#4486

THE FEASIBILITY OF ACHIEVING NECESSARY INITIAL MIXING WHEN USING TRACER GAS DECAYS FOR VENTILATION MEASUREMENTS

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The degree of initial mixing of tracer gas with building air was examined in four office buildings by using the tracer decay method both at low and at high ventilation rates. The results indicate that the tracer gas mixed well with building air at low ventilation rates (0.5 air changes per hour), but that at high ventilation rates (1.0 air changes per hour or above) good initial tracer gas mixing conditions were not achieved on a consistent basis.

INTRODUCTION

Ventilation is one of the most important factors that affects indoor air quality in office buildings. Therefore, whenever measurements are made of concentrations of pollutants in a building, the building's ventilation rate and ventilation efficiency should be measured at the same time.

The measurement of a building's ventilation rate often involves the release and detection of a tracer gas. Three tracer gas methods have been used in buildings: tracer decay; tracer step-up; and constant injection.

Tracer decay is the most frequently employed (1,2,3) method for measuring ventilation rates and efficiencies. This simple method involves labeling the indoor air by releasing a tracer gas into the building ventilation system for a short period of time, and monitoring the concentration decay of the tracer gas due to dilution with outdoor air. By applying appropriate techniques on site, the tracer decay method allows researchers to determine ventilation rates (4) and ventilation efficiencies both locally and spatially (3,5,6,7). However, a limitation of this relatively simple method is that, in order for the local ventilation rates and ventilation efficiencies to be calculable, the tracer gas must be well mixed with building air initially, and there should not be large variations in local ventilation efficiencies (8). In a system which is initially incompletely mixed, the decay curve slopes of the tracer concentrations at the various locations eventually become equal, indicating only the overall ventilation rate (8). Turk et al (9) claim that "satisfactory" mixing of the tracer gas can be assumed when concentrations at the sampling sites in the building are within 10% of one another. However, they give no scientific argument for this number. Further, they reported that, in the majority of the 38 commercial buildings they studied using the tracer decay technique, "satisfactory" mixing could not be achieved, particularly in those with multiple ventilation systems. Fisk et al (10,11) have suggested that the tracer step-up method, which does not require good initial mixing, should be employed instead. However, their suggestion is based on the conclusions of Turk et al, and so are based on the arbitrary assumption that 10% variation in tracer concentrations represents satisfactory mixing.

In the tracer step-up method (also referred to as the tracer build-up method), the outdoor air supplied by the Heating, Ventilating, and Air-Conditioning (HVAC) system(s) is labeled by the continuous release of a tracer gas into the outdoor or supply air stream. The tracer gas increase is monitored in the building until steady-state conditions have been achieved. Ventilation rates and efficiencies can be calculated based on this method (10,11). This method also allows researchers to label each outdoor air stream with a unique tracer gas so that the percentage of outdoor air supplied by each HVAC system to specific areas of a building can be calculated (12). While this method does not require good initial mixing of the tracer gas, there are several disadvantages. These include the fact that the tracer gas must thoroughly mix with the outdoor air stream (which may be impossible in some ventilation systems), that monitoring of the tracer gas concentration in the outdoor air stream may be difficult, that devices are required for controlling and measuring tracer gas flow, and that, in buildings with multiple outdoor air intakes in which a single tracer is released, the tracer gas concentration in each air stream must be the same.

The constant injection method is used along with passive sampling of tracer gas to obtain approximate, average ventilation rates over extended time periods (13). This technique requires a constant tracer source and good air mixing in each zone. This method cannot be used to measure ventilation efficiency since the data analysis is based on steady-state, mass balance models.

This paper examines the degree to which one of the assumptions required for use of the tracer decay method can be met in buildings with typical ventilation systems, specifically, to what degree can initial mixing of tracer gas with building air be achieved when the tracer decay method is used. To examine this question, tracer gas concentrations were monitored in four buildings at both low and high outdoor air change rates.

DESCRIPTION OF THE STUDY

The ventilation rates of four office buildings were measured, and the degree of initial mixing of the tracer gas with building air was examined in the course of studies (14,15) to determine the effectiveness of building "bake-out" for reduction of concentrations of volatile organic compounds. The coefficients of variation of initial tracer gas concentrations among sampling sites was determined. Initial was defined as the time at which the semi-log plots of tracer gas concentrations versus time begun to be linear. Coefficients of variation of these concentrations were calculated by the following equation:

$$coefficient\ of\ variation = \frac{\sqrt{\frac{\Sigma(x_i-\bar{x})^2}{n-1}}}{\bar{X}}\ X\ 100\%$$

where: x_i is the concentration at the ith sampling location
x is the average of x_i's, and
n is the number of sampling locations

Local air change rates were determined according to ASTM Standard E-741-83 (4) after SF_6 was released either into the supply air stream or into the return air stream depending on the HVAC system configuration of the building. Each building's average ventilation rate was obtained by taking the arithmetic mean of the local air change rates. The HVAC system(s) was running during each decay. Tracer gas decays were monitored both at low and high air change rates with a computer-controlled, multi-location sampling technique. This technique has been described in detail elsewhere (16).

DESCRIPTION OF THE BUILDINGS

Building 1 is a newly constructed, two-story building with a floor area of 4800 m^2 located in the San Francisco Bay area. The HVAC system of this building is a variable-air-volume, terminal reheat system with building pressure-controlled exhaust fans. The HVAC mechanical room is located in a penthouse above the second story. Tracer gas was released into the return air plenum when the outdoor air dampers were closed and also when they were slightly open. Tracer gas concentrations were sampled in the return air plenum and at two locations in each story.

Building 2 is an approximately forty-year old, two-story building with a floor area of 2000 m^2 also located in the San Francisco Bay area. Each story is served by one roof-mounted, packaged HVAC unit. Only the second story, which was recently remodelled, was studied. The second story was isolated from the first story by installing large panels of plastic sheeting on wood frames. The ventilation rate of this building was measured two times in two days. The outside air damper linkage was disconnected both times and the dampers set at the same position (approximately 20% of the fully open position) both times before the tracer gas was released. Five locations in the second story were monitored.

Building 3 is a newly constructed, four-story building with a floor area of 11,100 m^2 located in the Sacramento Valley. It has four roof-mounted, packaged HVAC units, with each unit serving a vertical section of the building through variable-air-volume boxes. The ventilation rate of this building was studied twice in two days. In both cases the outdoor air dampers of all HVAC units were closed. Equal amounts of tracer gas were injected into each unit. Each of the return air streams of the four HVAC units was sampled. In addition, one location on the third story and one location on the sixth story were sampled.

Building 4 is a newly constructed, three-story building with a floor area of approximately 4500 m^2 located in the San Francisco Bay area. Each story is served by a separate roof-mounted, packaged HVAC unit. Only the first story of this building was studied, and was separated from the other stories by keeping the stairway doors closed. Six locations throughout the first story were sampled.

RESULTS AND DISCUSSION

The coefficients of variation of the initial tracer concentrations at each of the locations for the four buildings studied are shown in Table 1.

Building 1: Tracer gas concentrations in the return air plenum were lower than in the other four locations of the building. This was consistent with the visual observation that there were leaks in the return air plenum through a connecting attic door and through the exhaust air dampers. For this reason the return air plenum data are not included in the coefficients of variation shown in Table 1. The average ventilation rate was approximately 0.5 air changes per hour (ach) when the outdoor air dampers were closed. The coefficients of variation at this low ventilation rate during five separate days of monitoring of this building ranged from 3 to 5% when the return air plenum tracer gas concentrations were excluded, and from 4 to 6% when the return air plenum tracer gas concentrations were included. During the course of one of these experiments (Experiment #3) and after monitoring the tracer gas decay for about two hours, additional tracer was released. Ninety minutes later the outdoor dampers were slightly opened, thus increasing the average ventilation rate to 1.19 ach (Experiment #6). After monitoring the tracer decay for 90 minutes, tracer was released again in the return air plenum while the average ventilation rate was increased to 1.43 ach (Experiment #7). The coefficients of variation of the initial concentrations under these conditions ranged from 7 to 18%.

Building 2: The average air change rate of this building was 1.3 ach. Data acquired at this ventilation rate indicate that satisfactory mixing was not achieved (the coefficients of variation of the initial tracer gas concentrations varied from 13 to 17%).

Building 3: The average air change rate under these conditions was approximately 0.5 ach. During Experiment #2 the coefficient of variation of the initial tracer gas concentrations was 5%. However, during Experiment #1, although the outdoor air dampers were closed, satisfactory mixing was never achieved (coefficient of variation = 14%). This is attributed to the fact that occupants of this building were moving in, and new furniture and supplies were being loaded through an open, loading-dock door.

Building 4: Average ventilation rates of this building were obtained under low ventilation (0.42 ach) and under high ventilation conditions (above 3.0 ach, with economizer on). Experiments #2 through #5 were conducted the same day using multiple tracer releases (each Experiment indicates a single tracer release and decay). At the low average ventilation rate, the coefficient of variation of the initial tracer gas concentrations was 4%, whereas at the high average ventilation rates, satisfactory initial mixing conditions were never achieved (coefficients of variation ranged from 14 to 21%).

CONCLUSIONS

The following conclusions can be drawn from the buildings studied based on the criterion of Turk et al that less than a 10% variation in initial concentrations indicates good mixing:

1. Low air change rates (approximately 0.5 ach). Coefficients of variation of the initial tracer gas concentrations ranged from 3 to 5%. Therefore, in all four buildings under these conditions, the tracer gas was well-mixed with building air, and accurate ventilation rates and ventilation efficiencies could be calculated for each area. Thus, it appears to be appropriate to use the tracer decay method in buildings in which the ventilation rate is low (e.g., when outdoor dampers are closed) and in which the recirculation rate is adequate for sufficient mixing.

2. High air change rates (1.0 ach and above). Under these conditions the coefficients of variation of the initial tracer gas concentrations ranged from 13 to 21%. Therefore, at air change rates of 1.0 ach or above, tracer gas mixing is more difficult to achieve than at lower ventilation rates.

However, it should be noted that no theoretical basis for the acceptance of 10% as a cutoff for satisfactory mixing has been proposed. It would therefore be useful for a sensitivity analysis to be done on the effect of the variation of initial tracer gas concentrations on the accuracy of the resulting local ventilation efficiencies, so that decisions on the adequacy of initial tracer mixing can be scientifically based.

ACKNOWLEDGEMENTS

Thanks are due to John R. Girman, California Indoor Air Quality Program, for making all the needed arrangements with building managers and occupants.

Table 1
Coefficients of Variation of Initial SF_6 Concentrations of Four Buildings With Various Ventilation Rates.

	Ventilation rate (ach)	Coefficient of variation (%)
Building 1		
Experiment #1	0.35	4*
Experiment #2	0.43	3*
Experiment #3	0.47	5*
Experiment #4	0.49	3*
Experiment #5	0.53	5*
Experiment #6	1.19	7*,**
Experiment #7	1.43	18*
Building 2		
Experiment #1	1.29	13
Experiment #2	1.30	17
Building 3		
Experiment #1	0.39	14***
Experiment #2	0.46	5
Building 4		
Experiment #1	0.42	4
Experiment #2	3.21	21
Experiment #3	3.41	19
Experiment #4	3.47	14
Experiment #5	3.55	17

* excluding return air plenum data due to observed air leaks
** outdoor dampers initially closed
*** loading door open and occupants moving in

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