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A MULTI-TRACER TECHNIQUE FOR STUDYING RATES OF VENTILATION, AIR DISTRIBUTION PATTERNS, AND AIR EXCHANGE EFFICIENCIES

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A MULTI-TRACER TECHNIQUE FOR STUDYING RATES OF VENTILATION, AIR DISTRIBUTION PATTERNS, AND AIR EXCHANGE EFFICIENCIES

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Abstract

A multiple tracer system has been utilized within commercial buildings to monitor ventilation rates, air exchange efficiencies, age of air at multiple indoor locations, and the fractions of air at a monitoring point that entered the building through a particular air handler and by infiltration. To label the incoming air, a distinct tracer gas is injected at a constant rate into each mechanically supplied outside-air or supply air stream. Gas chromatographs monitor tracer gas concentrations versus time in the major airstreams of the air handlers. Small "local samplers" at various indoor locations are utilized to monitor local ages of air. The standard methods of applying age distribution theory are modified to process the multiple tracer data. The experimental system and methods of data analysis are described, and the results of investigations in an office building when the ventilation systems maximized and minimized the recirculation of indoor air are reviewed. The standard deviation in the age of air measured at different locations within this office building is from 25% to 40% of the mean age. Our measurements did not yield evidence of substantial short-circuiting or displacement flow patterns.

Experimental Methods

A distinct tracer gas is injected at a constant rate into each stream of outside air supplied mechanically to the building or, more commonly, into each supply airstream upstream of the supply fan (the supply airstream consists of a mixture of outside and recirculated air). Injection of each tracer gas is initiated simultaneously. Using cart-mounted gas chromatographic systems, tracer gas concentrations are monitored as a function of time in the major ducts of the air-handling units (AHUs). Tracer injection is continued until

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concentrations in the return/exhaust ducts are stable (i.e., no longer increasing more than 5% to 10% per hour). During the period of tracer gas injection, small local samplers located in the occupied spaces pump air/tracer samples at a constant rate into one-liter sample bags, yielding samples with the time-average tracer gas concentrations. When tracer concentrations have stabilized, a syringe sample is collected manually at the location of each local sampler, and operation of the local sampler is terminated. Two tracer gases -- sulfur hexafluoride (185 ppb maximum concentration) and bromotrifluoromethane (490 ppb maximum concentration) -- were used for the studies described in this paper.

The experimental system, procedures, and results of checks of measurement accuracy have been described in previous papers (Fisk et al. 1985, 1988). Three factors complicate the measuring process and lead to reduced accuracy. First, the entry rates of outside air must be relatively constant during a test; otherwise, tracer gas concentrations will not stabilize. Economizer systems, which regulate the proportions of outside and recirculation air in the supply airstreams, must be deactivated during a test. Second, the mixing of tracer gas in the airstreams must be verified -- especially the mixing of the injected tracer in the supply airstream. Third, the outside and recirculated air often does not mix fully prior to passing through the supply fan; thus, accurate measurement of the average tracer gas concentrations in this "mixed" air is difficult.

Data Evaluation

Data evaluation procedures based on the application of age distribution theory to air within buildings by Sandberg and Sjoberg (1983) have been modified to account for the use of multiple tracer gases (see Fisk et al. 1988). The application of this theory to ventilation in complex buildings involves a number of approximations (Fisk et al. 1985,1988). The age (A_i) of tracer gas i at a location in the building or ductwork, which represents the age of a portion of the air at that location, is computed by a numerical integration of the equation

$$A_i = \int_o^\infty [1 - C_i(t)/C_i(\infty)]dt \qquad (1)$$

where C is a tracer gas concentration, subscript i refers to a specific tracer gas, t is the time since start of tracer injection, and ∞ is the time when concentrations have stabilized. Using the tracer concentrations in the bag and syringe samples associated with a local sampler, the age of a tracer gas is determined from

$$A_i = t(\infty)[1 - C_{bag}/C_{syringe}]. \tag{2}$$

Based on the time history of tracer concentration in air that exits the building or isolated zone, the spatial-average age ($\overline{A}_i$) of tracer gas i within the building or zone can be computed using the expression

$$\overline{A}_i = \left[(1/A_i) \int_o^\infty t[1 - C_i(t)/C_i(\infty)]dt \right]_{exiting\,air}. \tag{3}$$

In practice, air may exit the building or zone through several ducts and by exfiltration and the calculation indicated in Equation 3 is based on the concentration(s) in the major exhaust airstream(s).

A method is required to combine the age of each tracer gas and yield ages of air. The first step is a determination of the effective outside-air tracer gas concentration for each tracer ($CEFF_i$). When outside air enters through a duct of sufficient length, tracer is injected directly into the outside air and the resulting value of ($CEFF_i$) is measured. When tracer is injected into the supply airstream, $CEFF_i$ is the tracer concentration that would have resulted if the tracer was actually injected directly into the outside air and the following equation

$$CEFF_i = \dot{M}_i/Q_i \tag{4}$$

is employed where $\dot{M}_i$ is the tracer injection rate and Q_i is the flow rate of outside air into the AHU (determined by a simple mass balance; see Fisk et al. 1988). The fraction (Z_i) of air (within an air sample collected at $t(\infty)$) that entered the building from outside through the AHU where tracer i is injected is then

$$Z_i = C_i(\infty)/CEFF_i \tag{5}$$

and the fraction ($ZINF$) of air within the same sample that entered by infiltration is

$$ZINF = 1 - \sum_{i} Z_i. \tag{6}$$

Due to the previously noted difficulty in accurately measuring the mixed-air tracer gas concentration and, thus, determining Q_i and $CEFF_i$, considerable uncertainty (e.g., $\pm 20\%$ depending on the building) can exist in measured values of Z_i. $ZINF$ is determined with even less accuracy. The age of air at a specific location (A_{air}) is a weighted average of the ages of the individual tracer gases where the weighting factors are normalized values of Z_i, i.e.,

$$A_{air} = \sum_{i} \left[Z_i A_i / \sum_{i} Z_i \right]. \tag{7}$$

Implicit in Equation 7 is an assumption that the age of air that entered the building by infiltration (this air is not labeled by any tracer gas) equals the average age of air that entered through the AHUs. The same technique is used to estimate the spatial average age of "indoor" air within the building or zone ($\overline{A}_{indoor\,air}$) based on data from the return/exhaust airstreams, i.e.,

$$\overline{A}_{indoor\,air} = \sum_{i} [Z_i \overline{A}_i / \sum Z_i]. \tag{8}$$

Alternately, $\overline{A}_{indoor\,air}$ can be estimated by averaging the individual measured values of A_{air}.

A final parameter, the air exchange efficiency (E_a), is based on a ratio of the average age of air that is exiting the building ($\overline{A}_{exiting\,air}$) to twice the spatial average age of indoor air,

$$E_a = \overline{A}_{exiting\,air} / [2(\overline{A}_{indoor\,air})]. \tag{9}$$

Values of E_a below 0.5 indicate a generally inefficient short-circuiting flow pattern; E_a equals 0.5 when the indoor air is perfectly mixed, and E_a values greater than 0.5 indicate a generally more efficient displacement flow pattern (see Sandberg and Sjoberg 1983).

Example of Results

Tables 1 and 2 summarize results from three tests in a four-story office building with 44000 ft^2 (4100 m^2) of floor area and 100 occupants. The building contains private offices, open areas subdivided by 5.5 ft. (1.7m) high dividers into cubicles, and a few laboratories. Ventilation is provided by two identical packaged rooftop AHUs. AHU1 and AHU2 supply air to Floors 3 and 4 and Floors 1 and 2, respectively, through variable-air-volume control units and rectangular supply diffusers located at ceiling level. Return air is drawn through ceiling-mounted return grilles and the plenum located above the suspended ceiling. Return air flow to both AHUs is through the same vertical shaft. For two tests, the economizer control systems were set so that minimum amounts of outside air were supplied and measurements indicated that the supply airstreams contained 23% to 25% outside air. During the third test, the economizers were set so that the maximum amounts of outside air were continuously supplied (86% and 80% for AHU1 and AHU2, respectively). Thirteen to fifteen local samplers were placed fairly evenly throughout the occupied areas and collected samples at breathing level [3 ft (1 m)]. Three to eight additional samplers collected samples at different heights.

The data indicate that the air within the building is not thoroughly mixed. As expected, Floors 1 and 2 have a higher proportion of air from AHU2 and Floors 3 and 4 have a higher proportion of air from AHU1. When the minimum amounts of outside air are supplied, approximately 30% of the air in the building enters by infiltration. Supplying the maximum amount of outside air leads to a large reduction in infiltration.

With minimum outside air supply (maximum recirculation), the ratio of the maximum to minimum measured indoor age of air is approximately 2.1, and the standard deviations of the measured ages of air are approximately 25% of the mean age. With the maximum supply of outside air, this ratio increases to 3.5, and the standard deviation of the ages of air is 38% of the mean age. In the two tests with minimum outside air (maximum recirculation), the measured ages of air on Floors 3 and 4 are uniform within 0.2 h, but ages are much more variable on Floors 1 and 2.

The air exchange efficiency, based on the average age of air in the two return/exhaust ducts and the average of the ages measured with the local samplers, is 0.60 and 0.48 for the two tests with minimum outside air and 0.50 for the test with maximum outside air. These efficiencies are 0.55, 0.60, and 0.56 when Equations 3 and 8 (only the data from return/exhaust airstreams) are employed. Based on preliminary estimates of measurement uncertainty, these air exchange efficiencies are not significantly different from the 0.5 value that occurs with perfect mixing of the indoor air.

A more direct method of checking for the often-assumed short-circuiting of air between ceiling-mounted supply diffusers and return grilles (or for a vertical displacement flow) is to measure the age of air at different heights. Results of such measurements are presented in Table 2 and indicate that the age of air in this building does not vary substantially with height (differences of 0.05 h are considered insignificant). Findings from two other buildings are similar (Fisk et al. 1988).

Conclusions

The multi-tracer experimental technique yields detailed information on indoor air flow patterns and the spatial variability of ventilation within office buildings. The air within this office building is not thoroughly mixed. The standard deviation in the ages of air within this office building is from 25% to 40% of the mean age. Our measurements did not yield evidence of substantial short-circuiting or displacement flow patterns within the building.

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Table 1. Results of Multi-Tracer Monitoring in a Four-Story Office Building

Date & Test Conditions	Location & (# of Measurements)		Average % Air from: AHU1	AHU2	Inf.*	Age of Air (h) Min.	Max.	Avg.
06/02/88 Minimum Outside Air	Floors 1 & 2	(9)	0.30	0.41	0.29	1.0	1.5	1.2
	Floors 3 & 4	(9)	0.57	0.15	0.28	0.7	0.9	0.8
	Floors 1 - 4	(18)	0.44	0.28	0.28	0.7	1.5	1.0
	Floors 1 - 4	(-)	----	----	----	---	---	1.1+
	AHU 1 RDø	(1)	0.50	0.21	0.29	---	---	1.1
	AHU 2 RDø	(1)	0.43	0.28	0.29	---	---	1.2
06/06/88 Minimum Outside Air	Floors 1 & 2	(10)	0.24	0.39	0.37	0.9	1.7	1.1
	Floors 3 & 4	(9)	0.60	0.17	0.23	0.8	1.0	0.8
	Floors 1 - 4	(19)	0.41	0.28	0.30	0.8	1.7	1.0
	Floors 1 - 4	(-)	----	----	----	---	---	0.8+
	AHU1 RDø	(1)	0.48	0.23	0.29	---	---	0.9
	AHU2 RDø	(1)	0.39	0.27	0.34	---	---	1.0
06/17/88⊠ Maximum Outside Air	Floor 1	(5)	0.13	0.77	0.11	0.4	0.7	0.5
	Floor 2	(8)	0.14	0.87	-0.01	0.2	0.6	0.3
	Floor 3 & 4	(8)	0.94	0.05	0.02	0.2	0.5	0.3
	Floors 1 - 4	(21)	0.44	0.53	0.03	0.2	0.7	0.4
	Floors 1 - 4	(-)	----	----	----	---	---	0.3+
	AHU1 RDø	(1)	0.72	0.22	0.06	---	---	0.4
	AHU2 RDø	(1)	0.45	0.43	0.12	---	---	0.4

* Inf. = infiltration

ø RD = return/exhaust duct

\+ average age in building based on tracer concentration histories in return ducts

⊠ due to spatial variability and limited number of measurement sites, reported averages unlikely to accurately represent actual spatial averages

Table 2. Age of Air versus Height above Floor

Date & Test Conditions	Location Floor-Room	Ht.* (m)	Age (h)	Ht. (m)	Age (h)	Ht. (m)	Age (h)	Ht. (m)	Age (h)
06/02/88 Minimum Outside Air	1-34	1.0	1.16	---	---	---	---	RG+	1.20
	3-320	1.0	0.79	---	---	---	---	RG	0.82
	4-490	1.0	0.82	---	---	---	---	RG	0.87
06/06/88 Minimum Outside Air	1-34	1.0	1.35	---	---	---	---	RG	1.39
	2-Lab	1.0	0.97					EGø	0.96
	3-320	1.0	0.79					RG	0.84
	4-490	1.0	0.93					RG	0.98
06/17/88 Maximum Outside Air	1-34	1.0	0.41	1.7	0.62	---	---	RG	0.50
	2-6	0.3	0.25	1.2	0.24	1.8	0.25	RG	0.28
	3-320	1.0	0.40	---	---	---	---	RG	0.45
	4-490	1.0	0.20	---	---	---	---	RG	0.30

* Ht = height, 1m = 3.28 ft.
\+ RG = ceiling-level return grille
ø EG = ceiling level exhaust grille