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A Multiple Tracer System for Real-Time Measurement of Interzonal Airflows in Residences

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ABSTRACT: Airflows between different parts or zones of a residential dwelling may vary substantially over short time periods due to changes in meteorological conditions, HVAC operation, and occupant activity. The ability to measure interzonal airflows on a "real-time" basis can provide a realistic input for either predicting air pollutant concentrations at various locations within the dwelling or for modeling energy use.

An automated multiple tracer system that employs halocarbons and sulfur hexafluoride (SF_6) as the tracers was tested in a bilevel, single-family research house. The system employs a constant injection system for halocarbon release in two zones. An automated system samples each zone in the house four times each hour. Halocarbons and SF_6 are quantitated with a gas chromatograph with an electron capture detector.

Airflow rates between the upstairs and downstairs of the research house ranged from 33 to 610 m^3/h. The magnitude of the airflow rate was related to the percent of time that the furnace fan operated. Measurements of average interzonal airflow rates with PFTs were substantially lower than measurements with the halocarbon tracer system. Whole house air exchange rates calculated from the PFT and SF_6 decay measurements were nearly identical. For periods with concurrent halocarbon measurements and SF_6 decay measurements, whole house air exchange rates calculated with the halocarbons were lower than those calculated with the SF_6 decay method.

KEY WORDS: air exchange, air infiltration, indoor air quality, energy consumption, tracer gas decay, constant injection, constant concentration

Air exchange between indoors and outdoors is recognized as an important parameter related to indoor air quality and energy use in buildings. Air that infiltrates into a building may contain significant concentrations of outdoor pollutants. This same air, however, can serve to dilute the concentration of pollutants generated indoors. Infiltrating air also directly impacts on energy use in buildings due to the need to condition incoming air.

Airflows within a building can have a substantial impact on air quality and energy use in different areas (zones). As an example, although radon enters buildings primarily through the basement or lowest floor of the structure, concentrations of radon in the living space of a residence depend not only on the source strength in the basement, but also on the direction and magnitude of the airflows between the basement and the upstairs living space. Likewise, energy use is impacted by movement of air from unconditioned or marginally conditioned spaces such as basements, attics, and attached garages.

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In the design of indoor air quality monitoring programs, the researcher must have a clear understanding of the potential impact of air infiltration and interzonal air movements in the building to be monitored. These parameters will affect the number, location, and types of measurements required to characterize the air quality in the building.

This paper describes an automated multiple tracer gas system in use at the GEOMET research houses to characterize interzonal airflows. Examples of measurement results are presented and compared to results with other measurement methods.

Tracer Gas Methods

Tracer gas methods have been used for many years to measure the air exchange rates of a variety of different types of buildings. Three basic methods are currently used for the measurement: tracer gas decay, constant concentration, and constant injection. The tracer gas decay method is the simplest and most inexpensive of the three methods to implement. A standard practice, ASTM E 741-83, describes the technique [1]. The constant concentration method employs an automated system to simultaneously measure the tracer gas concentration and inject the appropriate quantity of tracer gas required to maintain a constant concentration [2]; the air exchange rate is related to the tracer release rate. With the constant injection method, tracer gas is released over extended time periods at a constant rate. The method requires a system for release at well-controlled rates because the air exchange rate is related to the tracer release rate. Both active and passive systems of tracer release and sampling have been used [3,4]. Fundamentals and applications of tracer gas methods for the measurement of air exchange have been presented in a number of published reviews [5–7].

Multiple Tracer Gas Methods

Tracer gas methods have been used most extensively to measure air exchange rates in buildings that can be treated as a single, well-mixed zone. However, for some indoor air quality problems, a quantitative characterization of interzonal air movements in the building is desirable. The concentration of indoor pollutants in different parts of the building, for example, depends on the source strength and the direction and magnitude of the airflows within the building. In some cases, the source of an indoor pollutant in a large building may be identified if the air movements within the building are known. Understanding the interzonal airflows in buildings can also contribute to a better understanding of the impact of other variables on indoor air quality. Interzonal airflows cannot be measured as routinely as single zone air exchange rates because of the complexity and cost of the measurement. However, in certain situations the measurement may be particularly valuable. Research on interzonal airflows in a range of building types is essential to a more complete understanding of air quality indoors.

The tracer gas decay method and the constant injection method can be adapted to measure interzonal airflows. Injection of a single tracer gas with monitoring of decay in two zones has been described [8], but the method has a number of limitations. The use of multiple tracer gases, one for each zone to be monitored, is the most practical approach for measuring interzonal airflow rates. Three halocarbon tracers were used by I'Anson et al. [9] to measure interzonal airflows with the tracer gas decay method. Constant injection systems with multiple tracers have been used successfully in field measurements and are in more widespread use than tracer gas decay methods. A diffusion-based constant injection system with four perfluorocarbon tracers (PFTs), developed at Brookhaven National Laboratory (BNL), has been used in single-family residences, apartment buildings, and large commercial buildings [4,10]. The system uses a passive release system and passive sampling with capillary adsorption tubes. The system has found widespread use for measurement of integrated air exchange rates and interzonal airflow rates over periods of several days to several weeks.

Fisk et al. [11] have described a constant injection system employing SF_6 and five halocarbon tracer gases for measuring ventilation rates and ventilation efficiencies in large buildings. Automated systems were used for tracer gas injection and sample collection; samples were returned to the laboratory for analysis by gas chromatography with an electron capture detector (GC-ECD).

Methods for analyzing results of multiple tracer gas measurements based on mass balance relationships have been described by Sinden [7]. Methods used in this work are described in a subsequent section.

Description of the Multiple Tracer Gas System

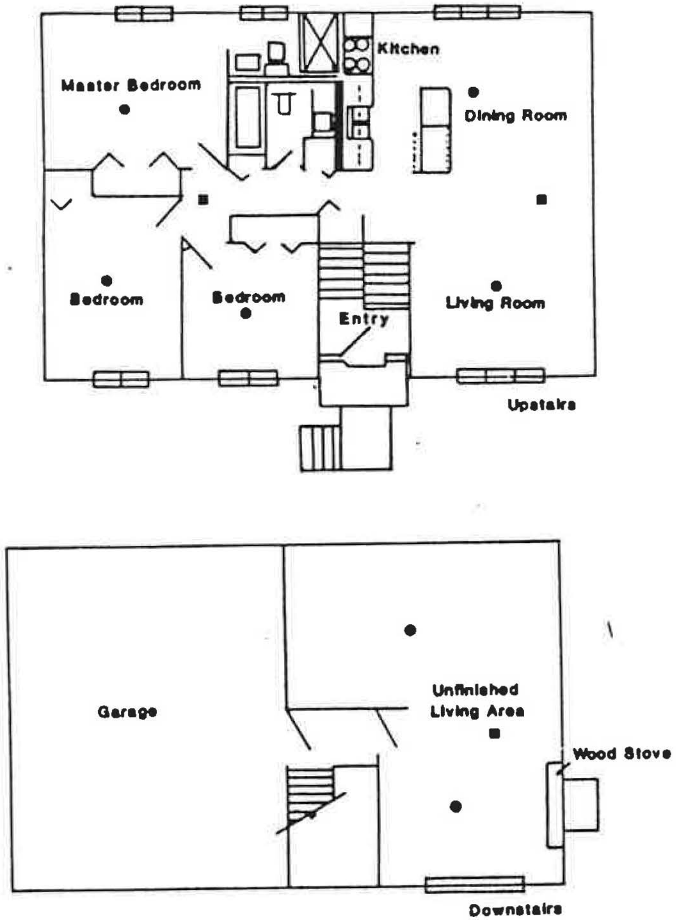
The multiple tracer system used in this study consists of a system for constant release of two halocarbon tracer gases and an automated sampling and analysis system for nearly "real-time" measurements of air exchange and interzonal airflow rates. The system has been tested at the two GEOMET research houses located northwest of Washington, D.C. Located on adjacent lots, the houses are of identical design and construction. The bilevel, wood-frame houses, constructed in 1982, each have a main living area and three bedrooms upstairs and a downstairs area that is divided into an unfinished living area and an integral garage. The floor plan is depicted in Fig. 1. Although unoccupied, the houses are modestly furnished and contain standard appliances (refrigerator, range, washer, dryer, etc.). A laboratory, fully equipped with analytical instrumentation, support equipment, and an automated data acquisition system (DAS), is situated between the houses. Sample lines and signal cables extend from the house to the laboratory so there are no analytical instruments or other heat sources related to monitoring equipment located in the houses. The houses and measurement system have been described in detail in previous reports [12,13].

Air infiltration is measured in the houses on a continual basis with the tracer gas decay method. A fully automated SF_6 injection system and sampling system is controlled by the DAS. The SF_6 samples are collected from the upstairs and downstairs of each house and outside with a sequential sampling system that cycles from zone to zone once every 3 min. Samples are analyzed with a GC-ECD system and recorded by the DAS.

PFT sources and samplers used in the study were supplied by BNL and were deployed according to their guidelines. PFT sources and samplers were located in four zones: upstairs, downstairs, the attic, and the garage. Sample collection periods were seven days in duration.

The measurement system for nearly "real-time" measurement of interzonal airflows consisted of a constant release system for two different halocarbon tracers, an automated sampling system, and a GC-ECD for measuring tracer gas concentration.

For the initial developmental work, two tracers were selected for measurement of airflows between the upstairs and downstairs of one house. Additionally, SF_6 was used in the tracer gas decay mode to determine whole house air exchange rates. A number of different tracers, including nitrous oxide, carbon dioxide, methane, ethane, carbon monoxide, helium, SF_6, halocarbons, and perfluorocarbons have been used in previous tracer studies [6]. The ideal tracer must be nontoxic, chemically unreactive, and background levels indoors and outdoors must be low relative to the concentrations used during the measurement period. All of the above tracers are acceptable. However, for a constant injection system, the ideal tracer should be easy to inject at a constant, controllable rate, and easy to detect with available instrumentation. For a multiple tracer system, a single analytical system capable of relatively



● Halocarbon release points

■ Halocarbon and SF_6 sampling sites

FIG. 1—*Floor plans for the GEOMET research houses.*

rapid analysis of all tracers is desirable. Both perfluorocarbons and halocarbons meet most of the criteria for the ideal tracer in a multiple tracer system. Perfluorocarbons, however, are liquids at room temperature, making evaporation and controlled release somewhat more complex than for a gaseous tracer. Perfluorocarbons are also substantially more expensive than halocarbons.

For this work, the halocarbons 114 ($C_2Cl_2F_4$ [dichlorotetrafluoroethane]) and 13B1 (CBF_3 [bromotrifluoromethane]) were selected for the two-zone work. Both halocarbons are gases at room temperature and can be easily separated from air and SF_6 by gas chromatography. Both gases are nontoxic at the ppm-level concentrations used (threshold limit value of 1000 ppm).

Halocarbon 114, at a tank (source) concentration of 2.2% in air, was released in the upstairs of the house and 13B1 (source concentration of 0.4% in air) was released downstairs. The release system consisted of the compressed gas cylinder, a two-stage pressure regulator, a sintered stainless steel filter element, and variable lengths of 0.010-in. inside diameter capillary tubing downstream of the regulator. Tracer gas was released at a single point in each room as depicted on Fig 1. Tracer gas injection rates were controlled by adjusting the length of the capillary tubing and pressure. Flow rates ranged from 20 to 100 cm^3/min in each room and were adjusted to provide volume-weighted release rates in each room. Concentrations in the house averaged 2000 ppb of halocarbon 114 and 200 ppb of halocarbon 13B1 during use of the system.

Air samples were collected sequentially from the upstairs and downstairs once every 7.5 min with an automated sampling system. Samples were collected at a single site in the downstairs and through a two-port manifold upstairs (Fig. 1).

The analytical system consisted of a Perkin-Elmer Sigma 300 GC-ECD and a 10-port Valco sampling valve. SF_6 and the halocarbons were separated on a 15 ft by ⅛ in. stainless steel column containing Porapak Q (80/100 mesh). Operating conditions included column temperature of 165°C, injector temperature of 175°C, detector temperature of 300°C, column flowrate of 30 cm^3/min, and makeup air at 30 cm^3/min. Rentention times were 1.1 min for air, 1.5 min for SF_6, 2.3 min for halocarbon 13B1 and 5.9 min for halocarbon 114. Calibration curves were developed for each tracer gas by performing multipoint calibrations using standards prepared by dilution methods.

Calculations

Interzonal flows were calculated using algorithms drawn from the multiple chamber description of the mass balance [*7,14*]. The mass balance for the two-zone case of the research houses was expressed through the equations

$$V_1 \frac{dC_{11}}{dt} = S_1 + Q_{21} C_{12} - Q_{12} C_{11} - Q_{10} C_{11} \quad (1)$$

$$V_2 \frac{dC_{22}}{dt} = S_2 + Q_{12} C_{21} - Q_{21} C_{22} - Q_{20} C_{22} \quad (2)$$

$$V_1 \frac{dC_{21}}{dt} = Q_{21} C_{22} - Q_{12} C_{21} - Q_{10} C_{21} \quad (3)$$

$$V_2 \frac{dC_{12}}{dt} = Q_{12} C_{11} - Q_{21} C_{12} - Q_{20} C_{12} \quad (4)$$

$$Q_{10} + Q_{12} = Q_{01} + Q_{21} \tag{5}$$

$$Q_{20} + Q_{21} = Q_{02} + Q_{12} \tag{6}$$

where

C_{ij} = tracer i concentration in zone j, ppm (mL/m^3),
S_i = tracer i release rate into zone i, mL/h,
Q_{ij} = transport from zone i to zone j, m^3/h, and
V_i = volume of zone i, m^3.

For calculation of airflows, the derivative was applied to the time varying tracer gas concentrations. In contrast, although similar expressions were employed by BNL to calculate average interzonal flows from the PFT experiments, the steady-state condition was assumed, which reduces the derivative, dC/dt, to zero [4].

Measurement Results

Multiple tracer tests with the halocarbon system were conducted in the research house retrofitted for energy conservation. Air exchange rates have been measured in this house, termed the *experimental house*, and in the control house on a nearly continuous basis since the houses were built. The experimental house is relatively "tight" in terms of air leakage and air exchange; average air exchange rates of 0.11, 0.22, and 0.46 were measured in the experimental house in the summer, fall, and winter, respectively, in previous monitoring studies using tracer gas decay [13].

During the last two winter seasons, both the multiple halocarbon tracer system and the BNL PFT system have been used on an intermittent basis to characterize air exchange and interzonal airflows in the experimental house. An example of infiltration, exfiltration, and interzonal airflow measurements with the halocarbon system is depicted in Fig. 2. Average hourly airflow rates (m^3/h) are presented for a period from 11 p.m. to midnight on January 21, 1987, and for the hour from 2 to 3 p.m. on the following afternoon.

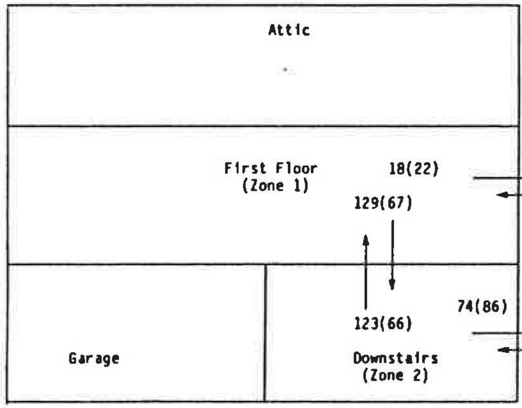


FIG. 2—*Average interzonal airflows (m^3/h) measured with halocarbon tracers in the experimental research house in January 1987. (Basement door closed, HVAC on demand, measurements for 2300 to midnight and 1400 to 1500.)*

The upstairs infiltration airflow of 23 m^3/h represents a nominal air infiltration rate of 0.11/h. The downstairs infiltration airflow of 69 m^3/h corresponds to an infiltration rate of 0.60/h. The higher infiltration rate downstairs was consistent with previous observations of substantially more rapid decay of SF_6 in the downstairs zone. Whole house air exchange rates calculated from measurements with the halocarbon constant release method ranged from 0.24 to 0.40/h (average of 0.27/h). During the same period, whole house air exchange measurements performed concurrently with the SF_6 decay method ranged from 0.39 to 0.71/h (average of 0.41/h). Air exchange rates measured with the halocarbon system were, on the average, 35% lower than measurements made with the SF_6 decay method. Additional tests comparing halocarbon measurements with SF_6 decay measurements and PFT measurements will address the reasons for these differences.

During this set of tests, the central heating system was operated normally and the door at the base of the stairs was closed. The heating system ductwork is of a conventional, unsealed design. The downstairs door, specially installed for experimental purposes, provides a relatively tight seal compared to standard interior doors. Airflows from the basement (volume of 115 m^3) to the upstairs (volume of 215 m^3) ranged from 43 to 123 m^3/h as depicted in Fig. 3 (during one particular hour, the airflow rate was 212 m^3/h, but slightly negative flows were calculated for that hour between the downstairs and outdoors). As shown in Fig. 3, the airflow rates in both directions between the upstairs and downstairs were similar and relatively high throughout the period. Because the basement door was closed and the down-

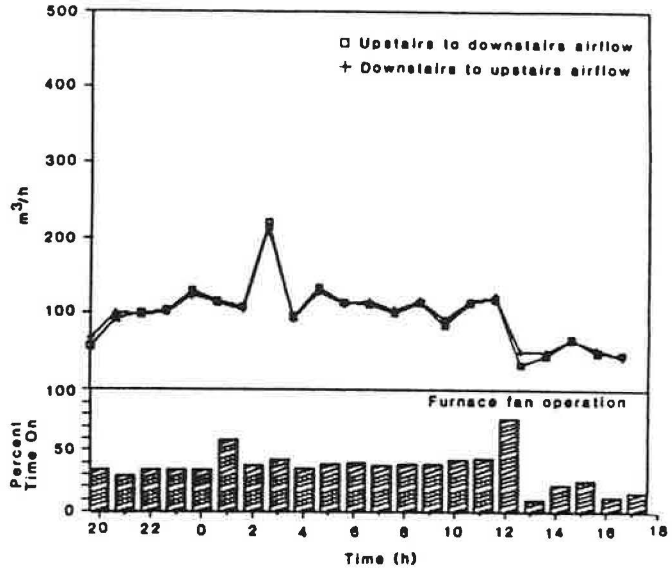


FIG. 3—*Interzonal airflows measured with halocarbon tracers between upstairs and downstairs of the experimental research house. Lower portion of figure depicts the percent of each hour that the furnace fan was operating. (January 1987, downstairs door closed; HVAC on demand.)*

stairs zone does not have a cold air return register, it was not expected that the flows between the upstairs (Zone 1) and downstairs (Zone 2) would be as high as depicted in Fig. 3. During this period, air in the house appears to be well mixed, despite the basement door being closed. This suggests a strong coupling between the two zones, possibly as a result of leakage of air into the depressurized cold air returns during furnace operation. Also included in Fig. 3 is a plot of furnace fan operation time (percent of time on during the hour). The magnitude of the interzonal airflows during this test period, although not highly correlated with fan activity, was related to the amount of time that the furnace fan was in operation. This relationship was most apparent during the afternoon hours when there was little furnace fan operation.

The relationship between furnace fan activity and the magnitude of upstairs/downstairs interzonal airflow rates was more closely correlated in tests with the basement door open (Fig. 4). Interzonal airflows during this period ranged from 49 to 610 m^3/h and were highest during periods of high fan operation. Airflows between upstairs and downstairs with the downstairs door open were two to three times higher than during the test period when the downstairs door was closed (Fig. 3).

Measurements of air infiltration and interzonal airflow with the constant relase halocarbon system were also compared to the constant release BNL-PFT system. During March 1986, PFTs were used to characterize airflows between the upstairs, downstairs, attic, and garage of the house. Four PFT sources were used, with at least one source device placed in each room. Samplers were placed in each zone and exposed for one week to ensure that sufficient tracer was collected from each of the four zones. Results of these PFT measurements are depicted in Fig. 5. Also included for comparison are example airflow rates measured with

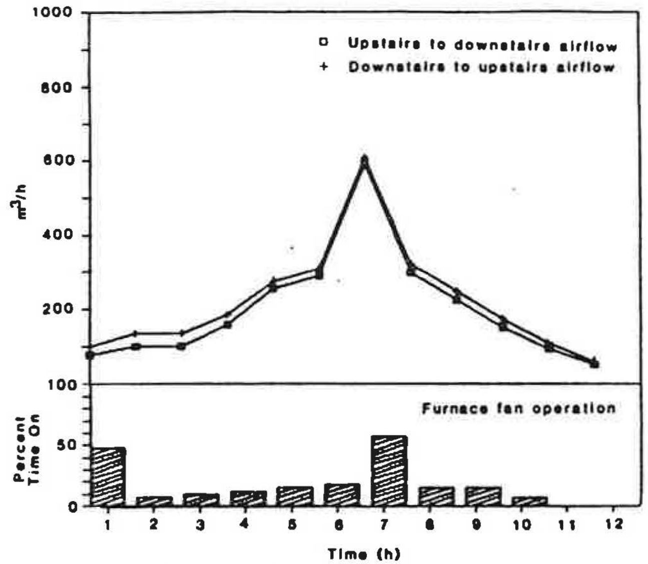


FIG. 4—*Interzonal airflows measured with halocarbon tracers between upstairs and downstairs of the experimental research house. Lower portion of figure depicts the percent of each hour that the furnace fan was operating. (March 1986, downstairs door open; HVAC on demand.)*

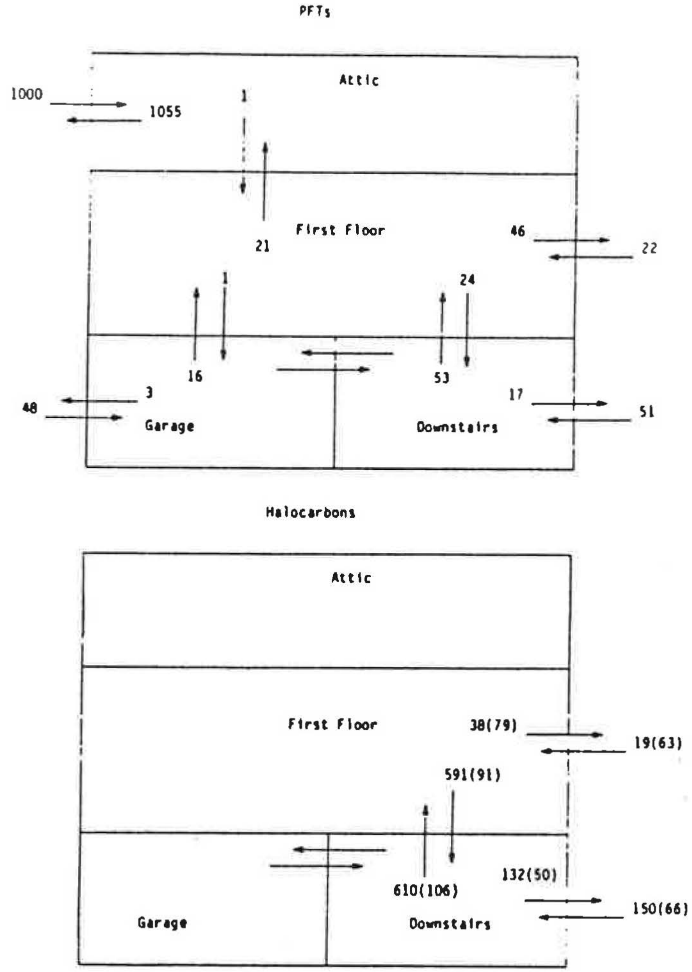


FIG. 5—(top) *Airflows (m^3/h) measured with PFTs in March 1986. Other flows are: attic to downstairs = 0.6 m^3/h; downstairs to attic = 24.3; attic to garage = 0; garage to attic = 10.3. Air exchange rate of conditioned space = 0.34.* (bottom) *Airflows (m^3/h) measured with halocarbon tracer system at 0700 and 1100 on 29 March 1986. Air exchange of conditioned space = 0.5 at 0700 and 0.38 at 1100. Basement door open.*

the halocarbon system after completion of the PFT sampling. Average air infiltration rates for the seven-day period calculated from the PFT measurements were 0.10, 0.45, 0.44, and 14.9/h for the upstairs, downstairs, garage, and attic, respectively. For the conditioned space, the upstairs plus the downstairs, the air infiltration rate was 0.34/h based on the PFT measurement. SF_6 decay measurements integrated over the same one-week period yielded a nearly identical air exchange rate of 0.33/h. For a 12-h period of halocarbon testing conducted following completion of the PFT measurements, the air exchange rate measured with the halocarbon system averaged 0.45/h. This value is consistent with predicted rates, but the halocarbon system could not be operated concurrently with the PFTs, so a direct comparison of air exchange rates could not be made.

As depicted in Fig. 5, average interzonal airflow rates measured with the PFTs were substantially lower than those measured with the halocarbon system. The 24 m^3/h airflow from upstairs to downstairs measured with PFTs was approximately 50% lower than the lowest flow (49 m^3/h) measured with the halocarbon system. Hourly airflow rates measured with the halocarbon system (Fig. 4) were as much as an order of magnitude higher than the week-long average interzonal rate measured with PFTs. Determining how these differences are related to variations in indoor and outdoor conditions and measurement system limitations will be the subject of future tests in the research houses.

Because of the stack effect in houses in the winter, a net airflow upward is expected. This effect was reflected in the PFT measurements that showed a two-fold higher flow rate from the basement to the first floor than in the opposite direction. The stack effect was also clearly demonstrated in the measured airflow from the first floor to the attic. Measurements with halocarbons, however, showed similar airflow rates in both directions between the upstairs and basement. The reason for this observation could not be determined from the limited set of winter time tests conducted. More extensive testing under a variety of conditions will be conducted in the upcoming winter season to address this issue.

Concluding Remarks

The preliminary data reported above demonstrate both the advantages and limitations of the halocarbon and the passive PFT constant release systems. With the PFTs, information on average air infiltration rates can be easily collected for both conditioned and unconditioned zones. Although both PFT and halocarbon systems can be used to measure air infiltration into zones with high air exchange rates if sufficient quantities of tracer gas are injected, the PFT system is better suited for measurement of interzonal airflows between conditioned and unconditioned zones. Large differences in tracer concentration between the conditioned and unconditioned zones and low airflow rates, such as from the attic to the downstairs, are measured more easily with a longer-term integrated PFT sample than with a "real-time" halocarbon system. The halocarbon "real-time" tracer system, however, provides short-term measurements that can be more easily related to changes in outdoor conditions (windspeed and direction, temperature, etc.), appliance operation (furnace use, fan operation, etc.), and other impact variables.

Future measurements with the halocarbon tracer system described in this paper will include concurrent measurements with PFTs and SF_6 (decay method) to assess the accuracy of the different test methods. The system will also include a third tracer for measurements in three zones. Testing will be conducted under a wider range of meteorological conditions, appliance operation, and occupant activities. Future developmental work will also address refinements of the system to make it amenable to transport and installation in other residential dwellings.

Acknowledgments

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