MN-00-10-3

Measurement of Ventilation and Interzonal Distribution in Single-Family Homes

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ABSTRACT

Ventilation air change rate, local mean age-of-air, and interzonal ventilation air distribution were measured for two single-family homes and eight ventilation systems. A multi-zone, single-gas, tracer gas decay measurement technique was used. A single-story, slab-on-grade, 1350 ft^2 house was tested in Las Vegas, Nevada, and a two-story, 3192 ft^2 house with basement was tested in Minneapolis, Minnesota. The ventilation systems studied included various configurations of exhaust, supply, and balanced ventilation, with and without whole-house recirculation by the central heating and cooling air-handler unit fan. Some of the systems were independent of the central air distribution system, while others were integrated with it. In general, results showed that all ventilation systems benefitted from periodic operation of the central fan, giving excellent uniformity of ventilation air distribution. Systems without central fan recirculation showed poor ventilation air distribution for closed rooms where there was no ventilation system duct.

INTRODUCTION

Supply ventilation systems draw outside air from a known location and deliver it to the interior living space. This known location should be selected to maximize the ventilation air quality. The ventilation air can be treated before distribution to the living space (i.e., one or more of being heated, cooled, dehumidified, filtered, cleaned). If supply ventilation air is not preconditioned, it should be mixed with recirculated indoor air to mitigate discomfort effects of the outside air and prevent condensation. In cold climates, to prevent condensation on ventilation supply registers, the mixing ratio should be a minimum of two parts inside air with one part outside air, based on −10°F outdoor dry-bulb temperature, 68°F indoor dry-bulb temperature, and 42°F indoor dew-point temperature. Supply ventilation will tend to pressurize an interior space relative to the outdoors, causing inside air to be forced out through leakage openings located randomly throughout the building envelope. This strategy is advantageous in warm-humid climates to minimize moisture entry into the building structure from outdoors.

Exhaust ventilation systems expel inside air to the outdoors, tending to depressurize an interior space relative to the outdoors, inducing infiltration. This strategy can be advantageous in climates with cold winters but should not be used in hot-humid climates. In mechanically cooled buildings in hot-humid climates, if interior negative pressure causes moisture-laden outdoor air to enter the building envelope, moisture can condense on cool surfaces, and, if restricted from drying to the inside, problems of material durability and indoor air quality can result. Exhaust ventilation systems in all climatic zones draw outside air from leakage openings and pathways located randomly throughout the building envelope; thus, it is not possible to treat the outside air before it enters the living space. The “ventilation” air could be fresh and healthy or it could be coming from locations with high pollutant concentrations. For example, ventilation air drawn from a garage, crawl space, basement sump, or from underneath a concrete slab may induce entry of fuel vapors, combustion gases, insecticides, radon gas, excessive water vapor, and fungal or mold spores.

Balanced ventilation systems exhaust inside air to the outdoors and supply outside air to indoors. Balanced ventilation, by definition, should not affect the pressure of an interior space relative to the outdoors, although in reality there may never be a true balance due to pressure fluctuations from wind,

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buoyancy forces (stack effect), and air conveyance system forces. This ventilation strategy can be used effectively in any climate. It is possible to filter or condition the ventilation air before it enters the living space.

Ventilation systems can be powered and ducted in many different ways. How the system is powered will affect both first cost and operating cost. How the system is ducted will affect first cost and the ability of the system to distribute ventilation air uniformly to all occupied spaces. For example, ventilation systems that utilize an existing central heating and cooling system's air-handler unit fan and ducts have low additional first cost and provide excellent ventilation air distribution but have relatively higher operating cost. Systems that utilize smaller, separate fans and ducts, and achieve comparable whole-house ventilation air distribution, have a relatively high first cost but lower operating cost. Table 1 shows a general matrix of the advantages and disadvantages of various generic ventilation systems. The term "fully ducted" denotes ducts extending from the air conveyance device to all bedrooms, to other habitable conditioned rooms with doors, and to the common areas. A ventilation system that was not fully ducted would be one where habitable and conditioned rooms were isolated from the ventilation system.

Because of the many ventilation system configurations available, and because of the significant differences in cost and performance, choosing between ventilation systems can be a complex task. Field testing was performed to help quantify performance characteristics to develop guidelines related to cost and performance.

The focus of this study was to evaluate the effectiveness of different ventilation systems in providing design ventilation rates and uniform distribution of ventilation air.

TEST SETUP AND INITIAL MEASUREMENTS

Las Vegas, Nevada

Two ventilation systems were installed in the same 1350 ft^2 house, in Las Vegas, Nevada, to individually evaluate their effectiveness in providing adequate air change rates and uniform distribution of outside air throughout the house. The house was a three-bedroom, two-bath, one-story wood frame with slab-on-grade foundation and attached two-car garage. The entire air distribution system for the central heating and cooling system was inside the conditioned space, within the thermal and air boundary of the unvented, "cathedralized" attic, wherein the insulation is installed directly below the roof sheathing instead of above the ceiling gypsum board (Rudd and Lstiburek 1998). This configuration eliminates air distribution system losses to the outside. To ensure adequate air distribution within the building envelope, total duct leakage should be limited to 10% of the system flow.

TABLE 1
Matrix of Advantages and Disadvantages of Ventilation Systems

System Type	First Cost	Operating Cost	Distribution Effectiveness	Confidence in Quality of Ventilation Air
Central-fan-integrated				
Central-fan-integrated, supply	low	med-high	high	high
Central-fan-integrated, balanced	med	med-high	high	high
Exhaust				
Upgraded bathroom exhaust fan	low	low	low	low
New exhaust fan, not fully ducted, without central fan recirculation	med	low	low	low
New exhaust fan, not fully ducted, with central fan recirculation	med	med-high	high	low
New exhaust fan, fully ducted	high	low	high	low
Supply				
New supply fan, not fully ducted, without central fan recirculation	med	low	low	high
New supply fan, not fully ducted, with central fan recirculation	med	med-high	high	high
New supply fan, fully ducted	high	low	high	high
Balanced				
New balanced fans, not fully ducted, without central fan recirculation	med-high	med	low	high
New balanced fans, not fully ducted, with central fan recirculation	med-high	med-high	high	high
New balanced fans, fully ducted	high	med	high	high

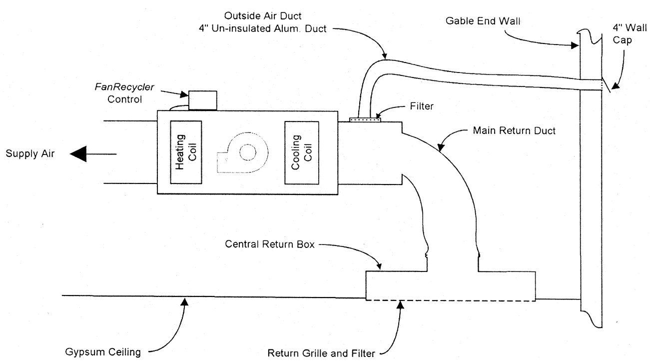

Figure 1 *Schematic of central-fan-integrated supply ventilation as installed in the house tested.*

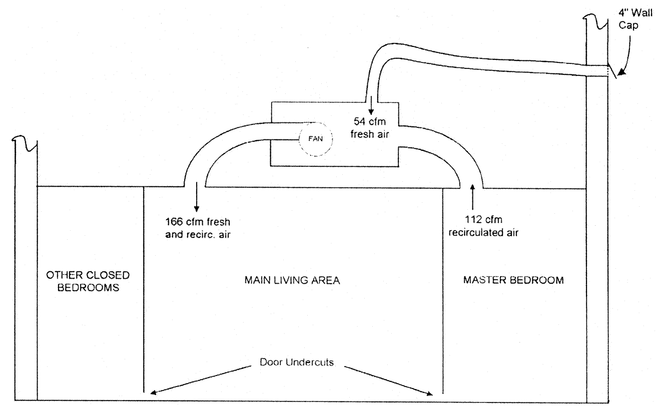

Figure 2 *Schematic of the separate supply ventilation system installed in the house tested.*

The first ventilation system tested was central-fan-integrated supply ventilation (Rudd 1998), wherein outside air was ducted from a high wall location on the building exterior to the return air side of the central heating and cooling system fan. This system utilized the existing central heating and cooling system's ducts and fan, located inside conditioned space, to distribute ventilation air and conditioned air at the same time. A fan recycling control (*ACH&R News* 1998; *Builder* 1998; *EDU* 1997, 2000) was used to cycle the central fan periodically to distribute ventilation air and provide whole-house mixing during periods when the central fan was inactive (i.e., no thermostat demand for heating or cooling). A schematic of the central-fan-integrated supply ventilation system installed in the test house is shown in Figure 1. The outside air duct was a four-inch-diameter expanded aluminum duct connected to a four-inch wall cap at the exterior wall and connected to the return plenum of the central heating and cooling air-handler unit through a transition box that held a standard 12-by-12-in. furnace filter. The outside air duct installed in this house was undersized according to the original design, allowing only 47 ft^3/min through the four-inch duct. The target outside airflow for this house was 80 ft^3/min, calculated by Equation 1 (Rudd 1998) and the following given parameters:

- 40 ft^3/min continuous ventilation required for the occupants of the three-bedroom house
- 33% central fan duty cycle
- 0.10 air changes per hour in between central fan cycles
- house volume of 12,150 ft^3

$$\dot{Q}_{cfan} = \frac{(\dot{Q}_{cont}) - \left[\frac{I}{60}V(1-f)\right]}{f} \qquad (1)$$

where

$\dot{Q}_{cfan}$ = intermittent outside airflow rate through the central fan (ft^3/min)

$\dot{Q}_{cont}$ = continuous outside airflow rate required (ft^3/min)

I = estimate of natural air change when central fan is not operating (h^{-1})

V = volume of conditioned space (ft^3)

f = fan duty cycle fraction

The actual outside airflow was measured two ways, using a calibrated fan and a hot-wire anemometer traverse. The pressure in the outside air duct was –52 Pa with respect to the outdoors. To achieve the target 80 ft^3/min of outside air with this configuration, a five-inch-diameter insulated flex duct with a six-inch wall cap and a balancing damper should have been used. Outside air duct pressure should have been adjusted with the balancing damper to obtain –30 Pa upstream of the balancing damper. A number of configurations have been used to conduct outside air to the air handler return for effective airflow and filter access. Recommendations are given in a later section of this paper.

The second system was a separate supply ventilation system, not connected to the central air distribution ducts, wherein a separate fan drew 54 ft^3/min of outside air and 112 ft^3/min of inside air from the master bedroom and delivered the 166 ft^3/min of mixed air to the main living area of the house. Figure 2 shows a schematic of this system. The flows used followed a 1:2 ratio of outside air to recirculated air, based on the existing outside airflow of the central-fan-integrated system. Airflows were measured and balanced using a calibrated fan and velocity probe. Recirculated inside air was drawn from the master bedroom instead of the main living area to test the hypothesis that fresher air from the main living area would tend to move back to the master bedroom to replace the recirculated air. Depending on the house layout, this would likely raise the system's first cost but far less than a fully ducted separate system.

Air change rate and ventilation air distribution effectiveness were measured using a computer-controlled multi-zone gas analyzer. Sulfur hexafluoride (SF_6) was the tracer gas. The gas analyzer was programmed to measure SF_6 concentration at approximately two-minute intervals in six locations (zones): southeast bedroom, southwest bedroom, main living

TABLE 2
Airflow Rate Measurements (ft^3/min) for the Blending Ventilator

	Central AHU Fan OFF		Central AHU Fan ON	
	Flow Grid	Calibrated Fan	Flow Grid	Calibrated Fan
Outside air intake	47		56	
Exhaust air	70	70	56	60
Recirculated house air	188			

area hall, living room, master bedroom, and master bathroom. During the testing, all interior doors were closed to represent overnight sleeping conditions. It is during this time that effective distribution of ventilation air is most needed. Small box fans or oscillating fans were used to achieve well-mixed conditions inside each individual zone.

Minneapolis, Minnesota

Six different ventilation strategies were tested in a new 3192 ft^2 home near Minneapolis, Minnesota. The testing occurred on 14-16 December 1998. The construction was a 4-bedroom, 2.5-bath, 2-story wood frame with basement, and attached 3-car garage. The building air leakage and air distribution duct leakage characteristics were measured by fan pressurization tests (Nelson 1999). Building air leakage was 734 ft^3/min at 50 Pa pressure differential, which translated to 1.63 air changes per hour at 50 Pa, and the effective leakage area was 32.2 in.^{2} at 4 Pa pressure differential. All air distribution ducts were inside conditioned space. Total duct leakage (supply and return both to inside and outside) and duct leakage to outdoors was 227 ft^3/min and 44 ft^3/min, respectively, at 25 Pa pressure differential.

In order to evaluate only the differences between ventilation systems, other systems in the house were isolated as much as possible. The bathroom and kitchen exhausts were not used. The dryer vent was sealed off. The gas-fired domestic hot water heater and the gas furnace were shut off during testing, and combustion air inlets were sealed. The house was heated by portable electric heaters spaced around the house. The heaters were computer controlled based on a representative temperature measurement for each heater, and space temperature was controlled to within 1°F.

The first of six different ventilation systems tested was a single-point exhaust system. The exhaust fan was a continuous-duty-rated, bathroom-type fan located in the ceiling of the second-story hall. The exhaust fan was controlled by a standard line voltage wall switch. The rated power draw of the exhaust fan was 17.4 W. The manufacturer's rated flow of 90 ft^3/min was slightly higher than the average measurement of 83 ft^3/min, measured by calibrated fan, calibrated flow box, flow hood, and on/off house depressurization with measured leakage curve (Nelson 1999). For ventilation testing, no timer or speed control was used, and the fan was operated continuously at maximum speed.

The second ventilation system tested included the continuous single-point exhaust system with periodic whole-house mixing by the central heating and cooling system's air-handler unit (AHU) fan. The central fan was operated by a fan recycling control that causes the fan to operate for a period of time if it has been inactive for a period of time. This system was tested at three levels of time intervals for fan recycling: (a) 20 minutes off, 10 minutes on (33% duty cycle); (b) 35 minutes off, 10 minutes on (22% duty cycle); and (c) 50 minutes off, 10 minutes on (17% duty cycle).

The third ventilation system tested was a continuously operated blending ventilator unit. This unit had a single fan that drew in outside air, blended it with inside air, and exhausted some of the mixed air to outside while supplying the balance to the return air plenum of the central heating and cooling system. The rated power draw of the blending ventilator was 136 W. The manufacturer rates the outside air intake and exhaust flows at 60 ft^3/min and the house return and supply air at 180 ft^3/min. Since this system was connected to the central air distribution system, airflow measurements were made with the central fan on and off. The flow rate measurements were made by in-line flow grid and calibrated fan. Table 2 shows the measured results.

Measurements were made to determine the extent of outside air delivered to the house by the blending ventilator. Tracer gas concentration measurements were made in the two inlet and the two outlet ducts of the ventilator. Table 3 shows these measurements along with the airflow rates. The ratio of tracer gas concentration in the exhaust air to return air gives the fraction of return air that is in the exhaust air. The amount of outside air in the exhaust is then found by subtraction. Likewise, the ratio of tracer gas concentration in the supply air to return air gives the fraction of return air that was in the supply air. Using the measured airflow rates and fractions, the quantity of outside air in the exhaust and supply airstreams was calculated. Checking the final airflow balance, the sum of the outside air quantities in the exhaust and supply airstreams was equal to the measured airflow rate in the outside air inlet. By this analysis, only 24 ft^3/min of outside air, out of 47 ft^3/min, was actually delivered to the house.

The fourth ventilation system included the continuously operated blending ventilator with periodic whole-house mixing by the central heating and cooling system's air-handler unit fan via the fan recycling control. This system was tested

TABLE 3
Measurements and Results of Outside Air Delivered to House by Blending Ventilator

Duct Description	Measured Gas Concentration (ppm)	Measured Airflow Rate (ft^3/min)	Outside Air Fraction and Flow Rate
Outside air inlet	0	47	
Return air inlet	1.75	188	
Supply outlet	1.40	122	0.20; 24 ft^3/min
Exhaust outlet	1.18	70	0.326; 23 ft^3/min

at two levels of time intervals for fan recycling: (a) 20 minutes off, 10 minutes on, and (b) 50 minutes off, 10 minutes on.

The fifth ventilation system was continuously operated central-fan-integrated supply ventilation. Use of an efficient ECM (electronically commutated motor) fan would lower the operating cost of this system. The system included an eight-inch-diameter insulated flexible duct connected from an outside air inlet to the central air-handler unit return plenum. A balancing damper allowed airflow rate adjustment. An outside airflow rate of 70 ft^3/min was selected to give an 8% outside air fraction. The outside airflow rate was measured by in-line flow grid. The air-handler unit had a four-speed fan that was factory set to the medium-low speed. This speed was not changed during testing of the ventilation systems. The total airflow rate, measured by Nelson (1999), and power draw were measured for each speed. Table 4 shows the measured results.

Return plenum static pressure measured –100 Pa, and supply plenum static pressure measured +20 Pa, with respect to the basement. Assuming a pressure drop of 50 Pa for the cooling coil and furnace heat exchanger, the external static pressure for the air-handler fan was 170 Pa (0.68 in. w.c.). That exceeded the fan's rated external static pressure of 125 Pa (0.5 in. w.c.). The high external static pressure was caused by undersized ducts (Nelson 1999).

The sixth ventilation system included periodic central-fan-integrated supply ventilation with continuous exhaust. The central fan was operated at intervals of 20 minutes off and 10 minutes on. The total ventilation system was balanced during times when the central air-handler unit fan was operating, drawing in outdoor air from a known location. This system allows the designer to know where the ventilation air is coming from at least part of the time and would be especially beneficial for colder climates.

Air change rate and ventilation air distribution effectiveness were evaluated using tracer-gas concentration decay measurements made by a computer-controlled multi-zone gas analyzer. Sulfur hexafluoride (SF_6) was the tracer gas. The gas analyzer was programmed to measure the SF_6 concentration at approximately two-minute intervals in six locations: basement, open stairwell between first and second floor, northwest bedroom, southwest bedroom, master bedroom, and northeast bedroom. During the testing, all interior doors were closed to represent sleeping conditions. It is during that time that effective distribution of ventilation air is most needed. Small box fans or oscillating fans were used to achieve well-mixed conditions inside each individual zone. The doors were reopened between tests when whole-house air recirculation was needed to achieve uniform tracer gas concentrations before starting the next test.

TABLE 4
Airflow Rate and Power Draw Characteristics of Central Air-Handler Unit

Fan Speed	Power (VA)	Airflow Rate (ft^3/min)	Normalized Power (VA/ft^3/min)
Low	300	875	0.34
Med-Low	324	900	0.36
Med-High	372	910	0.41
High	504	940	0.54

TESTING SEQUENCE, ANALYSIS AND RESULTS

The houses were not analyzed as a single zone but were broken up into six zones, which was the number of sampling channels available with the gas analyzer. The six zones included the central common area and rooms that could be isolated from the common area with doors. Before each test, a known volume of tracer-gas was injected into the return side of the central air distribution system and mixed to a uniform concentration throughout all the zones. At that time, doors to the individual zones were closed, and the tracer-gas concentration decay was monitored while mixing fans inside the zones kept conditions well mixed. In essence, we started with a house that had no pollutant (tracer gas) and no source of that pollutant, then injected that pollutant and mixed it to a uniform concentration throughout the house, then closed doors to split the house into multiple zones that were weakly coupled to each other by unintended leakage areas in the construction and strongly coupled to each other through a central heating and cooling air distribution duct system. The central air distribution system was sometimes an active part of the different ventilation systems (i.e., blower operation) and sometimes not, but it was always available as a passive part of the different ventilation systems (i.e., open ducts but no blower operation). Because of the multiple zone condition, it was not possible to distinguish between dilution of tracer gas due to outside air directly supplied to the zone and that supplied indirectly to the zone via another zone, but all of the outside air was accounted for (Persily 1993). In the concentration-decay technique, outside air supplied by the ventilation system is lumped with outside air supplied by infiltration. Several tests were conducted to establish a baseline air change rate due to natural air infiltration only, which was always low (on the order of five to ten times less) compared to that with ventilation and infiltration lumped together.

Calculation of local mean age-of-air gives the time elapsed since a measured volume of inside air has come from outdoors. Intuitively, air that has stayed resident indoors for a longer period of time can be thought to have lower air quality due to a potentially higher concentration of indoor pollutants being generated. Local mean age-of-air was calculated according to Equation 2 (Grieve 1991) using the first moment method (Sandberg and Sjöberg 1983) from the tracer gas concentration-decay data for each zone. This experimental and analytical technique was also used by Sakaguchi and Akabayashi (1998) for a similar study in Japan. If the zone air is perfectly mixed, local mean age-of-air will be equal to the room-average age of air (Grieve 1991) and will be the inverse of the air change rate (Persily 1993). In this study, small box fans and oscillating fans were used to achieve well-mixed conditions inside each individual zone.

$$\langle\bar{\tau}\rangle = \frac{\left(\frac{1}{8}C_o \cdot \Delta\tau^2 + \frac{1}{2}C_M \cdot \Delta\tau \cdot \tau_M + \sum_{j=1}^{M-1} C_j \cdot \tau_j \cdot \Delta\tau\right) + \left(\frac{C_M}{\lambda_{\exp}}\left(\tau_M + \frac{1}{\lambda_{\exp}}\right)\right)}{\left(\frac{1}{2}(C_o + C_M) \cdot \Delta\tau + \sum_{j=1}^{M-1} C_j \cdot \Delta\tau\right) + \left(\frac{C_M}{\lambda_{\exp}}\right)} \tag{2}$$

where

C_o = initial concentration measured,

C_j = concentration measurement j,

C_M = final concentration measured,

M = total number of measurements,

$\Delta\tau$ = sampling interval,

λ_{exp} = slope of ln(C) versus time in the exponential decay region,

τ_j = time of measurement j,

τ_M = total measuring time,

According to the well-known tracer-gas concentration decay analysis technique for steady-state, well-mixed, single-zone measurements, the room air change rate is given by (ASTM 1993)

$$I = \frac{\ln(C_f/C_o)}{t} \tag{3}$$

		Air Change Rate (h -1) Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Natural infiltration		0.03	0.01	0.06	-70	80
Continuous central-fan-integrated supply ventilation		0.34	0.33	0.34	-1	1
Periodic central-fan-integrated supply ventilation		0.10	0.10	0.11	-3	6
Blending supply ventilation	Test 1	0.21	0.09	0.25	-56	21
	Test 2	0.15	0.10	0.20	-32	36
	avg:	0.18	0.10	0.23	-44	29

Figure 3 *Measured air change rate results for the Las Vegas house.*

where

I = air change rate (h^{-1}),

C_f = final concentration (ppm),

C_o = initial concentration (ppm),

t = time period between initial and final concentration measurements (h).

Although application of Equation 3 to this work is not theoretically pure—because Equation 3 is derived for a single zone—it can yet be useful and practical for obtaining good answers as to the relative differences in ventilation air distribution effectiveness of the different systems. While it should be understood that the air change rate for each zone includes direct and indirect introduction of outside air and that under lived-in conditions, pollutant removal may be slower due to pollutant generation (Sherman 1999). In this study, the air change rate calculated as the inverse of the local mean age-of-air was always within 5% of the air change rate calculated by Equation 3 for all the tests and all the rooms.

For the purposes of evaluating the effectiveness of ventilation air distribution between all rooms of the house, we selected a range of ±25% about the mean for air change rate and age-of-air to represent acceptable ventilation air distribution.

Las Vegas, Nevada

Figure 3 shows the air change rate results for tests of the central-fan-integrated supply ventilation system and the separate blending supply ventilation system.

Testing occurred between 8 and 10 August 1998. To begin testing, the central heating and cooling system fan was turned on and SF_6 tracer gas was released into the return air grille. As the fan continued to operate, the tracer gas was mixed throughout the house until, after about 45 minutes, a uniform concentration of about 4 parts per million (ppm) was reached.

At this point, the first test period for the central-fan-integrated supply ventilation system began. With the central fan operating constantly and the outside air duct open, a very uniform air change rate of between 0.33 and 0.34 was achieved in all six of the monitored spaces.

Natural infiltration was measured next to provide a baseline for comparison to the ventilation systems. Natural infil-

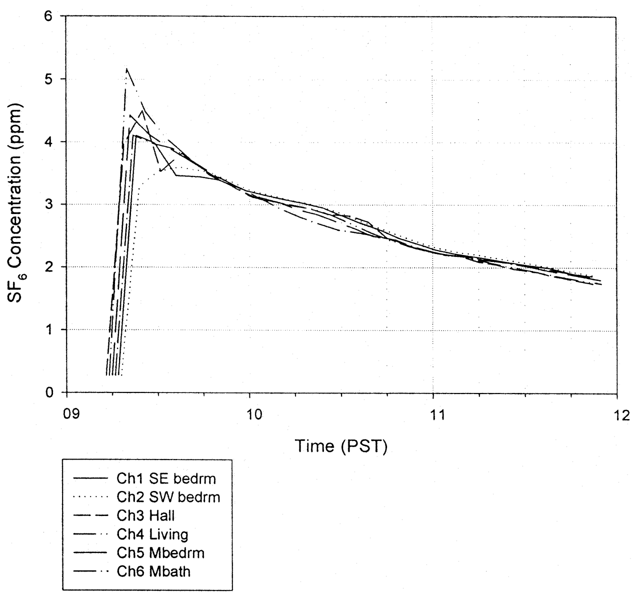

Figure 4 *Tracer gas injection into outside air inlet of central-fan-integrated supply ventilation system showing how uniformly ventilation air is distributed throughout the house.*

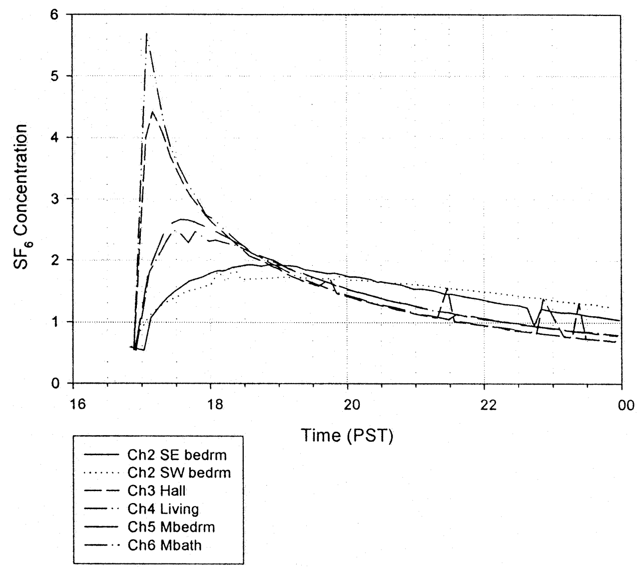

Figure 5 *Tracer gas injection into outside air inlet of the separate supply ventilation system showing how non-uniformly ventilation air is distributed throughout the house.*

tration was very low, between 0.01 and 0.06, and not very uniform across the six zones. Within both of the two zones where more than one sample point was taken, the air change rate was consistent. The master bedroom and master bath, which were one zone, had the lowest air change rate (0.01), similar to the southwest bedroom (0.02). The main living area zone, which was represented by the hall and living room sampling locations, had the highest air change rate (0.05 to 0.06) along with the southeast bedroom (0.05).

The second central-fan-integrated ventilation test represented normal operating conditions. The cooling system was set to operate normally, and the fan recycling control was set to operate the fan for 10 minutes if it had not operated for 20 minutes, giving a guaranteed 33% duty cycle. During this 12.46-hour test period (overnight), the air change rate averaged between 0.10 and 0.11 for all of the monitored locations. Very uniform distribution of ventilation air was achieved with the central fan operating one-third of the time. However, the volume of ventilation airflow was lower than desired due to an undersized outside air duct.

Before the beginning of the separate supply ventilation system tests, tracer gas was again injected into the house with the central fan operating continuously. However, this time it was not injected into the central return but into the outside air duct inlet on the exterior of the building. Referring to Figure 4, plotting of the tracer gas growth in all six monitored locations qualitatively shows how uniformly ventilation air is distributed with the central-fan-integrated ventilation system.

Once the tracer gas concentration was uniform throughout the house, the first of the separate supply ventilation system tests was begun. The outside air duct to the return air side of the central fan was sealed off. The central fan was disabled. The separate supply fan was turned on, drawing 54 ft^3/min from outdoors and 112 ft^3/min from the master bedroom and supplying the resulting 166 ft^3/min of mixed air to the main living area. These airflow rates were measured by calibrated fan and hot wire anemometer traverse. Air change rates varied widely between the six monitored locations, from 0.09 to 0.25 ach. The master bedroom, master bathroom, hall, and living room locations all averaged closely between 0.23 and 0.25, showing that drawing recirculated air from the master bedroom zone did indeed induce outside air distribution to that zone. However, the southeast and southwest bedrooms received inadequate outside air as evidenced by the much lower air change rates, 0.19 and 0.09, respectively.

Next, the central cooling system was enabled and the central fan was set to operate continuously. This allowed cooling of the house while also reaveraging the tracer concentration throughout the house. The beneficial effect of central fan operation along with the separate supply ventilation fan operation became obvious. The redistribution of tracer gas caused a large air change in the two bedrooms that had been starved for outside air.

To begin the last test of the separate supply ventilation system, central fan operation was disabled. Tracer gas was then injected into the outside air inlet of the separate supply ventilation fan. Referring to Figure 5, a plot of the tracer gas growth in all six monitored locations graphically shows how

		Air Change Rate (h^{-1})				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Natural infiltration	Test 1	0.07	0.06	0.12	-22	58
	Test 2	0.07	0.04	0.14	-38	104
	Test 3	0.06	0.02	0.13	-60	104
	avg:	0.07	0.04	0.13	-40	89
		Age-of-Air (h)				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
	Test 1	14.0	8.3	16.9	-41	20
	Test 2	16.7	6.9	22.9	-59	37
	Test 3	23.9	7.9	40.7	-67	70
	avg:	18.2	7.7	26.8	-56	43

Figure 6 *Natural infiltration testing results.*

		Air Change Rate (h^{-1})				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Continuous exhaust		0.22	0.12	0.28	-47	28
		Age-of-Air (h)				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
		4.9	3.4	8.5	-30	72

		Air Change Rate (h^{-1})				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Continuous exhaust with periodic AHU mixing	Test 1	0.23	0.21	0.26	-10	13
	Test 2	0.20	0.15	0.22	-21	15
	Test 3	0.21	0.19	0.21	-7	3
	avg:	0.21	0.19	0.23	-13	11
		Age-of-Air (h)				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
	Test 1	4.2	3.7	4.6	-12	9
	Test 2	5.1	4.3	6.3	-14	25
	Test 3	4.7	4.6	5.0	-3	7
	avg:	4.7	4.2	5.3	-10	14

Figure 7 *Continuous exhaust ventilation, with and without periodic recirculation by the central air-handling unit fan.*

		Air Change Rate (h^{-1})				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Continuous blending ventilator		0.24	0.10	0.42	-60	77
		Age-of-Air (h)				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
		5.0	2.3	10.3	-54	106

		Air Change Rate (h^{-1})				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Continuous blending ventilator with periodic AHU mixing	Test 1	0.20	0.18	0.21	-11	7
	Test 2	0.19	0.16	0.24	-16	24
	avg:	0.19	0.17	0.22	-13	15
		Age-of-Air (h)				
		Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
	Test 1	5.0	4.6	5.5	-7	11
	Test 2	5.2	4.4	6.0	-16	14
	avg:	5.1	4.5	5.7	-12	12

Figure 8 *Continuous blending (balanced) ventilation, with and without periodic recirculation by the central air-handling unit fan.*

nonuniformly ventilation air was distributed with the separate supply ventilation system. Over the next 16.15 hours (overnight), average air change rates ranged between 0.10 for the southwest bedroom to 0.20 for the living room. During this test, air change rates in the master bedroom zone were not as close to those in the main living area zone as they had been in the previous test, and air change rates in the other bedrooms were significantly lower. Based on these data, the ventilation air distribution performance of the separate supply ventilation system is poor. However, as shown by the redistribution effect of central fan operation, a fan recycling control installed on the central heating and cooling system blower would correct this deficiency.

Minneapolis, Minnesota

To obtain the baseline natural infiltration of the house, three tracer gas decay tests were completed with no fan operation at different times during the testing of the ventilation systems. Summarized natural infiltration results are presented in Figure 6. The air change rate ranged between 60% less and 104% more than the average of the six measurement locations. The corresponding age-of-air ranged between 67% less and 70% more than the average. Besides showing very little air exchange with the outside, these data show how nonuniform natural infiltration would be if it were relied on for providing outside air for occupants.

Infiltration was also tested with the central air-handler fan operating continuously. This was to evaluate the impact of duct leakage and mechanically induced infiltration due to pressure differentials created with door closure. There was little deviation in air change rate when the central fan was on, indicating low duct leakage and mechanically induced infiltration; however, the variance between measurement points was significantly reduced due to mixing.

Continuous exhaust ventilation was evaluated with and without recirculation by the central AHU fan. Figure 7 shows the summarized data for these tests. In a test of continuous exhaust ventilation without central fan operation, the air change rate ranged from 47% less to 28% more than the average of the six measurement locations, and the age-of-air ranged from 30% less to 72% more the average. The exhaust system without central fan recirculation showed relatively poor ventilation air distribution. When central fan recirculation was combined with continuous exhaust, ventilation air distribution was good. As noted earlier, this was tested at three different central fan recycling periods that gave 33%, 22%, and 17% duty cycle. Interestingly, as little as ten minutes of central fan operation each hour was sufficient to maintain uniform ventilation air distribution. The air change rate varied from 21% less to 15% more than the average of all six measurement locations over all three tests.

Continuous blending (balanced) ventilation was also evaluated with and without periodic recirculation by the central AHU fan. Figure 8 shows that without central fan recirculation the air change rate ranged from 60% less to 77% more

	Air Change Rate (h^{-1})				
	Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Continuous AHU supply	0.23	0.21	0.24	-9	4
	Age-of-Air (h)				
	Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
	4.3	4.1	4.7	-5	10

Figure 9 *Continuous central-fan-integrated supply ventilation.*

	Air Change Rate (h^{-1})				
	Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
Continuous exhaust with periodic AHU supply	0.24	0.22	0.27	-9	15
	Age-of-Air (h)				
	Avg of 6 Locations	Min of 6 Locations	Max of 6 Locations	% Below	% Above
	4.1	3.6	4.5	-14	8

Figure 10 *Periodic central-fan-integrated supply ventilation with continuous exhaust.*

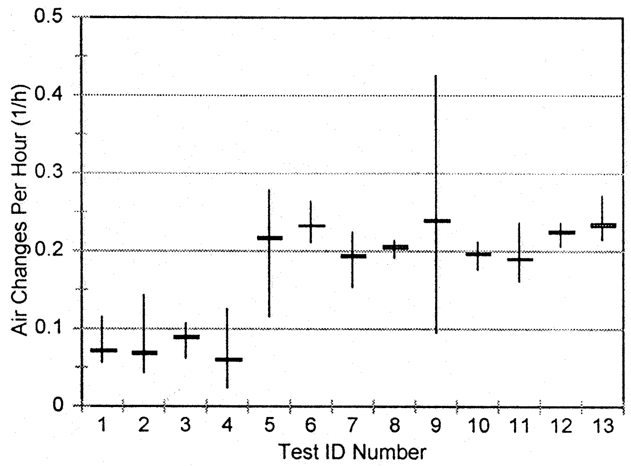

Figure 11 *Minneapolis ventilation study, high/low/mean plot of air change rates from six zones for each test.*

than the average of the six measurement locations. The age-of-air ranged from 54% less to 106% more than the average. This system showed relatively poor ventilation air distribution. When two levels of periodic central fan recirculation (33% and 17% duty cycle) were combined with continuous exhaust, the ventilation air distribution was good, providing air change rates that varied from the average by –16% to +24% and age-of-air varying by –16% to +14%.

Continuously operated central-fan-integrated supply ventilation was evaluated. As expected, this system showed the best ventilation air distribution. Referring to Figure 9, the air change rate ranged from only 9% less to 4% more between all six measurement locations. Age-of-air ranged from 5% less to 10% more than the average.

Periodic central-fan-integrated supply ventilation was also evaluated along with continuous exhaust. The measurements are presented in Figure 10. This system provided excellent results consistent with the continuous central-fan-integrated supply ventilation system, with only slightly wider variation between all six measurement locations.

Data plotted in Figure 11 show the mean and range of air change rates from all six measurement locations for each ventilation system test. To remind the reader, the measured outside airflow rate was 83 ft^3/min for the exhaust system, between 47 and 56 ft^3/min for the blending ventilator system, depending on whether the central air-handler fan was operating or not, and 70 ft^3/min (8% outside air fraction) for the central-fan-integrated supply system. The ventilation test ID numbers relate as follows:

- 1,2,4 natural infiltration
- 3 infiltration with central air-handler unit fan operating continuously
- 5 continuous exhaust, no AHU mixing
- 6 continuous exhaust with AHU mixing at 20 min off, 10 min on
- 7 continuous exhaust with AHU mixing at 35 min off, 10 min on
- 8 continuous exhaust with AHU mixing at 50 min off, 10 min on
- 9 continuous blending ventilator, no AHU mixing
- 10 continuous blending ventilator with AHU mixing at 20 min off, 10 min on
- 11 continuous blending ventilator with AHU mixing at 50 min off, 10 min on
- 12 continuous central-fan-integrated supply ventilation
- 13 continuous exhaust with periodic central-fan-integrated supply ventilation at 20 min off, 10 min on

The ventilation systems with at least ten minutes of central air-handler unit fan operation each hour showed good ventilation air distribution. For those systems, air change rate and age-of-air for the six individual zones varied between –21% and +25% from the mean. The ventilation systems tested with no central fan operation showed poor ventilation air distribution, with air change rate and age-of-air for the individual zones varying between –67% and +143% from the mean.

SYSTEM DESIGN RECOMMENDATIONS

The following recommendations are given for the Las Vegas house central-fan-integrated supply ventilation system to better achieve adequate outside airflow and filter access. An attic-mounted air handler with an outside air duct connected to an extended collar above the main return air filter grille assembly allows enough available negative pressure to draw in outside air with a five-inch or six-inch duct, depending on the size of the house, and the outside air filter is also accessible from below for regular maintenance. The design airflow should always be set with a balancing damper. In another configuration, an attic-mounted air handler had the outside air duct connected to the top of the main return air filter grille assembly. While this location provides less available negative pressure than the configuration with the extended collar, a larger duct can be installed to compensate for the lower pressure and the outside air filter is still accessible for regular maintenance.

CONCLUSIONS

Multi-zone tracer gas measurement was used to evaluate the effect on air change rate, age-of-air, and ventilation air distribution for eight ventilation systems installed in two houses. For the Las Vegas house, the periodically operated central-fan-integrated supply ventilation system showed excellent uniformity of ventilation air distribution; however, the installed outside air duct was not large enough to provide the desired ventilation airflow. The continuously operated separate supply ventilation system provided the desired ventilation airflow for the main living area and, to a lesser extent, the master bedroom; however, it showed poor ventilation air distribution for closed bedrooms where there was no ventilation system duct.

For the house in Minneapolis, all ventilation systems tested provided adequate outside air exchange and ventilation air distribution as long as there was periodic whole-house mixing provided by the central air distribution system. For the systems tested without central air-handler unit operation, the local mean age-of-air and air change rates varied greatly from each other, indicating poor ventilation air distribution.

Sakaguchi and Akabayashi (1998) came to the same conclusion, stating, "The spatial distribution of local mean age of air (TP) and local air exchange efficiency (EP) is very large when a circulating fan [central air-conditioning fan] is not operating, but when a fan is working the distribution of TP and EP is relatively small."

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Building Technologies, State and Community Programs, Building America Program, George James, Program Manager. Some of the ventilation systems tested here have been used extensively by production homebuilders as part of the USDOE Building America Program. The tracer-gas injection and measurement equipment and the computer-controlled space heating system were provided by the National Renewable Energy Laboratory.

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