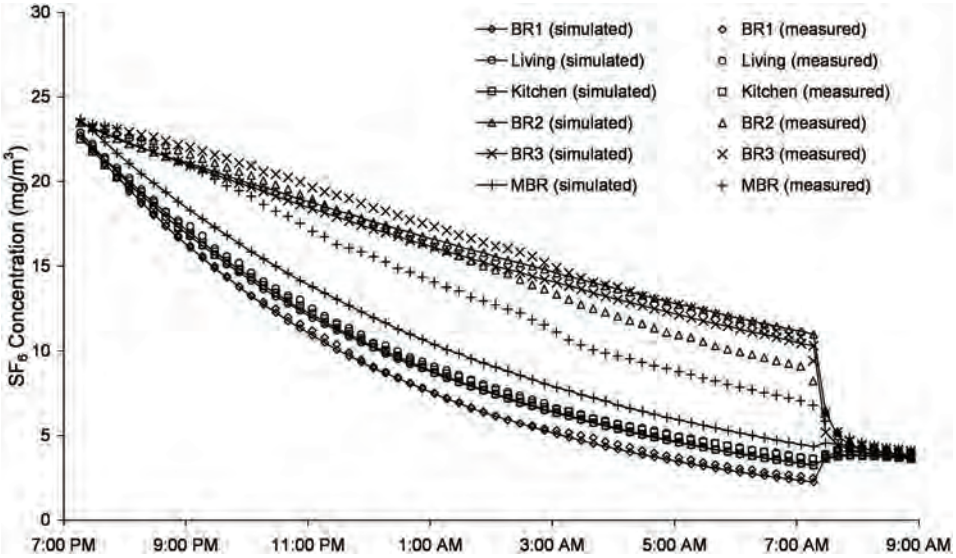

Figure 6 *Comparison of testing and modeling results for test 10 (laundry exhaust without mixing).*

Table 4. ASTM D5157 Parameters for Test 10

ASTM D5157 Parameter	r	m	$b/\overline{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	**>0.9**	**0.75 to 1.25**	**<0.25**	**<0.25**	**<0.25**	**<0.5**
Test Zone						
BR1	1.00	1.01	-0.03	0.00	-0.02	0.01
Living	1.00	1.00	-0.04	0.00	-0.04	0.00
Kitchen	1.00	1.04	-0.05	0.00	-0.01	0.04
BR2	0.99	0.91	0.13	0.01	0.04	-0.08
BR3	1.00	0.96	-0.02	0.00	-0.05	-0.03
MBR	0.98	0.97	-0.17	0.06	-0.22	-0.01

zones which had values of $b/\overline{C}_o$ slightly above the adequate level and values of m significantly closer to the adequate level than most of the remaining tests. Test 3 was different than the other mixed tests in that it had a low ventilation rate (33% of the 62.2 rate). The other test that has values outside the adequate range is test 14, which has values outside the adequate range for m and $b/\overline{C}_o$ in the MBR zone and marginal values for the same parameters in the BR2 and BR3 zones. In addition, while none of the parameters of tests 15-17 fall outside of the adequate level, the values for m and $b/\overline{C}_o$ are marginal for all zones. This reinforces the hypothesis that infiltration is the most difficult physical phenomenon to model correctly in the current model.

Infiltration is dependent on the distribution of leakage around the enclosure. When infiltration is the dominant (or only) source of air exchange with the outdoors, the accuracy of the model will depend more heavily on having the correct enclosure leakage distribution than when ventilation rates are higher. Similarly, when air movement within the house is determined by natural forces (such as in the tests with no mixing), the accuracy of the model will depend more heavily on having the correct enclosure leakage distribution than when air movement within the house is performed via a mechanical system.

DISCUSSION OF ERROR

Judging by the graphical comparisons of tracer gas decay curves, the general behavior of the house and ventilation systems appear to be well represented by the model; however

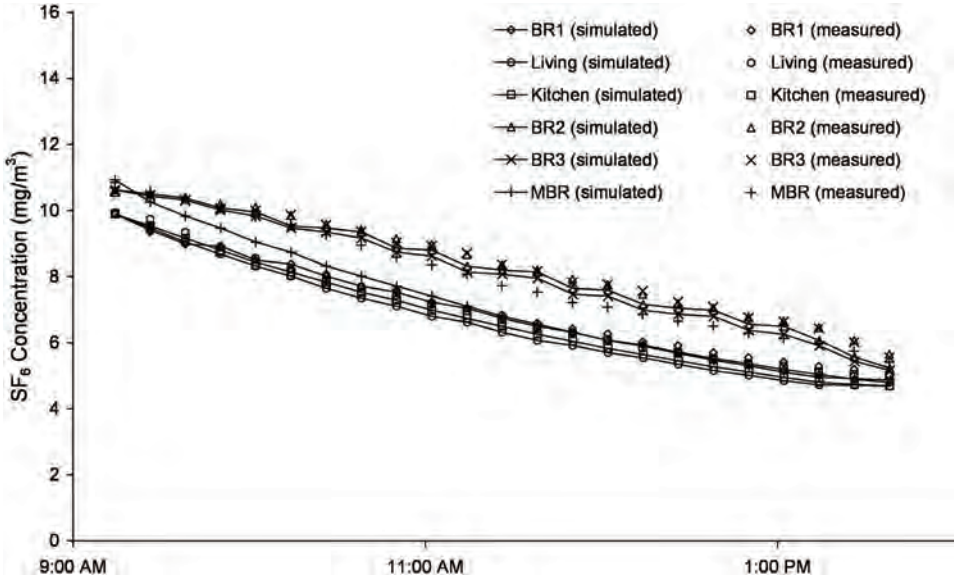

Figure 7 *Comparison of testing and modeling results for test 11 (master bathroom exhaust with mixing).*

Table 5. ASTM D5157 Parameters for Test 11

ASTM D5157 Parameter	r	m	$b/\overline{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test Zone						
BR1	1.00	1.07	-0.08	0.00	-0.01	0.07
Living	1.00	1.04	-0.08	0.00	-0.05	0.04
Kitchen	1.00	1.09	-0.11	0.00	-0.02	0.09
BR2	1.00	1.06	-0.08	0.00	-0.02	0.06
BR3	1.00	1.09	-0.12	0.00	-0.04	0.09
MBR	0.99	1.10	-0.20	0.01	-0.11	0.10

there are some unexplained shapes in the test data that indicates the model is not capturing all of the physical phenomena occurring in the house. Given the complexity and number of unknowns about the system being modeled, it was expected that the predicted and observed data sets would not converge precisely, particularly in those cases which depend most heavily on knowledge of the enclosure leakage distribution. It is possible that other assumptions, such as wind direction and shielding factors, are also contributing to the error.

EXTENSION OF MODEL TO OTHER SYSTEMS

The computer model allows modeling of systems that were not present in the tested house. It also allows comparison of different ventilation systems under identical environmental conditions, which is generally not true in field testing. In order to demonstrate this ability, a balanced ventilation system was compared with the tested supply and exhaust ventilation systems under identical environmental conditions.

The balanced ventilation system consisted of a supply system that distributed outside air to each bedroom at a rate of 7.5 cfm (3.5 L/s) and the first floor living area at a rate of 33 cfm (15.6 L/s), and exhausted air from the laundry room at a rate of 63 cfm (29.7 L/s). The balanced ventilation system was tested with and without mixing via the AHU. Table 10 describes the different systems modeled as an extension of the tracer gas testing. For all of these cases, the bedroom doors were closed; the transfer grills were open; and the ventilation rate was 63 cfm (29.7 L/s). All of the cases were simulated over a 12 hour test period and then mixing was initiated with using the AHU.

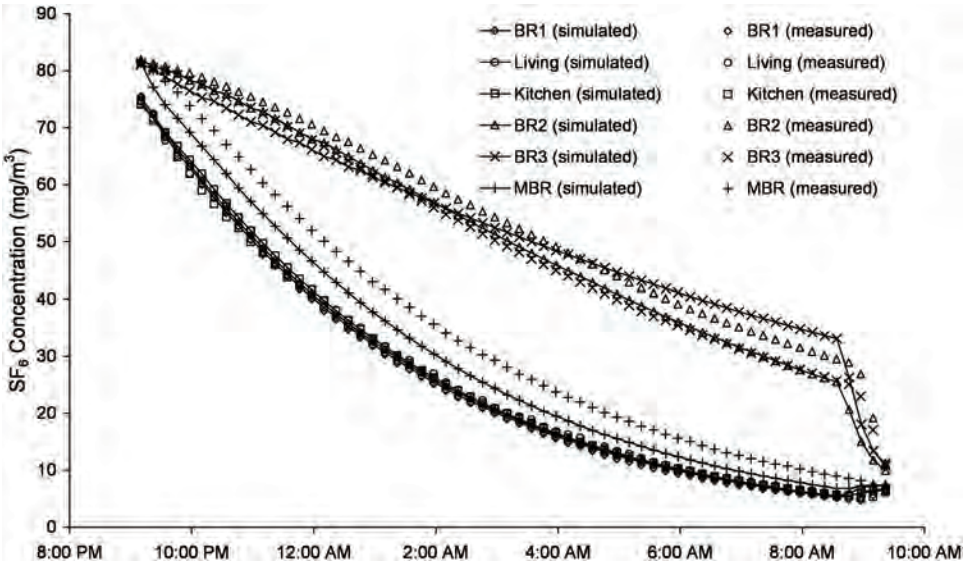

Figure 8 *Comparison of testing and modeling results for test 12 (master bathroom exhaust without mixing).*

Table 6. ASTM D5157 Parameters for Test 12

ASTM D5157 Parameter	r	m	$b/\overline{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	**>0.9**	**0.75 to 1.25**	**<0.25**	**<0.25**	**<0.25**	**<0.5**
Test Zone						
BR1	1.00	0.99	0.04	0.00	0.03	-0.01
Living	1.00	1.00	-0.04	0.00	-0.04	0.00
Kitchen	1.00	1.03	-0.03	0.00	0.00	0.03
BR2	1.00	1.00	-0.02	0.00	-0.02	0.01
BR3	0.99	0.87	0.17	0.01	0.04	-0.12
MBR	1.00	0.98	-0.09	0.01	-0.11	-0.01

As a simple metric, the effective exponential decay rate was calculated for each of the extension cases. The effective exponential decay rate was calculated for each room in each test, as defined in Equation 4:

$$\tau = \ln(C_i/C_f)/\Delta t \quad (4)$$

where

τ = the effective exponential decay rate (1/hr)

C_i = the initial tracer gas concentration, at the beginning of the test

C_f = the final tracer gas concentration, at the end of the test (just before mixing was restarted)

Δt = the time elapsed during the test (hr)

Table 11 shows the effective decay rates for each main room of each of the extension cases simulated. The mixed cases (cases 1, 2, and 4) have uniform decay rates from room to room, while the unmixed cases have decay rates that vary from room to room. Table 11 also shows that the balanced ventilation systems have faster decay of contaminants than either the supply or exhaust systems, due to the fact that balanced ventilation does not cause net pressurization or depressurization of the house and therefore does not displace a portion of the natural infiltration as unbalanced systems do.

A note of caution is in order. The tracer gas testing occurred at a time when the outdoor temperature ranged from 41-64 °F (5-18 °C). The extension cases were modeled with similar outdoor temperature conditions. As described in an earlier section, the calibrated model has a finite error due to uncertainty in the enclosure leakage distribution. The magnitude of this error will grow as the enclosure leakage becomes more important, i.e. at low ventilation rates and in harsher

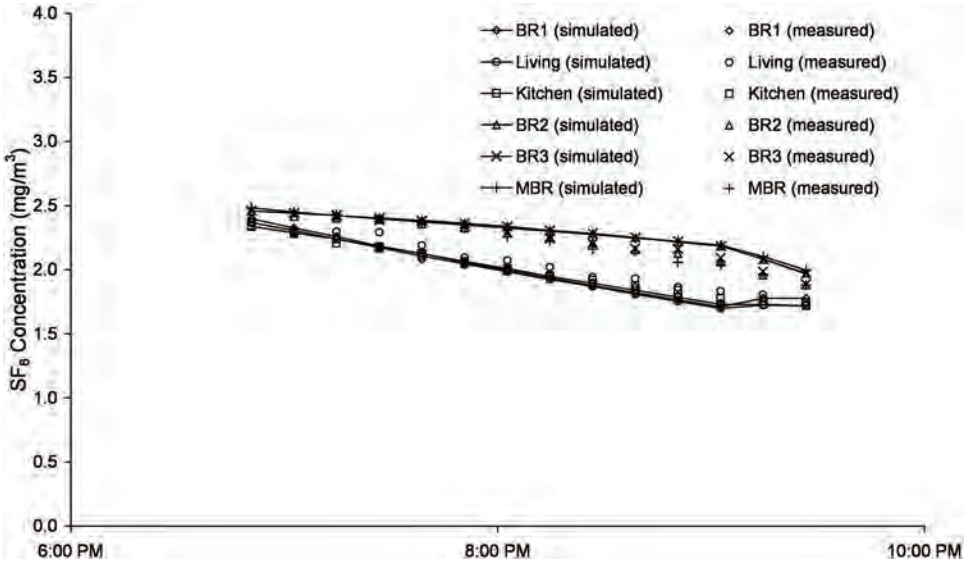

Figure 9 *Comparison of testing and modeling results for test 14 (natural infiltration).*

Table 7. ASTM D5157 Parameters for Test 14

ASTM D5157 Parameter	r	m	$b/\bar{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test Zone						
BR1	0.99	1.04	-0.04	0.00	0.00	0.05
Living	0.99	1.09	-0.13	0.00	-0.04	0.10
Kitchen	1.00	1.10	-0.10	0.00	-0.01	0.10
BR2	0.99	0.79	0.24	0.00	0.03	-0.22
BR3	0.99	0.80	0.22	0.00	0.02	-0.21
MBR	0.98	0.70	0.33	0.00	0.03	-0.33

climates. Certain systems will be more robust with regard to this error than others; for example a CFIS system which maintains a well-mixed condition within the house will be more robust than a single-point exhaust ventilation system with a radiant-heating system and therefore no AHU.

CONCLUSION

This work demonstrated that with detailed enclosure and room-to-room air leakage testing, a calibrated model can be created that replicates the results of tracer gas decay tests when appropriate environmental conditions are known. Agreement between the model and the tested results was closer for those cases where the house was mixed by operation of the AHU than when it was not mixed. Likewise, agreement was closer when ventilation rates were higher than when rates were lower or zero. Evaluation of the individual zone concentrations by ASTM D5157 showed generally adequate agreement between the predicted and observed data sets. Two of the seventeen tests showed at least one statistical parameter outside of the adequate ranges suggested by D5157. Finally, the calibrated model can be used to predict behavior of ventilation systems or strategies not installed or tested in the actual house; however caution must be taken so that the unknowns in the distribution of the enclosure leakage do not lead to unacceptably large error in the model's predictions.

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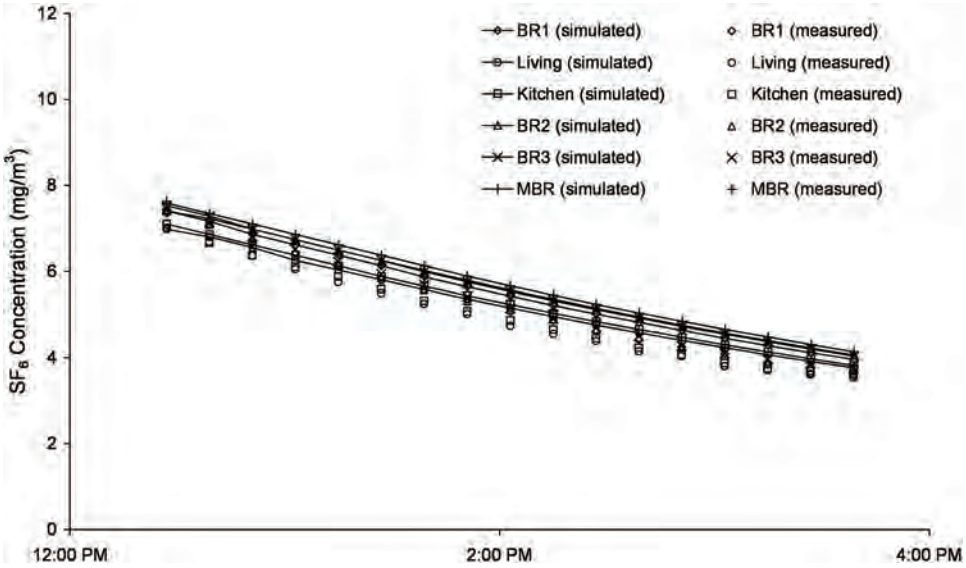

Figure 10 *Comparison of testing and modeling results for test 17 (AHU bump).*

Table 8. ASTM D5157 Parameters for Test 17

ASTM D5157 Parameter	r	m	$b/\bar{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test Zone						
BR1	1.00	0.90	0.15	0.00	0.06	-0.10
Living	1.00	0.92	0.14	0.00	0.06	-0.08
Kitchen	1.00	0.94	0.13	0.00	0.06	-0.06
BR2	1.00	0.89	0.18	0.01	0.07	-0.11
BR3	1.00	0.92	0.14	0.00	0.06	-0.08
MBR	1.00	0.88	0.17	0.00	0.05	-0.12

Table 9. ASTM D5157 Parameters for All Tests

ASTM D5157 Parameter	r	m	$b/\bar{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test 1: CFI Supply Test, Doors Closed, Transfer Grills Open, 95% of the 62.2 Rate						
BR1	1.00	0.90	0.15	0.00	0.06	-0.10
Living	1.00	0.92	0.14	0.00	0.06	-0.08
Kitchen	1.00	0.94	0.13	0.00	0.06	-0.06
BR2	1.00	0.89	0.18	0.01	0.07	-0.11
BR3	1.00	0.92	0.14	0.00	0.06	-0.08
MBR	1.00	0.88	0.17	0.00	0.05	-0.12
Test 2: CFI Supply Test, Doors Closed, Transfer Grills Open, 60% of the 62.2 Rate						
BR1	1.00	1.01	-0.01	0.00	-0.01	0.01
Living	1.00	0.98	0.04	0.00	0.01	-0.02
Kitchen	1.00	0.97	0.07	0.00	0.04	-0.03
BR2	1.00	0.95	0.08	0.00	0.04	-0.05
BR3	1.00	0.95	0.07	0.00	0.02	-0.05
MBR	1.00	0.95	0.06	0.00	0.01	-0.05
Test 3: CFI Supply Test, Doors Closed, Transfer Grills Open, 33% of the 62.2 Rate						
BR1	1.00	0.85	0.21	0.00	0.06	-0.16
Living	1.00	0.82	0.25	0.01	0.07	-0.19
Kitchen	1.00	0.83	0.26	0.01	0.08	-0.19
BR2	0.99	0.81	0.27	0.01	0.07	-0.21
BR3	1.00	0.82	0.25	0.01	0.06	-0.19
MBR	1.00	0.81	0.24	0.00	0.05	-0.20
Test 4: CFI Supply Test, Doors Closed, Transfer Grills Closed, 60% of the 62.2 Rate						
BR1	1.00	0.96	0.03	0.00	-0.01	-0.04
Living	1.00	0.98	0.04	0.00	0.02	-0.02
Kitchen	1.00	0.99	0.05	0.00	0.05	-0.01
BR2	1.00	0.97	0.07	0.00	0.04	-0.03
BR3	1.00	0.99	0.06	0.00	0.05	-0.01
MBR	1.00	0.97	0.04	0.00	0.01	-0.03
Test 5: Laundry Exhaust Test, AHU 20 Min. Off/10 Min On, Doors Closed, Transfer Grills Open						
BR1	1.00	0.96	0.05	0.00	0.02	-0.04
Living	1.00	0.95	0.08	0.00	0.03	-0.05
Kitchen	1.00	0.96	0.09	0.00	0.05	-0.04
BR2	1.00	0.96	0.05	0.00	0.01	-0.04
BR3	1.00	0.93	0.07	0.00	0.00	-0.07
MBR	1.00	0.92	0.05	0.00	-0.03	-0.08

Table 9. ASTM D5157 Parameters for All Tests *(continued)*

ASTM D5157 Parameter	r	m	$b/\bar{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test 6: Laundry Exhaust Test, AHU 25 Min. Off/5 Min On, Doors Closed, Transfer Grills Open						
BR1	1.00	1.02	0.05	0.00	0.06	0.02
Living	1.00	1.00	0.00	0.00	0.00	0.00
Kitchen	1.00	1.03	0.01	0.00	0.04	0.03
BR2	1.00	0.99	0.00	0.00	-0.02	-0.01
BR3	1.00	0.97	0.00	0.00	-0.03	-0.03
MBR	1.00	0.96	-0.06	0.01	-0.11	-0.04
Test 7: Laundry Exhaust Test, AHU 25 Min. Off/5 Min On, Doors Closed, Transfer Grills Closed						
BR1	1.00	1.02	-0.03	0.00	-0.01	0.02
Living	1.00	1.00	-0.01	0.00	-0.01	0.00
Kitchen	1.00	1.02	-0.03	0.00	-0.01	0.02
BR2	1.00	1.00	0.01	0.00	0.01	0.00
BR3	1.00	0.98	0.00	0.00	-0.02	-0.02
MBR	0.99	0.93	0.00	0.01	-0.08	-0.06
Test 8: Laundry Exhaust Test, AHU Off, Doors Open, Transfer Grills Open						
BR1	1.00	1.04	-0.06	0.00	-0.02	0.05
Living	0.99	1.04	-0.07	0.00	-0.03	0.04
Kitchen	1.00	1.03	-0.05	0.00	-0.02	0.04
BR2	1.00	0.94	0.05	0.00	-0.01	-0.06
BR3	1.00	0.98	0.00	0.00	-0.01	-0.01
MBR	1.00	0.93	0.07	0.00	0.00	-0.07
Test 9: Laundry Exhaust Test, AHU Off, Doors Closed, Transfer Grills Open						
BR1	1.00	1.02	-0.02	0.00	0.00	0.02
Living	1.00	0.96	0.04	0.00	0.01	-0.04
Kitchen	1.00	0.99	0.06	0.00	0.05	-0.01
BR2	1.00	0.95	0.07	0.00	0.03	-0.05
BR3	0.99	0.96	0.12	0.01	0.08	-0.03
MBR	1.00	0.96	0.04	0.00	0.00	-0.04
Test 10: Laundry Exhaust Test, AHU Off, Doors Closed, Transfer Grills Closed						
BR1	1.00	1.01	-0.03	0.00	-0.02	0.01
Living	1.00	1.00	-0.04	0.00	-0.04	0.00
Kitchen	1.00	1.04	-0.05	0.00	-0.01	0.04
BR2	0.99	0.91	0.13	0.01	0.04	-0.08
BR3	1.00	0.96	-0.02	0.00	-0.05	-0.03
MBR	0.98	0.97	-0.17	0.06	-0.22	-0.01

Table 9. ASTM D5157 Parameters for All Tests *(continued)*

ASTM D5157 Parameter	r	m	$b/\bar{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test 11: MBA Exhaust Test, AHU 25 Min. Off/5 Min On, Doors Closed, Transfer Grills Open						
BR1	1.00	1.07	-0.08	0.00	-0.01	0.07
Living	1.00	1.04	-0.08	0.00	-0.05	0.04
Kitchen	1.00	1.09	-0.11	0.00	-0.02	0.09
BR2	1.00	1.06	-0.08	0.00	-0.02	0.06
BR3	1.00	1.09	-0.12	0.00	-0.04	0.09
MBR	0.99	1.10	-0.20	0.01	-0.11	0.10
Test 12: MBA Exhaust Test, AHU Off, Doors Closed, Transfer Grills Open						
BR1	1.00	0.99	0.04	0.00	0.03	-0.01
Living	1.00	1.00	-0.04	0.00	-0.04	0.00
Kitchen	1.00	1.03	-0.03	0.00	0.00	0.03
BR2	1.00	1.00	-0.02	0.00	-0.02	0.01
BR3	0.99	0.87	0.17	0.01	0.04	-0.12
MBR	1.00	0.98	-0.09	0.01	-0.11	-0.01
Test 13: MBA Exhaust Test, AHU Off, Doors Closed, Transfer Grills Closed						
BR1	1.00	0.98	0.07	0.00	0.05	-0.02
Living	1.00	1.00	-0.03	0.00	-0.04	0.00
Kitchen	1.00	1.02	-0.01	0.00	0.01	0.02
BR2	0.99	0.97	-0.04	0.01	-0.07	-0.01
BR3	0.98	0.84	0.21	0.01	0.05	-0.16
MBR	1.00	0.97	-0.11	0.02	-0.15	-0.03
Test 14: Natural Infiltration Test, AHU Off, Doors Open, Transfer Grills Open						
BR1	0.99	1.04	-0.04	0.00	0.00	0.05
Living	0.99	1.09	-0.13	0.00	-0.04	0.10
Kitchen	1.00	1.10	-0.10	0.00	-0.01	0.10
BR2	0.99	0.79	0.24	0.00	0.03	-0.22
BR3	0.99	0.80	0.22	0.00	0.02	-0.21
MBR	0.98	0.70	0.33	0.00	0.03	-0.33
Test 15: Air Handler Bump Test, AHU On, Doors Open, Transfer Grills Open						
BR1	0.99	0.78	0.25	0.00	0.03	-0.24
Living	1.00	0.85	0.16	0.00	0.02	-0.16
Kitchen	1.00	0.91	0.10	0.00	0.01	-0.09
BR2	1.00	0.88	0.13	0.00	0.02	-0.12
BR3	1.00	0.87	0.14	0.00	0.01	-0.14
MBR	1.00	0.83	0.19	0.00	0.02	-0.19

Table 9. ASTM D5157 Parameters for All Tests *(continued)*

ASTM D5157 Parameter	r	m	$b/\bar{C}_o$	NMSE	FB	FS
ASTM D5157 "Adequate" Range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
Test 16: Air Handler Bump Test, AHU On, Doors Closed, Transfer Grills Open						
BR1	1.00	0.85	0.18	0.00	0.04	-0.15
Living	1.00	0.92	0.11	0.00	0.03	-0.08
Kitchen	1.00	0.87	0.16	0.00	0.03	-0.14
BR2	1.00	0.86	0.18	0.00	0.04	-0.15
BR3	1.00	0.88	0.15	0.00	0.03	-0.12
MBR	1.00	0.86	0.18	0.00	0.03	-0.15
Test 17: Air Handler Bump Test, AHU On, Doors Closed, Transfer Grills Closed						
BR1	1.00	0.90	0.15	0.00	0.06	-0.10
Living	1.00	0.92	0.14	0.00	0.06	-0.08
Kitchen	1.00	0.94	0.13	0.00	0.06	-0.06
BR2	1.00	0.89	0.18	0.01	0.07	-0.11
BR3	1.00	0.92	0.14	0.00	0.06	-0.08
MBR	1.00	0.88	0.17	0.00	0.05	-0.12

Table 10. Extension Cases Simulated

Case Number	Description
1	CFIS, AHU 20 min off/10 min on
2	Laundry exhaust, AHU 20 min off/10 min on
3	Laundry exhaust, AHU off
4	Balanced, AHU 20 min off/10 min on
5	Balanced, AHU off

Table 11. Effective Decay Rates of Extension Cases Simulated, 1/hr

Case	BR1	Living	Kitchen	BR2	BR3	MBR
1	0.21	0.20	0.20	0.20	0.20	0.20
2	0.16	0.16	0.16	0.15	0.15	0.15
3	0.19	0.16	0.16	0.07	0.09	0.14
4	0.23	0.23	0.23	0.24	0.23	0.21
5	0.40	0.27	0.26	0.37	0.34	0.15

the tracer gas testing, Collin Olson of The Energy Conservatory and Dave Bohac of the Minnesota Center for Energy and Environment for their help with detailed enclosure leakage testing, and finally Steven Emmerich, Stuart Dols, and George Walton at the National Institute of Standards and Technology for their assistance with the CONTAM software.

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APPENDIX

In order to provide a reasonable starting point for the calibration process, detailed enclosure and room-to-room air leakage testing was performed in another house located near and built by the same builder as the house tested in Hendron (2007). The substitute house was the same model as the house described in Hendron (2007), except the substitute house tested had two additional bedrooms and one additional bathroom on the second floor, for a total of six bedrooms and four bathrooms. The tests performed are listed in Table A-1. This testing provided a starting point for inputs to the CONTAM model. The testing, calculations, and resulting inputs are described below.

Test #1: Overall Enclosure Leakage

Overall enclosure leakage was measured by performing a standard multipoint blower door test. The large door between the garage and the outdoors was open during this test to prevent formation of a buffer zone in the garage. The following results were obtained: 1608 CFM50 (759 L/s at 50 Pa), C=124.4 (+/-1.8%) cfm/Pa^n, n=0.65. This test showed that the overall enclosure leakage of this house is similar to the house tested by Hendron, which was 1346 CFM50 (635 L/s at 50 Pa). The slightly larger leakage in the substitute test was not surprising due to the additional bedrooms and bathroom.

Test #2: Bedroom Enclosure Leakage

This test was performed similar to a duct-leakage-to-outside test. The house was brought to -50 Pa (0.2 in. of water) using the blower door, then one-by-one the bedroom leakages were measured using a duct pressurization fan and a blower door frame and shroud in the door to that room. For this test, all ducts and transfer grills were closed, and all doors except the zone being tested were opened. The measured room-by-room enclosure leakages and calculated flow coefficients are shown in Table A-2. The sum of the leakage measured in the bedrooms was 613 CFM50 (289 L/s at 50 Pa) or 38% of the total leakage of 1608 CFM50 (759 L/s at 50 Pa). The remainder of the leakage is assumed to be to the main living area of the house.

Test #3: Bedroom Leakage to Other Zones

This test was a qualitative measure of how much leakage there was between the bedroom zones. In this test, the house was first set up with all windows, bedroom doors, ducts, and transfer grills closed, and the house at -50 Pa (-0.2 in. of water). The pressure field in the house was measured, and then one at a time the windows in each bedroom were opened and the pressure field measured again. Because the blower door was not adjusted during the test, the overall house pressure changed when a bedroom window was opened; however since the house was still depressurized to at least -40 Pa (-0.16 in. of water) the ratio of pressure differences $\Delta P_{i,o}/\Delta P_{m,o}$ (where $\Delta P_{i,o}$ is the pressure difference from bedroom i to the outdoors and $\Delta P_{m,o}$ is the pressure difference from the main body of the house to outdoors) provides a sufficient qualitative indication of significant leakage pathways between bedrooms. For example, if the ratio of pressure differences for room A is changes significantly when room B's window is opened, that indicates that there is a significant leakage pathway between room A and room B. Table A-3 contains the results of this test. The results of the test show that each zone is isolated from the other zones. No zones showed changes in the ratio of pressure differences greater than 0.04 when another zone was opened to outside. This shows that the zones can be considered to leak only to the outdoors and the main living space when the ducts are not considered (since the ducts were taped over for this test).

Table A-1. Tests Performed on Substitute House

Test #	Test Description	Ducts	Transfer Grills	Bedroom Doors
1	Overall enclosure leakage	Open	Open	Open
2	Room-by-room enclosure leakage	Closed	Closed	Open
3	Room-by-room leakage to other rooms	Closed	Closed	Closed
4	Room-by-room leakage to main living space	Closed	Closed	Closed
5	Characterization of transfer grills	NA	NA	NA
6	Overall duct leakage	Closed	NA	Open
7	Duct leakage to outside	Closed	NA	Open

Table A-2. Results from Test 2

Room	Enclosure Leakage		Percentage of Total Leakage Area	Flow Coefficient, cfm/Pa^n	
Units	cfm at 0.2 in. of water	L/s at 50 Pa	Percent	cfm/Pa^n	L/s/Pa^n
Master BR	256	121	16%	20	9
Bedroom 1	65	31	4%	5	2
Bedroom 2	57	27	4%	4	2
Bedroom 3	60	28	4%	5	2
Bedroom 4	88	42	5%	7	3
Bedroom 5	87	41	5%	7	3
Main living space	995	470	62%	77	36
Total	1608	759	100%	124	59

Table A-3. Results from Test 3

		With this Zone Open to Outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Pressure with respect to outdoors, Pa	MBR	-35.6	0.0	-29.1	-31.2	-30.6	-31.6	-31.0
	BR1	-47.3	-39.0	0.1	-40.8	-40.6	-41.7	-40.3
	BR2	-45.1	-37.3	-35.9	-0.3	-37.7	-39.6	-38.5
	BR3	-45.5	-37.0	-36.3	-38.8	1.2	-40.1	-39.0
	BR4	-37.9	-31.0	-29.4	-32.4	-31.8	0.0	-30.6
	BR5	-42.9	-35.4	-34.2	-36.8	-36.4	-36.9	-0.7
	Main living space	-51.0	-42.1	-40.5	-43.9	-43.6	-44.9	-43.4
Pressure with respect to outdoors, in. of water	MBR	-0.143	0.000	-0.117	-0.125	-0.123	-0.127	-0.124
	BR1	-0.190	-0.157	0.000	-0.164	-0.163	-0.167	-0.162
	BR2	-0.181	-0.150	-0.144	-0.001	-0.151	-0.159	-0.155
	BR3	-0.183	-0.149	-0.146	-0.156	0.005	-0.161	-0.157
	BR4	-0.152	-0.124	-0.118	-0.130	-0.128	0.000	-0.123
	BR5	-0.172	-0.142	-0.137	-0.148	-0.146	-0.148	-0.003
	Main living space	-0.205	-0.169	-0.163	-0.176	-0.175	-0.180	-0.174
Ratio of pressure differences ($\Delta P_{i,o}/\Delta P_{m,o}$)	MBR	0.70	0.00	0.72	0.71	0.70	0.70	0.71
	BR1	0.93	0.93	0.00	0.93	0.93	0.93	0.93
	BR2	0.88	0.89	0.89	0.01	0.86	0.88	0.89
	BR3	0.89	0.88	0.90	0.88	-0.03	0.89	0.90
	BR4	0.74	0.74	0.73	0.74	0.73	0.00	0.71
	BR5	0.84	0.84	0.84	0.84	0.83	0.82	0.02
Difference from no zones open	MBR	NA	-0.70	0.02	0.01	0.00	0.01	0.02
	BR1	NA	0.00	-0.93	0.00	0.00	0.00	0.00
	BR2	NA	0.00	0.00	-0.88	-0.02	0.00	0.00
	BR3	NA	-0.01	0.00	-0.01	-0.92	0.00	0.01
	BR4	NA	-0.01	-0.02	-0.01	-0.01	-0.74	-0.04
	BR5	NA	0.00	0.00	0.00	-0.01	-0.02	-0.83

Test #4: Room-by-Room Leakage to Main Living Space

In this test, the house was taken to two different depressurization levels, with the doors, ducts, and transfer grills closed, and the pressure of the bedrooms with respect to the living space was recorded. The measured values are in Table A-4.

In this test, each room has a flow into it (from outdoors) and out of it (to the main living space), and these two flows are assumed to be equal. By using the flow equation twice (once for each flow), and using values previously established for the flow coefficient (C) (established in test #2) and pressure exponent (n) (established in test #1), the following system of equations results:

General flow equation:

$$Q = C \cdot (\Delta P)^n$$

where

Q = flow rate of air
C = flow coefficient
ΔP = pressure difference along the flow path
n = pressure exponent for the flow path

Apply the general flow equation to the exterior wall of a zone (the wall between the zone and the outdoors):

$$Q_o = C_o \cdot (\Delta P_o)^{n_o},$$

where the subscripts indicate that the value is for the flow from the outside.

Now apply the general flow equation to the interior wall of a zone (the wall between the zone and the main living space):

$$Q_i = C_i \cdot (\Delta P_i)^{n_i}$$

where the subscripts indicate that the value is for the flow to the inside.

Assuming these two flows are equal, we can then rearrange the equation to get:

$$C_i = (\Delta P_o)^{n_o} / (\Delta P_i)^{n_i} \cdot C_o$$

By using the previously-established values of C_o (from Table A-2) and n_o=0.65 for the exterior wall, we have two unknowns: C_i and n_i. By running the test at two different pressures (ΔP_o and ΔP_o'), we have two equations with two unknowns, and can solve the system of equations for n_i and then plug the value into the equation above to solve for C_i.

$$n_i = n_o \cdot \ln(\Delta P_o'/\Delta P_o)/\ln(\Delta P_i'/\Delta P_i) \quad \text{(A-1)}$$

By applying this system to each of the bedrooms, C_o and n_i were found for leakage between the zone and the main living space. Table A-5 shows the results. The values for n_i are near 0.5, which is the value for orifice flow and the theoretical minimum value for n in the general flow equation. This makes sense, since the dominant leakage path between the bedrooms and main living space is usually the door, particularly the door undercut. The differences between the flow coefficients are due to the door width, undercut dimension, and flooring type present under each door. The master bedroom has a 3 ft (0.91 m) wide door, where the other bedrooms have 2.5 ft (0.76 m) wide doors. The door undercuts are 0.5 +/- 0.125 in. (12.7 +/- 3.2 mm). Additionally, all of the bedrooms have carpet flooring, but bedroom 1 is adjacent to a living space with wood flooring, which allows more air to flow through the door undercut.

Several of the values for n_i are lower than the 0.5 theoretical minimum. This can be explained by a simple error analysis. Each of the parameters in Equation A-1 has an associated error value. In particular, the calculated value for n_i is sensitive to the assumed value for n_o (which was measured for the whole house but not for the individual bedrooms) and the measured ΔP_i (which is small relative to the accuracy of the instrument). Estimated errors in either of these parameters explain the calculated values of n_i below the theoretical minimum of 0.5. Table A-6 contains the estimate error for each parameter and recalculated values for the calculated pressure exponent n_i for Bedroom 3.

Table A-4. Measured Values for Test 4

Room	Pressure wrt Living Space (Pa)		Pressure wrt Living Space (in. of water)	
	with house at -15 Pa	with house at -51 Pa	with house at -0.06 in. of water	with house at -0.2 in. of water
Master BR	+3.4	+15.4	+0.014	+0.062
Bedroom 1	+0.8	+3.7	+0.003	+0.015
Bedroom 2	+1.2	+5.9	+0.005	+0.024
Bedroom 3	+1.1	+5.5	+0.004	+0.022
Bedroom 4	+3.2	+13.1	+0.013	+0.053
Bedroom 5	+1.7	+8.1	+0.007	+0.033

Table A-5. Results from Test 4

Room	Flow Coefficient, C_i		Pressure Exponent, n_i
Units	cfm/Pa^n	L/s/Pa^n	Unitless
Master BR	54.3	25.6	0.49
Bedroom 1	32.0	15.1	0.51
Bedroom 2	22.5	10.6	0.49
Bedroom 3	24.8	11.7	0.48
Bedroom 4	18.2	8.6	0.54
Bedroom 5	28.2	13.3	0.49

Table A-6. Error Analysis for Test 4

Parameter (x)	Estimated Error (Ɛ)	$n_i = f(x)$	$n_i = f(x - Ɛ)$	$n_i = f(x + Ɛ)$
ΔP_o	0.2 Pa*	0.48	0.49	0.48
ΔP_o'	0.2 Pa	0.48	0.48	0.48
ΔP_i	0.2 Pa	0.48	0.43	0.54
ΔP_i'	0.2 Pa	0.48	0.49	0.47
n_o	0.05	0.48	0.45	0.52

*0.2 Pa = 0.0008 in. of water

Table A-7. Results from Test 5

Transfer Grill Location	Flow Coefficient, C		Flow Exponent, n
Units	cfm/Pa^n	L/s/Pa^n	Unitless
Master Bedroom	61	29	0.52
Other Bedrooms	27	13	0.53

Test #5: Transfer Grill Characterization

This test was intended to determine the pressure-flow characteristics of the transfer grills installed in this house. The transfer grills in the bedrooms other than the master bedroom consisted of a louvered grill on either side of the wall above the bedroom door and are intended to provide a return air path when the AHU is on and the bedroom door is closed. The gross area of each grill is approximately 5.5 in. by 9.5 in. (0.14 m by 0.24 m), with approximately 50% open area. The master bedroom transfer grill is in a chase that extends the full height of the wall. The gross grill size is approximately 13.5 in. by 9.5 in. (0.34 m by 0.24 m), with approximately 50% open area.

In order to determine the flow characteristics, a cardboard box was fixed on one side of a transfer grill, with the duct pressurization fan and duct exhausting air out of the box. The flow was measured at several pressure differentials across the grill, and the results are shown in Table A-7.

Test #6: Overall Duct Leakage

Overall duct leakage was measured using the duct pressurization fan exhausting from the return grill. The total leakage at 25 Pascals (0.1 in. of water) was 63 cfm (30 L/s), approximately 4% of the design AHU flow of 1600 cfm (755 L/s) and 6% of the measured supply flow of 1010 cfm (477 L/s).

Test #7: Duct Leakage to Outside

A duct leakage to outside test was performed by depressurizing the house to -25 Pa (0.1 in. of water). With the duct pressurization fan off, the pressure in the return with respect to the house was only +0.2 Pa (0.0008 in. of water). The duct leakage to outside was significantly below 20 cfm (9.4 L/s), the lowest measurable flow of the duct pressurization fan.

About this Paper

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