A COMPARISON OF DISPLACEMENT EFFICIENCY, DECAY TIME CONSTANT, AND AGE OF AIR FOR ISOTHERMAL FLOW IN AN IMPERFECTLY MIXED ENCLOSURE

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This paper compares three methods of characterizing the delivery of ventilation air to occupants in a room: displacement efficiency, decay time constant, and age of air. Displacement efficiency measures the percent delivery of ventilation air to a room per volume change of air supplied by the ventilation system. The decay time constant method uses the observed decay rate of a contaminant to calculate the ventilation rate that would produce the same rate of decay if air in the room were perfectly mixed. The age of air is a measure of how long a particular volume of air has been in the room before it is exhausted. Detailed experimental data from a simple benchmark test geometry are used to compare these methods and examine the impacts of truncation errors in the analysis. The comparison focuses on the ability of the measurement techniques to detect spatial variations in ventilation performance in an imperfectly mixed flow. These results can be used to guide researchers and designers to select and appropriately apply methods for characterizing ventilation system performance.

INTRODUCTION

During the energy crisis of the 1970s the minimum recommended ventilation rate for general office space was reduced from 15 cfm (ASHRAE Fundamentals 1977) to 5 cfm (ASHRAE Fundamentals 1981, 1985) to conserve energy. However, complaints about indoor air quality have become a serious problem in the 1980s. ASHRAE currently recommends that designers either adjust the ventilation rate to control indoor air pollutants or provide outside air at a minimum of 15 cfm per occupant (20 cfm for office buildings) (ASHRAE Fundamentals 1989, ASHRAE Standard 62-1989).

Energy-conserving buildings have been linked to health complaints from building occupants. Brundage et al. (1988) reported a 56% increase in acute respiratory infections among Army recruits housed in energy-efficient buildings as compared to those in conventional housing. Because of the nonspecific nature of health complaints and the lack of medical information concerning human response to low levels of indoor pollutants, it is currently difficult or impossible to resolve complaints about air quality by focusing solely on source control. Adequate ventilation therefore remains a primary way to control indoor contaminants.

Maintaining acceptable air quality using ventilation techniques can conflict with the goal of reducing building conditioning costs by minimizing ventilation air. Accurate diagnostic techniques that can detect local variations in ventilation system performance are required for HVAC design, code enforcement, equipment development and building maintenance. Local variations in ventilation performance can be caused by duct leakage, internal room flow blockage, inadequate air distribution and inappropriate control of outside air dampers.

DESCRIPTION OF TEST APPARATUS

Standard similitude analysis demonstrates that small-scale water tests will reproduce full-scale air tests with the same boundary conditions for isothermal flows (Anderson and Mehos 1988). The use of water allows a test chamber's size to be reduced by a factor of four with respect to air, reducing testing costs.

Therefore, to simulate air flow in a room, we constructed a clear enclosure (42 cm high, 69 cm wide and 38 cm deep) with a planar inlet in the top, left corner as shown in Figure 1. This geometry was chosen to provide a benchmark data set for comparison of ventilation efficiency measurements. Isothermal tests were conducted with no recirculation. A return was located at the top right corner of the enclosure. The flow and temperature fields were allowed to stabilize over a 12-hour period. A neutrally buoyant dye was injected into a mixing tank and then pumped into the clear enclosure. Concentrations were determined using a video imaging system and subsequent digitizing of the data. The supply was maintained at a constant temperature during the tests.

The height of the tank is used to nondimensionalize the x and y coordinates. The origin (X,Y) = (0,0) is defined as the lower left corner of the enclosure and the top right corner at (1.65,1) as shown in Figure 1.

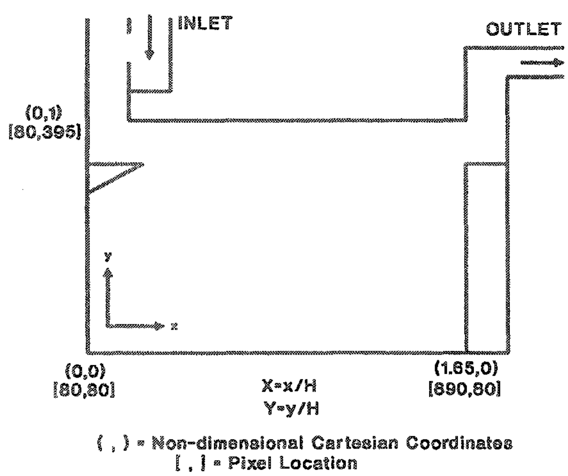

Figure 1. Schematic of Test Cell

TEST METHOD AND DATA COLLECTION

The video imaging system used to provide optical measurements had a resolution of 756 x 486 pixels and an aspect ratio of 0.8571. The intensity of each pixel (representing the concentration) was assigned a numerical value. To reduce the number of data points to a more manageable number and to reduce random fluctuations, an averaging technique was used. Average values were calculated for 72 discrete locations (using a 12 x 6 grid) by averaging points (with equal weighting) within a 5 x 5 area. These 72 points were used to calculate the decay time constant and the age of air.

A transfer function, β, related the digitized output to the actual intensity. Our testing showed that this transfer function was itself a function of the background light intensity of the tank. The data were processed with $\beta[I_0(x,y)]$, where the intensity I_0 was related to the local concentration via a Beer's Law relationship (Martin et al. 1989).

To reduce random fluctuations, four images were captured and averaged before dye was injected. After injection of the dye stream images were captured every 40 seconds. Our procedure was to establish isothermal flow within the enclosure; to isolate the storage tank while maintaining flow in the enclosure; to inject and mix dye in the storage tank; and finally to redirect flow through the storage tank, which now contained well-mixed dye.

The inlet jet velocity was maintained at a constant value during the test. The jet Reynolds number was Re = 1000 ±3, ensuring that the jet was turbulent. The overall tank had a nominal time constant (volume/flow rate) of 351 s corresponding to 10 volume changes per hour.

DISPLACEMENT EFFICIENCY

The displacement efficiency method (Anderson and Mehos 1988) provides a direct measure of the ability of a ventilation system to deliver ventilation air to different locations in a room. The displacement efficiency measures the fraction of the test section volume that is replaced during the time that one volume change is supplied. It is given by

$$\eta_d = \int_{t=0}^{t=\tau} \frac{(C_{out} - C_{in})}{(C_o - C_{in})\tau_{nom}} \, dt \qquad (1)$$

where

C_{in} concentration of inlet flow
C_o initial concentration in the enclosure
C_{out} concentration of outlet flow
τ_{nom} nominal time constant (volume/flow rate), 351 s.

A value less than one indicates the presence of short-circuiting. A perfectly mixed flow has a displacement efficiency of 0.63.

The time of flight, which is the time it takes the dye to reach a certain location after entering the tank, was about 120 s for the lower left corner and between 80 and 120 s for the center. By the time the fluid reached the lower left corner, much of the energy of the turbulent fluctuations had dissipated and the fluid flow was much smoother.

A contour plot of the displacement efficiency is shown in Figure 2. The average displacement efficiency was 0.523. That is, 52.3% of the resident fluid had been displaced or removed from the enclosure at $t = \tau_{nom}$, where τ_{nom} is the time required to supply one volume change to the test chamber. Figure 2 shows a "dead zone" which had reduced ventilation.

DECAY TIME CONSTANT

In tracer gas decay tests or tests involving a step reduction in the concentration of the supply, entire rooms are treated as one well-mixed zone (ASTM 1983). For a well-mixed enclosure with steady, incompressible flow, this leads to a simple exponential relation between concentration and time. The relation also holds for tests involving a sudden increase in the concentration of the supply, provided that the quantity C^* is replaced by $(1-C^*)$. Step increases in concentration were used in the present study, leading to

$$C^*(t) = 1 - \exp(-t/\tau_d) \qquad (2)$$

where τ_d is the decay time constant. An alternate expression, useful for plotting results, is

$$\ln(1-C^*) = -t/\tau_d \, . \qquad (3)$$

The quantity $\ln(1-C^*)$ can be plotted versus time as a straight line on a semilog plot with a slope of $-1/\tau_d$ to obtain the decay time constant.

Even though airflow in buildings generally is not well mixed, one objective of this study was to determine if Equation (3) could be used to provide an exponential curve fit to local contaminant decay data. The time constant derived from this curve fit provided an estimate of the ventilation rate that would be required to produce an equivalent decay rate, if the room were well mixed.

If each of the 72 averaged points represented a well-mixed subvolume which had an exponential decay, the data on a semilog plot would follow a straight line. The lower left corner had the closest fit to an exponential decay because most of the large eddies had dissipated. Locations near the jet (along the top and right side) showed greater variations, presumably because of turbulence. The greatest fluctuations from an exponential decay occurred near the end of the test. As the test progressed, C^* approached 1, causing $(1-C^*)$ to be a very small number; and the natural log of a small number is a very large negative number. Therefore, small changes in the concentration near the end of the test can lead to large changes in the decay constant calculated using Equation (3).

Figures 3a and 3b show contour plots of the decay constant calculated at two times. A dead zone was observed to the right of the center of the enclosure that persisted throughout the test, though the overall features of the flow varied significantly with time. These two plots show variations in decay constant ranging from under 400 s to about 750 s. The subvolume decay constants were expected to be higher than the nominal time constant of 351 s for the entire enclosure, because some of the fluid short-circuited between the supply and return.

The calculation of the decay constant excluded the early data points before dye reached that location.

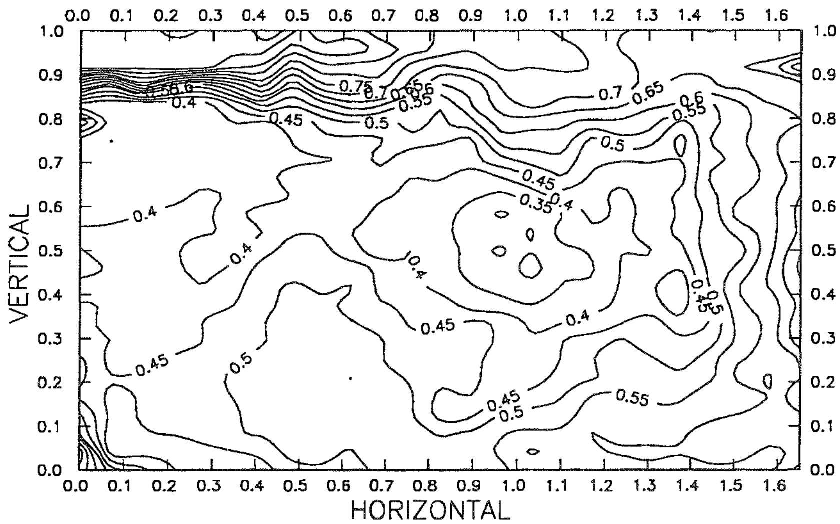

Figure 2. Displacement Efficiency - ($\tau_{nominal}$ = 351 s)

If the concentration was less than 0.05 (indicating that no dye was present) and it appeared to decrease (due to random error) at the next time step, the prior data point was discarded. At the jet inlet the data collection rate was too slow for the change in the concentration to be detected. Generally there was little effect whether the early points were eliminated or not.

AGE OF AIR

The age of air is a measure of ventilation efficiency in that local ages can be determined. The age of air indicates the length of time a particular volume of fluid remains in a room before it is ventilated (Sandberg 1983). Poor ventilation efficiency is indicated in high age of air by specific locales. The age of air is given by

$$\tau_{age} = \int_{t=0}^{t=\infty} \frac{(C_{in} - C)}{(C_{in} - C_o)} dt \ , \quad (4)$$

or in nondimensional terms for a step increase in concentration

$$\tau_{age} = \int_0^{\infty} (1 - C^*) dt \ , \quad (5)$$

where C^* represents the mass being added to the enclosure and ($1-C^*$) the absence of concentration, i.e., "fresh" air.

The age of air is typically determined by integrating over one or two volume changes and then fitting an exponential curve fit from the end of the test data ($t = t_1$) to the tail end of the data,

$$\tau_{age} = \int_0^{t_1} (1-C^*)dt + \int_{t_1}^{\infty} (1-C^*)dt \ . \quad (6)$$

We integrated C^* from the start of the test up to about 4.5 time constants later using the forward difference formulation

$$\tau_i = [\{(1-C^*_{i+1}) + (1-C^*_i)\}/2] \ (\Delta t) \ , \quad (7)$$

where τ_i is the contribution of the i^{th} time step. The numerical integration part of the age of air is then

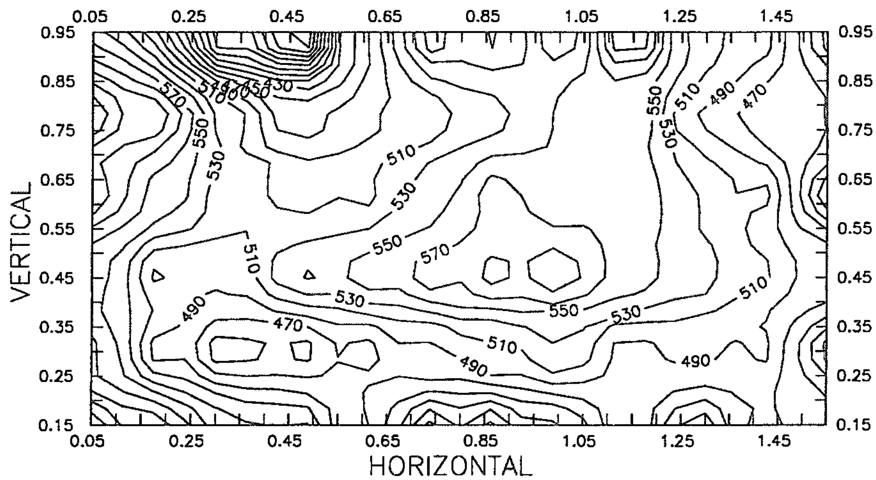

Figure 3a. Decay Tau at 1591 s - ($\tau_{nominal}$ = 351 s)

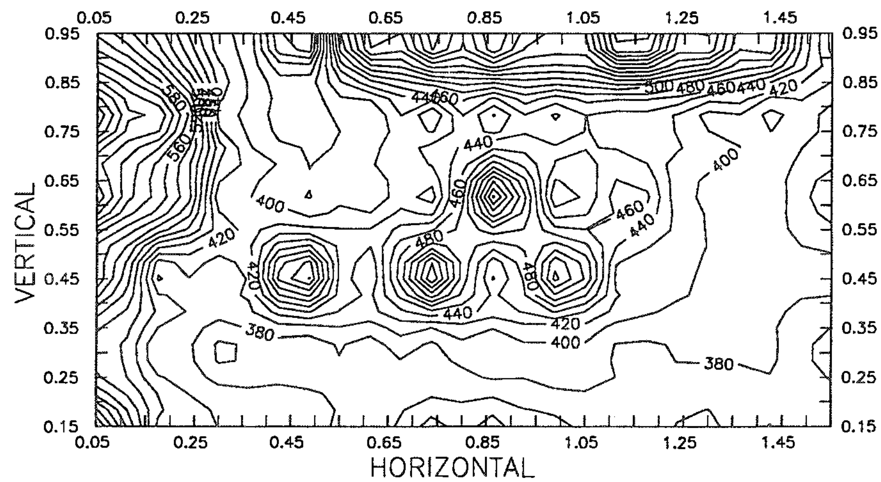

Figure 3b. Decay Tau at 2640 s - ($\tau_{nominal}$ = 351 s)

$$\tau_{age,num} = \Sigma\tau_i, \qquad i = 1, 2, \ldots, (N-1) \ , \tag{8}$$

where i = 1 corresponds to t = 0. The exponential tail fit was calculated using

$$\tau_{age,tail} = \int_{t_1}^{\infty} \exp(-t/\tau_c)dt \ , \tag{9}$$

where τ_c is the decay tau from the experimental data (determined using the procedure in the previous section). Equation (9) reduces to

$$\tau_{age,tail} = \tau_c \exp(-t_1/\tau_c) \ . \tag{10}$$

The age of air is then determined from

$$\tau_{age} = \tau_{age,num} + \tau_{age,tail} \ , \tag{11}$$

which can also be expressed as

$$\tau_{age} = \tau_{age,num}[1 + \exp(-t_1/\tau_{age,num})] \ . \tag{12}$$

Note that if the enclosure is well mixed, then Equation (2) can be rearranged and integrated to get

$$\int_0^\infty \exp(-t/\tau)dt = \int_0^\infty (1-C^*)dt \ , \tag{13}$$

which reduces to

$$\tau = \int_0^\infty (1-C^*)dt \ . \tag{14}$$

Hence, for a well-mixed tank the age of air equals the decay time constant. One can also conclude that for a small subvolume which can be considered well mixed, these two quantities would also be equal.

The tail contribution went to zero as the test progressed and the numerical integration part began to reach a steady value. At the left side of the enclosure, the age of air values began to reach a steady value after about 1200 s while near the center of the tank, steady values were reached in about 700 s. The exponential tail contributed about 50% of the total age of air at $(t/\tau) = 1$, about 20% at $(t/\tau) = 2$, less than 15% at $(t/\tau) = 3$, and from 1 to 9% at $(t/\tau) = 4$.

Shortly after the start of the test, a dead zone was observed in which the age of air was about 780 s. This dead zone was maintained throughout the test, although the age of air within it decreased to 670 s by t = 431 s and stayed there until the end of the test.

Figures 4a and 4b show a contour plot of the age of air at t = 1591 s and t = 2640 s. The dead zone to the right of the center can be seen as a region of higher age-of-air values. Unlike the exponential decay method, the addition of another data point (at 2640 s) had little effect on the final results. It was necessary to include the early points to correctly account for the time of flight for the dye to reach that area. However, the early steady points were eliminated for calculation of the exponential tail.

EXHAUST AGE OF AIR

A weighted age of air can also be calculated for the room (Grieve 1989). Sometimes referred to as a room-average age, it is given by the first moment of the area between the plot of the concentration and 1.0 divided by that area, or

$$\tau_{age,mean} = \int_0^\infty t(1-C^*_{exh})dt \ / \int_0^\infty (1-C^*_{exh})dt \ , \tag{15}$$

where C^*_{exh} is the nondimensional concentration in the exhaust. The denominator can be divided into two parts, a numerically integrated part and an exponential part, exactly as in Equation (6). The numerator is treated analogously. The part using experimental data (before $t = t_1$) is integrated numerically. The concentration in the tail part is assumed to increase exponentially (or conversely $1-C^*$ decreases exponentially) after time t_1. This results in

$$\tau_{age,mean,tail} = (\tau^2)(1 + t_1/\tau)\exp(-t/\tau) \ , \tag{16}$$

where τ is the absolute value of the inverse of the slope (that is the time constant) calculated from $\log(1-C^*)$ versus time using data from the start of the test only until $t = t_1$.

The denominator in Equation (15) is the exhaust local age of air and is shown in Figure 5 along with the room-average age of air. The room-average age of air is on the order of 650 s, which is in the range of values shown in Figures 4a and 4b.

A measure of the ventilation efficiency can be calculated by dividing the exhaust local age of air by the room-average age of air measured in the exhaust, or

$$[\int_0^\infty (1-C^*_{exh})dt]^2 / \int_0^\infty t(1-C^*_{exh})dt \ . \tag{17}$$

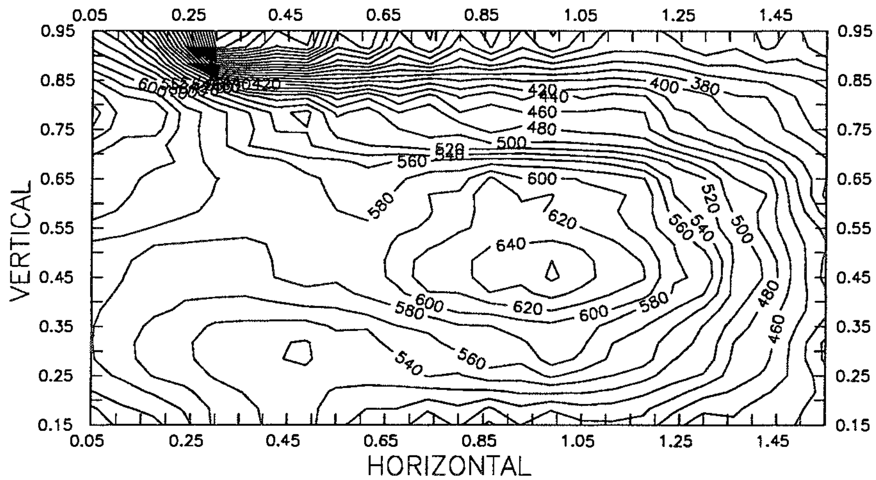

Figure 4a. Age of Air at 1591 s - ($\tau_{nominal}$ = 351 s)

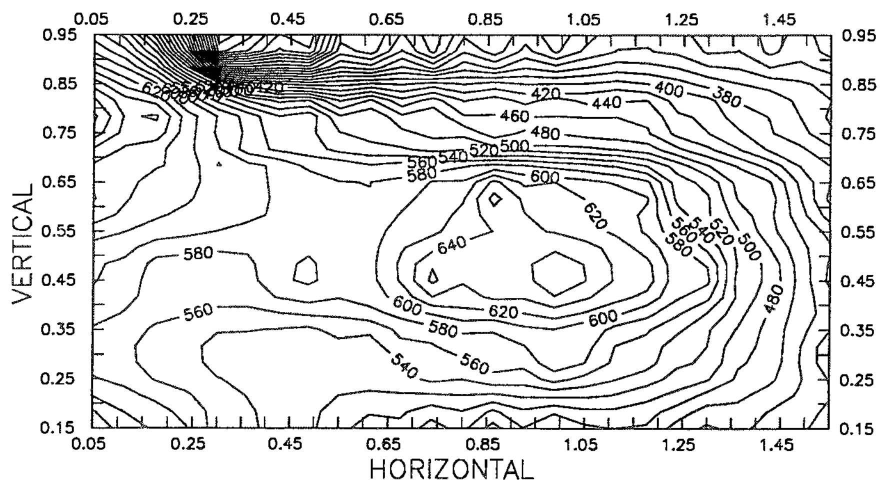

Figure 4b. Age of Air at 2640 s - ($\tau_{nominal}$ = 351 s)

The result is shown in Figure 6. The average value for the entire test volume is about 0.52.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the exponential decay method is very sensitive to small changes in concentration near the end of the test, as C^* approaches 1. Therefore, the monitoring for the decay tau should cease before the concentration is of the same order as the random error of the measurement process. Although subvolumes can be approximated as being well mixed, turbulence can cause large fluctuations in the concentration.

The age-of-air method shows physically meaningful results that are not easily influenced by data near the end of the test. An analysis of the age of air in the exhaust provides useful information about the room-average age of air, the ventilation efficiency, and multiple time constants. The room-average decay tau was calculated at about 53% for a particular case of imperfectly mixed isothermal flow in an enclosure. The room-average displacement efficiency was about 52%. A measure of the ventilation performance, calculated by dividing the exhaust local age of air by the room average age of air as measured in the exhaust, was 52%.

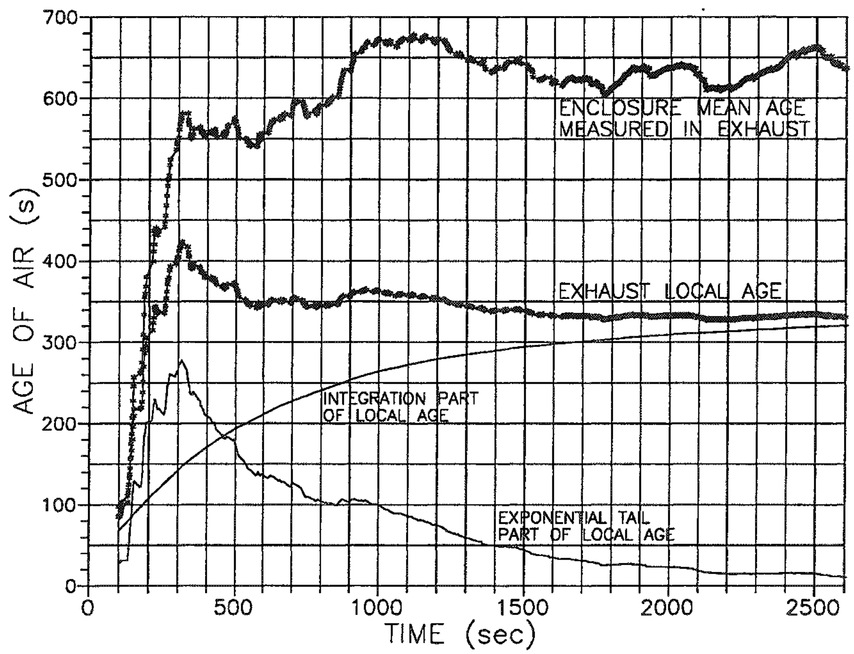

Figure 5. Exhaust Age of Air

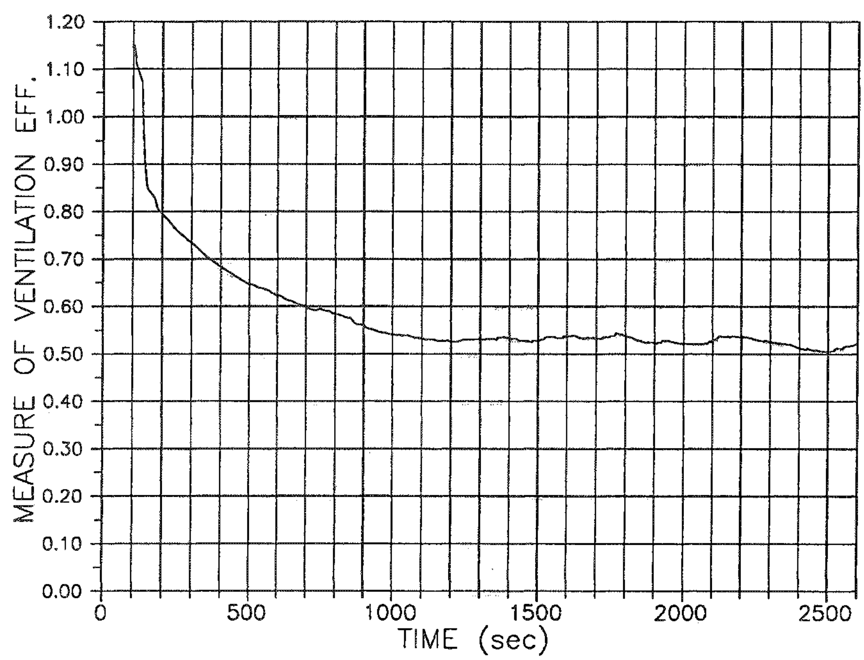

Figure 6. Local Exhaust Age/Enclosure Mean Age

Both the age-of-air and decay time constant methods are susceptible to error as the concentration decreases to the magnitude of the random error. However, although there is only a minor effect on the age of air, there is a significant effect on the decay time constant. Researchers must be able to estimate the random error of their apparatus and analyze their data accordingly.

These test results were used to compare different methods of characterizing flow in an enclosure (such as a room) with a flow that was not well mixed. Although a single point measurement is inadequate to characterize the flow in a room, especially to identify dead zones, all three measurement approaches evaluated in the present paper appear to be sensitive to local variations in delivery of outside air by the ventilation system.

Further work is needed to better understand the interaction of building subvolumes and the impact of system design of the formation of dead zones or zones of recirculation (which trap contaminants) in actual buildings.

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