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Ventilation Effectiveness in Mechanically Ventilated Office Buildings

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U.S. DEPARTMENT OF COMMERCE
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Abstract

Mechanical ventilation systems in large office buildings are designed to meet space conditioning loads and to maintain acceptable indoor air quality. In order to achieve acceptable air quality, the ventilation systems are designed to bring in a minimum amount of outside air whenever the building is occupied. In addition to minimum outside air intake levels, there must also be adequate distribution of this air within the building. Although the net ventilation rate of a building or room may be sufficient, poor air distribution may lead to some areas within the space being inadequately ventilated. The concept of ventilation effectiveness has been developed to quantify the air distribution characteristics of a ventilated space. This paper examines several definitions of ventilation effectiveness and associated tracer gas measurement techniques. Techniques for making ventilation effectiveness measurements in mechanically ventilated office buildings are discussed with reference to building and mechanical equipment design and tracer gas instrumentation. Specific strategies are proposed for measuring ventilation effectiveness on different scales ranging from individual rooms to whole buildings.

Key words: air distribution; building performance; measurement; mechanical ventilation; tracer gas measurement; ventilation; ventilation effectiveness; ventilation system performance.

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NOMENCLATURE

A_e, A_j	constants in two-zone ventilation model
C	tracer gas or pollutant concentration
C_e	exhaust air concentration
C_j	concentration at point J
C_s	supply air concentration
$\overline{C}$	average concentration in a space
$f(t)$	frequency distribution of fluid elements leaving a space
$F(t)$	age distribution of fluid elements leaving a space
k	number of zones in a multi-zone model
m	volume of tracer gas injection
$\dot{m}$	tracer gas injection rate gas (vol/t)
N	ventilation rate (t^{-1})
Q	airflow rate (vol/t)
Q_{ij}	airflow rate from zone i to zone j (vol/t)
Q_s	supply airflow rate (vol/t)
r	fraction of exhaust air which is recirculated
s	fraction of supply air which bypasses occupied zone
t	time
V	room or building volume
$\langle \varepsilon_a \rangle$	room average relative air-diffusion ventilation efficiency
$\varepsilon_{a,j}$	relative air-diffusion ventilation efficiency at point J
ε_a'	local air exchange indicator
ε_j	steady-state relative ventilation efficiency
$\overline{\varepsilon}$	room average steady-state relative ventilation efficiency
ε_r	pollutant removal efficiency

ε_t	instantaneous transient relative ventilation efficiency
$\overline{\varepsilon}_t$	room average instantaneous transient relative ventilation efficiency
ε_t'	integral transient relative ventilation efficiency
η	ventilation efficiency from Janssen model
$\phi(t)$	frequency distribution of fluid elements within a space
$\Phi(t)$	age distribution of fluid elements within a space
σ	constant in two-zone ventilation model, or mixing factor
τ_n	inverse of air exchange rate (t)
τ_t	turnover time (t)
$\mu_f^{(1)}$	mean residence time of contaminant leaving the room (t)
$\mu_\phi^{(1)}$	room average of the internal age (t)
$\mu_{\phi_j}^{(1)}$	mean age of the internal air at point J (t)

1. INTRODUCTION

The establishment of minimum ventilation rates in buildings to maintain the health and comfort of occupants has been a subject of interest for many years and continues to be an important area of concern. Efforts to conserve energy for space conditioning have led to reduced building ventilation rates, and increased concern about minimum outside air intake levels. Standards and recommendations for minimum ventilation rates are generally in units of volumetric airflow rate per person or per unit floor area, and depend on room type (kitchen, conference room) and activity (smoking) (ASHRAE 1981). Building ventilation systems are designed to satisfy these minimum outside air intake levels whenever the building is occupied. Even if the ventilation system is bringing in a sufficient amount of outside air, the air may not be well distributed within the interior space. Airflow rate, supply air temperature, and the location, size and type of supply outlets and return grilles affect the distribution of the ventilation air. The concepts of ventilation effectiveness (Sandberg 1981, Skåret and Mathisen 1982) are used to quantify the effectiveness of ventilation air in removing the existing air within a room and replacing it with freshly conditioned air.

When evaluating a ventilation system's ability to remove an internally generated pollutant, the pollutant emission characteristics are important. If the pollutant is generated continuously, or for a period of time which is long compared to the inverse of the building air exchange rate, the ventilation system's air distribution performance is characterized by the equilibrium concentration of the pollutant at various locations. Brief pollutant discharges are characterized by time-integrated exposures to the pollutant and peak concentrations. The spatial characteristics of pollutant emission is another important factor, i.e. whether the pollutant is emitted from specific locations or uniformly over a large area.

The ventilation effectiveness for a space and its ventilation system is determined by several variables, including differences between the supply and room air tempertures. The temperatures of room surfaces in relation to the room air temperature also affect the airflow within the room, as do the type and position of supply and exhaust air openings and the flow rates through them. The direction and extent of spread of the airflow from supply terminals has been studied as a function of the variables discussed above (Straub et al 1956 and 1957, Nevins 1976), and design guidelines exist for the selection of supply outlets (ASHRAE 1985). These terminals are generally selected to provide good mixing of the supply air with the room air in order to avoid subjecting the occupants directly to the supply air temperature, or to excessive temperature variations and drafts. The concepts of "effective draft temperature" and the Air Diffusion Performance Index (ADPI) have been developed to quantify air diffusion performance in terms of thermal comfort (ASHRAE 1985).

While ventilation effectiveness has become an active field of study in recent years, ventilation system performance has been studied for many years (Lidwell 1960, Jennings and Armstrong 1971, Kusuda 1976). Most of the recent ventilation effectiveness research has involved experiments in test rooms with reconfigurable intake and exhaust openings and controllable supply air temperatures and ventilation rates (Sandberg 1981 and 1983, Sandberg, Blomqvist and Sjöberg 1982, Malmström and Ahlgren 1982, Skåret and Mathisen 1982 and 1983). In these tests, ventilation effectiveness is measured as a function of opening position, airflow rate and temperature difference between the supply and room air. While these experiments have been extremely valuable, the test conditions are quite different from the situation encountered in offices in real buildings. In real offices, air enters and leaves from locations other than the supply and exhaust air openings. There are leaky windows, doors to other offices, and additional openings in the room boundary. The extent to which these other airflows affect ventilation effectiveness is not clear. The ventilation effectiveness can still be measured in real offices, but the results may not lend themselves to straightforward interpretation. Additional ventilation effectiveness measurements have been conducted in naturally (Maldonado and Woods 1983) and mechanically (Offermann et al 1983) ventilated residential buildings. There have also been a limited number of measurements in large mechanically ventilated buildings (Skåret and Mathisen 1985).

This report is concerned with the measurement of ventilation effectiveness in office buildings. Office buildings and their mechanical ventilation equipment are discussed, along with tracer gas equipment for ventilation effectiveness measurements. Several definitions of ventilation effectiveness are presented and related to the situation encountered in office buildings. Finally, experimental techniques are proposed for use in office buildings to measure ventilation effectiveness in individual offices, zones within buildings, and whole buildings. An appendix gives examples of techniques for measuring ventilation effectiveness in office spaces, including tracer gas injection and sampling locations.

2. BUILDING DESIGN AND EQUIPMENT

Office buildings vary in size, zoning, air handling equipment, and air distribution system design. All of these factors must be considered when designing experiments to measure ventilation effectiveness. Tests may be designed to study a single room, a zone containing several rooms, or a whole building. The specific area of interest will affect which techniques can be used and how they are applied.

The design of air distribution systems in office buildings is quite varied and cannot be completely covered here, but additional information is available elsewhere (ASHRAE 1984). Office buildings air handlers, located in mechanical equipment rooms, serve particular sections or zones of a building. The number of air handlers and the manner in which the occupied space is divided into zones varies greatly among buildings. The air handlers contain supply fans that force conditioned air through a system of ductwork to supply air terminals in the occupied space. The air leaves the space predominantly through exhaust or return air grilles, and enters a network of return ducts. The return air is generally drawn by a return air fan back to the mechanical equipment room. Some of the return air is exhausted to the outside and the rest is recirculated back into the supply airstream, where it mixes with new outside air. The amount of air that is recirculated and the amount of outside air intake is determined by the HVAC control system, based on the outdoor conditions and the space conditioning load. There is also a significant amount of airflow into and out of the building due to envelope leakage, often similar in magnitude to the intentional ventilation rate. The ventilation requirements mentioned earlier translate into a design minimum rate of outside air intake, intended to be brought into the supply airstream independent of the amount of recirculation or total airflow. This design minimum is supposed to be achieved either by employing a minimum position of the outside air intake dampers or a subset of the intake dampers that never close. Some building operators rely on uncontrolled air leakage through the building envelope to provide a sufficient amount of outside air and close the outside air intake dampers completely. This strategy provides little or no control over air distribution and indoor air quality.

Within a conditioned zone, even a single room, there are generally several supply air outlets served by a common supply duct. Similarly, there are several exhaust air openings that feed into the return air system. In this report we are discussing systems which employ supply air outlets which are designed to entrain room air into the primary supply airstream. Figure 1 shows a schematic of an air distribution network for an office building zone. A supply air shaft, which also serves other areas, passes through this zone, and a supply air duct branches off of the shaft to serve this zone. The supply duct branches off further to several supply air outlets throughout the space. In most modern office buildings, the ductwork shown in figure 1 is located above a dropped ceiling, while the space below may be divided by internal partitions. The space above the dropped ceiling is generally used as a return air plenum, i.e. the exhaust or return air grilles are simply openings in the dropped ceiling through which air flows from the occupied space. The return air plenum is generally open over an entire floor. This return air flows through the plenum and enters the return air shaft through an opening in that shaft. In general, there are only about two or three such openings into the return air shaft on each floor.

3. TRACER GAS EQUIPMENT

The ventilation effectiveness measurement techniques discussed below employ tracer gases to either simulate a pollutant or to tag the supply air. In designing these tests, one must consider the characteristics of the tracer gas analysis equipment including the range of measurable concentration and the sampling frequency. Since one often needs to measure the concentration at several locations, the sampling frequency of the equipment determines how often the concentration at each location can be measured. For some ventilation effectiveness measurement techniques, an average tracer gas concentration is useful and can be obtained by filling an air sample container over an appropriate interval of time.

Ventilation effectiveness measurements also require tracer gas injection equipment. The injection flow rates must be matched to the measurable concentration range, the ventilation airflow rates, and the volumes of the zones of interest. It is generally desirable to inject a tracer gas, which simulates a pollutant, in an unobtrusive manner, i.e. at low enough flow rates such that the airflow patterns within the room are not disturbed.

There are many tracer gases and concentration measuring devices which can be used in ventilation effectiveness measurements. Many of these devices have been previously employed to study infiltration and ventilation in buildings (Hunt 1980), and include automated systems that can operate unattended for long periods of time (Grot, Hunt and Harrje 1980, Grot 1982). Equipment capable of measuring the concentrations of several different tracer gases has been used to study airflows between different zones in a building and can be useful in studies of ventilation effectiveness (I'Anson et al 1982, Dietz et al 1984).

4. THEORETICAL BACKGROUND

Several definitions and theoretical frameworks have been used to discuss ventilation effectiveness. Three approaches to ventilation effectiveness are discussed below. The first type of ventilation effectiveness measures are referred to as "concentration efficiencies" and are based on relations between gas concentrations in the supply air, the exhaust air, and at various locations in the room. Efficiencies based on age distributions and residence times, using approaches of chemical reactor engineering, are also presented. Finally, multi-tracer techniques to measure interzone airflow rates are discussed.

Figure 2 depicts three important cases of ventilation air movement which are referred to in discussions of ventilation effectiveness. Maximum ventilation effectiveness is associated with the idealized case in which the supply air displaces the room air without mixing, so-called "piston flow." While piston flow corresponds to maximum ventilation effectiveness, it may lead to undesirable thermal comfort conditions. In some discussions of ventilation effectiveness, the idealized case of perfect mixing serves as a reference. Perfect mixing is defined to occur when the supply air or an internally generated pollutant is uniformly and instantaneously mixed with all the room air, thus the pollutant concentration is uniform throughout the room. Ventilation effectiveness is generally minimized when a significant portion of the supply air "short-circuits" the occupied zone and flows out of the space without reaching the occupants.

4.1 Concentration Efficiencies

4.1.1 Definitions

Much work has been done using ventilation efficiencies based on relations between pollutant, or tracer gas, concentrations in a room or zone. The first group of these definitions are based on a ventilation system's steady-state performance. The steady-state relative ventilation efficiency ε_j, denoted as ε^r_j by Sandberg (1981) and ε_{II} by others (Skåret 1982, Malmström and Ahlgren 1982), expresses how the system's ventilation effectiveness varies throughout a room. It is defined as

$$\varepsilon_j = (C_e - C_s) / (C_j - C_s) \qquad (1)$$

where

C_e = concentration in the exhaust air

C_j = concentration at point J in the room

C_s = concentration in the supply air.

These are concentrations of a general pollutant, or a tracer gas, which may be carried in the supply stream and/or generated within the room. For many pollutants, the supply air concentration C_s is practically zero when there is no recirculation of the return air. The concentration at point J can be replaced by the average room concentration $\overline{C}$ to define a room average relative ventilation efficiency $\overline{\varepsilon}$.

For a pollutant generated within a room, one can examine the three cases shown in figure 2. In the case of perfect mixing, the tracer concentration is uniform throughout the room and equal to the exhaust concentration, thus the relative ventilation efficiency equals one. The case of perfect mixing then serves as a reference. When there is less than perfect mixing, the exhaust air concentration may be higher than the concentration at a point J within the room, depending on the location of the pollutant source and the point J, leading to values of ε_j which are greater than one. This is generally a favorable situation. In the extreme case of piston flow, the value of ε_j depends on the position of point J relative to the location of the pollutant source. If the pollutant is generated downstream of point J, then C_j will equal C_s and the relative ventilation efficiency is infinite. When there is short circuiting of the supply air to the exhaust air outlet, and the pollutant is generated in the space which is being bypassed by the ventilation air, C_j will be greater than C_e. The relative efficiency is then less than one, a generally undesirable situation.

Sandberg also defines "transient" ventilation efficiencies for the situation in which a room starts with a spatially homogenous pollutant concentration and there are no pollutant sources. If the air within the room is perfectly mixed, the concentration C decreases with time t according to

$$C = C(0)e^{-Nt} \tag{2}$$

where N is the ventilation rate of the room in exchanges per hour and C(0) is the initial pollutant concentration. In the more typical case of imperfect mixing, the concentration decay is more complex and can be analyzed by dividing the room into a number of perfectly mixed zones which exchange air with each other. The mathematics for multi-zone decay is discussed by Sinden (1978). In multi-zone models, the concentration in each zone is the sum of k decay terms similar in form to eq (2), where k is the number of zones in the model. After some time t_o, the concentrations in all the zones decay at the same rate and the ratio of the concentrations in any two zones is a constant. In a specific two zone application, one zone represents the occupied space, characterized by C_j, and the other zone is characterized by the exhaust air concentration C_e. Thus, after a sufficiently long time ($t>>t_o$), these concentrations are given by

$$C_e(t) = A_e e^{-N\sigma t} \tag{3a}$$

$$C_j(t) = A_j e^{-N\sigma t} \tag{3b}$$

where A_e, A_j and σ are constants. As noted above, after a sufficiently long time the ratio of $C_e(t)$ to $C_j(t)$ becomes constant. Sandberg defines this ratio as the "transient relative ventilation efficiency,"

$$\varepsilon_t = C_e(t) \;/\; C_j(t). \tag{4}$$

As in the case of the steady-state relative ventilation efficiency, the average room concentration $\overline{C}(t)$ can be substituted for $C_j(t)$ to define a room average transient efficiency $\overline{\varepsilon}_t$. The constant σ in eq (3) has been referred to as a mixing factor (Kusuda 1976) and proposed as a measure of ventilation effectiveness (Skåret and Mathisen 1983). Sandberg cautions against considering $N\sigma$ to be a local ventilation rate because spatial differences in ventilation capability will be underestimated and the value depends on when the measurements are made (Sandberg 1981).

Sandberg defines an integral transient ventilation efficiency based on the areas under the dilution curves,

$$\varepsilon_t' = \int_0^\infty C_e(t)dt \Big/ \int_0^\infty C_j(t)dt. \qquad (5)$$

The value of ε_t' corresponds to the steady-state relative ventilation efficiency ε_j for a homogeneous, unobtrusive pollution source in a room. This equivalency can be generalized to an arbitrary pollution source distribution. When the initial concentration distribution used in the determination of ε_t' is "geometrically similar" to the steady-state pollution source distribution corresponding to ε_j, then the transient ventilation efficiency ε_t' equals the steady-state ventilation efficiency ε_j.

All of these concentration definitions are based on a model of the office space in which all the air flows in through a supply vent and out through an exhaust vent. In real buildings, air also enters and leaves through windows, doors to the outside and adjacent offices, and other air leakage locations. Some of this air is from outside and some is "stale" air from other occupied spaces. These additional air flows are not accounted for by the above definitions.

4.1.2 Two-Zone Model

A two-zone model, in which the space under consideration is divided horizontally into two perfectly mixed zones, is often used to study office ventilation effectiveness. Figure 3 shows four different cases of supply and exhaust air vent location for a two-zone ventilation model. The diagrams are only meant to depict in which zone the supply and exhaust vents are located, not the number of vents or their specific locations within the zone. Q is the airflow into and out of the total space volume, and βQ is the flow between the zones where β is a fraction which ranges from zero to infinity. $\beta = 0$ corresponds to no mixing, and $\beta = \infty$ corresponds to complete mixing between the zones. Case A is representative of the vent arrangement found in most modern U.S. office buildings, and some have suggested that it may lead to situations where a significant fraction of the supply air short-circuits the occupied zone.

Sandberg (1981) has applied the two-zone model, for cases A and D, and for the case of perfect mixing, to calculate the steady-state relative ventilation efficiency ε_j. He assumes the two zones are of equal volume, and characterizes the upper zone by the exhaust air concentration C_e. He solves for the steady-state pollutant concentration in the lower, occupied zone C_j and the ventilation efficiency ε_j, depending on whether the pollutant is released in the lower zone, upper zone or uniformly in both zones. One can determine both the ventilation efficiency and the mixing coefficient β from C_j, C_e, the room volume V, and the tracer gas injection rate m.

Others (Skåret and Mathisen 1982, Malmström and Ahlgren 1982) have also used a two-zone model to calculate ventilation efficiencies as a function of the mixing parameter β. They consider all four of the cases shown in figure 3, and use this two-zone approach in test rooms to make actual measurements of ventilation efficiency as a function of vent position, ventilation rate, and the temperature difference between the supply and the room air. When the supply air terminal is located in the upper zone, the ventilation efficiency decreases as the supply air overtemperature increases, due to thermal stratification. The highest ventilation efficiencies are measured when the supply and exhaust air vents are located in different zones. For these cases, C and D, the ventilation efficiency decreases with increasing values of β, while for case A, an increase in β leads to increased ventilation efficiency.

Figure 4 shows calculated values of ventilation efficiency for two cases of a two-zone model as a function of the mixing parameter β (Sandberg 1981). As mentioned above, when the supply and exhaust vents are in different zones, the ventilation efficiency is greater than 1.0 and an increase in mixing between the two zones decreases the ventilation efficiency. When both vents are in the upper zone, an increase in mixing increases the ventilation efficiency towards one. Figure 5 shows measured values of the integral transient ventilation efficiency ε_t' at various heights in a small test room (41 m^3) with an exhaust inlet located on a sidewall, 0.2 m below the ceiling, and a supply outlet mounted in the center of the ceiling (Sandberg 1981). The ventilation efficiency is plotted against air exchange rate for various temperature differences between the supply and room air. In general, the larger the temperature difference, the lower the ventilation efficiency, presumably due to increased thermal stratification. Also, except for the largest temperature difference, the ventilation efficiency increases with increasing air exchange rate.

As mentioned earlier, these two-zone approaches assume air flows in and out of the room only through the vents. In real offices, there are many other airflows. If one includes the additional airflows, the relations between equilibrium concentrations, ventilation rate, and ventilation efficiency no longer apply. In addition, mechanical ventilation systems often employ recirculation of the exhaust air and this is not dealt with in these models. Janssen has developed a two-zone approach to ventilation effectiveness which includes recirculation and is based on the schematic of office ventilation shown in figure 6 (Harrje and Janssen 1984). In this model s is the fraction of the supply airflow Q_s which bypasses the occupied part of the room, and r is the fraction of the exhaust air which is recirculated and mixed with the new outside air. Janssen defines a ventilation efficiency as

$$\eta = (Q_{01} - Q_{10-s}) / Q_{01} = (1-s) / (1-sr) \qquad (6)$$

where Q_{01} is the flow rate of outside air into the building and Q_{10-s} is the amount of this outside air which bypasses the occupied space and is exhausted. This ventilation efficiency has a maximum value of 100%, corresponding to no bypassing (s=0). One can measure its value by injecting a tracer gas into the supply air such that the exhaust air concentration builds up before the concentration in the occupied zone. While this may be difficult in some cases, if it is possible then one can use the decay in exhaust air concentration to determine η. While this model accounts for recirculation, it neglects flow between the occupied zone and the rest of the building and its value will be influenced by air leakage through the building envelope.

4.2 Age Distributions

Age distributions and residence times have been used in the analysis of fluid flow through chemical reactors to quantify departures from perfect mixing and piston flow (Danckwerts 1953). Sandberg (1983) and others (Skåret and Mathisen 1985) have employed these concepts in the study of ventilation airflow. The age of a fluid element is defined to be the time that has passed since the element entered the space. Three populations of fluid elements of interest are defined: the total internal population of all elements within the space, the local internal population at some point within the space, and the external population of elements leaving the space. Each population is characterized by a cumulative age distribution F(t), which is the fraction of the population with an age less than or equal to t. A frequency distribution f(t) is defined as the derivative of F(t). Sandberg describes how to measure some of the age and frequency distribution functions of the three populations described above using tracer gas methods. These measurement procedures are reproduced in table 1 (Sandberg 1983). F anf f are the age distribution and frequency distribution, respectively, of the fluid elements leaving the room, while Φ and ϕ are the age and frequency distributions of the population within the room.

One defines moments of these frequency distributions for use in the analysis of air quality and ventilation effectiveness. The nth moment of the frequency distribution is

$$\mu_f^{(n)} = \int_0^\infty t^n f(t)\, dt \qquad (7a)$$

$$= n \int_0^\infty t^{(n-1)} [1-F(t)]\, dt \quad (n>0). \qquad (7b)$$

The first moment $\mu_f^{(1)}$ is equal to the mean age for the population described by the frequency distribution f(t).

Sandberg (1983) defines a "relative air-diffusion efficiency" $\langle\varepsilon_a\rangle$ according to

$$\langle\varepsilon_a\rangle = \tau_n/\mu_\phi^{(1)}. \qquad (8)$$

$\mu_\phi^{(1)}$ is the room average of the internal air age, and τ_n is the inverse of the air exchange rate of the space. One may also define an air-diffusion efficiency at a point J $\varepsilon_{a,j}$ by substituting the average internal air age at point J $\mu_{\phi_j}^{(1)}$ into eq (8). For the idealized case of perfect mixing, $\mu_\phi^{(1)}$ equals τ_n, and the air diffusion efficiency is one. For pure piston flow, $\langle\varepsilon_a\rangle$ equals 2.0. Skåret and Mathisen (1985) define an air exchange efficiency which is equal to $\langle\varepsilon_a\rangle$ divided by 2.0. They characterize local conditions with a local air exchange indicator

$$\varepsilon_a' = \mu_\phi^{(1)} / \mu_{\phi_j}^{(1)} \qquad (9)$$

If the local interior air age $\mu_{\phi_j}^{(1)}$ is less than the room average age $\mu_\phi^{(1)}$, a generally favorable situation at that location, then ε_a' has a value greater than one. Another quantity of interest is the mean residence time of an internally generated contaminant leaving the room $\mu_f^{(1)}$. This quantity can be determined in several ways, and compared to τ_n to evaluate ventilation system performance.

As in the case of concentration efficiencies, age distribution analysis is based on the assumption that air only enters through supply inlets and only leaves through exhaust outlets. Additional inflows and outflows complicate the situation, and it is not clear how the interpretation of the measured results should be modified. Also, existing tracer gas measurement techniques assume that the ventilation system operates under conditions of 100% outside air intake (no recirculation of return air). The various ages are still useful concepts, but their measurement under recirculation is more difficult.

4.3 Multi-Zone Approach

We have reviewed ventilation efficiencies based on measured concentrations and on residence times. These concepts are straightforward to apply and interpret for spaces in which air flows only through the supply and exhaust air vents. In real office buildings, however, there are many more airflows than the four shown in figure 3. In the airflow schematic shown in figure 7, zone #1 can be considered to be the occupied portion of a room and #2 the ventilation zone, corresponding to case A in figure 3. Zone #3 is the rest of the building, and the background is the outside. There are three zones exchanging air with each other and the outside, for a total of twelve airflows.

Multi-zone airflow analysis techniques have been discussed previously, along with the use of multiple tracer gases to determine all the various airflow rates (Sinden 1978, I'Anson et al 1982, Dietz et al 1984). In the multi-zone techniques which we consider, the building is divided into three zones, as shown in figure 7, and a different tracer gas is released in each zone. If tracer gas A is released into zone 1, tracer B into zone 2 and C into 3, then the concentration of tracer gas A in each zone is described by the following equations

$$dC_{1A}/dt = \dot{m}_A - C_{1A}\,(Q_{10} + Q_{12} + Q_{13}) + C_{2A}Q_{21} + C_{3A}Q_{31} \qquad (10a)$$

$$dC_{2A}/dt = - C_{2A}\,(Q_{20} + Q_{21} + Q_{23}) + C_{1A}Q_{12} + C_{3A}Q_{32} \qquad (10b)$$

$$dC_{3A}/dt = - C_{3A}\,(Q_{30} + Q_{31} + Q_{32}) + C_{1A}Q_{13} + C_{2A}Q_{23}. \qquad (10c)$$

Q_{ij} is the air flow rate from zone i to zone j, $\dot{m}_x$ is the injection rate of tracer gas x, and C_{ix} is the concentration of tracer x in zone i. There are similar sets of equations for tracer gases B and C.

In a steady-state application, there is constant injection of a different tracer gas into each zone. After a sufficiently long period of time, one measures the equilibrium concentration of each of the three tracer gases in each of the three zones. From these measured concentrations and the injection rates, one determines the airflow rates shown in figure 7. In another technique, a pulse of a different tracer gas is released into each zone and the subsequent tracer concentrations are monitored. From the measured concentration and eq (10), one can solve for all the airflows in figure 7. These techniques involve more complex tracer gas concentration measurement and injection procedures, but they provide a complete description of the airflows involved.

5. EXPERIMENTAL TECHNIQUES

The following section describes the experimental application of the ventilation effectiveness definitions described above. The various techniques are discussed with reference to isolated zones, large zones, and whole buildings. An isolated zone is a room or space with its own supply and exhaust vents, and is enclosed by walls but not further divided by walls. Such a zone may exchange air with the outside through windows and other leakage sites, and with the rest of the building through doorways and other openings. Isolated zones without air leakage are used in most of the previous experimental work done in test rooms. Large zones consist of several offices or isolated zones, and are generally subdivided by permanent partitions. They may be served by one or more air handlers, and they may share these air handlers with other zones. An example of a large zone is an entire floor of a building. All of these techniques are based on the assumption that there is no recirculation of return air.

5.1 Concentration Efficiencies

The following experimental techniques are designed to measure the concentration efficiencies discussed in section 4.1.1. The first technique involves the steady-state relative ventilation efficiency ε_j employing a two-zone model (case A in figure 3) and a constant injection of tracer gas at a known rate $\dot{m}$ into the working space. To simulate a diffuse pollutant source, one should employ a diffuse tracer gas release, such as a well-distributed, multi-point injection. If one is simulating the release of carbon dioxide or odors from people, then the use of single injection points is appropriate. The number of injection points should be based on reasonable levels of occupant density. The simulation of a diffuse pollutant release, for example from carpets, requires a more homogeneous tracer gas source.

The lower, occupied portion of the room is characterized by the tracer concentration C_j, and the upper zone by the exhaust concentration C_e. This situation has been analyzed by Sandberg (1983). The steady-state concentration in the occupied zone is

$$C_j = ((\beta+1) / \beta) \dot{m}V/Q, \tag{11}$$

the steady-state concentration in the exhaust is

$$C_e = \dot{m}V/Q, \tag{12}$$

and the steady-state relative ventilation efficiency is

$$\varepsilon_j = C_e / C_j = \beta/(\beta+1). \tag{13}$$

β is the mixing parameter discussed in section 4.1.2. From measurements of these two steady-state concentrations, the injection rate $\dot{m}$, and the room volume V, one can estimate the ventilation efficiency ε_j, the mixing parameter β, and the airflow rate Q. These measurements are conducted with the HVAC system running at 100% outside air so that the supply air concentration is zero. In general, there will be several exhaust air vents serving the test space and they should all be monitored. To avoid errors due to fluctuations in the concentrations, average concentrations can be obtained with air sample containers. To obtain tracer concentrations within the range of one's analysis equipment, for the injection flow rates which can be accurately measured, a dilute mixture of tracer gas may be required. The amount of dilution can be estimated from eq (12) assuming reasonable values for the air exchange rate and the tracer injection rate and concentration. Since the room being tested will exchange air through locations other than the HVAC air terminals, the estimates of Q, β and ε_j will not be exact. These additional airflows will decrease both C_j and C_e by unknown amounts and may increase or decrease the measured value of ε_j. Some of the additional air will flow in from outside while the rest will be from other locations within the building. To keep such concerns to a minimum, this measurement procedure is best applied to zones which are as isolated as possible from the rest of the building and the outdoors. To measure ε_j in a large zone or whole building, one must release the tracer uniformly throughout the entire occupied space. Such an injection strategy may be difficult.

The measurement of the transient ventilation efficiencies defined by eq (4) and (5) requires a uniform tracer gas concentration throughout the space in question. This initial condition can be achieved by injecting tracer into the supply duct at a constant rate and waiting until all locations in the space are at the same concentration. The test begins at t=0 with an essentially uniform tracer distribution within the space and the HVAC system running at 100% outside air. One then monitors the decay in tracer concentration within the space C_j and in the associated exhaust C_e.

After a sufficient period of time, the concentrations at all locations will decay at the same rate. The transient relative ventilation efficiency is then given by eq (4)

$$\varepsilon_t = C_e(t) \,/\, C_j(t). \qquad (4)$$

In this case $C_e(t)$ should be the average concentration for all exhausts, although the differences among the separate exhaust vents may be of interest. C_j can be measured at several locations within the space to obtain information on local variations in ventilation effectiveness. After a sufficient period of time, the efficiency in eq (4) will have a constant value except for random variations. To avoid errors due to such fluctuations, average concentrations can be measured at each location using air sample containers which are filled over an appropriate length of time. If this averaging period starts at t=0 and ends when all concentrations have decreased to zero, the ratio of the average concentrations in the exhaust and at point J is equal to ε_t in eq (5). This technique can be applied simultaneously to isolated zones and to larger zones. In determining the ventilation efficiency for a given zone, one uses the exhaust air concentration for that zone. Since the injection strategy is simpler for measurements of the transient efficiencies, and since the value of ε_t is related to the steady state efficiency ε_j, it may be more appropriate in large zones to measure the transient efficiency than the steady-state efficiency. The fact that the measurement of ε_t begins with a uniform tracer gas concentration throughout the space means that it is similar in value to the steady-state ventilation efficiency ε_j for a pollutant source which is uniform throughout the space.

5.2 Age Distributions

There are several ways to characterize ventilation effectiveness using age distribution techniques. The techniques vary in the tracer gas injection procedures and in the concentration measurement locations. Four different experimental procedures are outlined in table 2 and discussed below.

The first experiment involves the injection of tracer into the room at a constant rate $\dot{m}$ to simulate a pollutant source. The mean residence time of the contaminant leaving the room can the be computed according to (see table 1)

$$\mu_f^{(1)} = \tau_t = \int_0^\infty [1-F(t)]\, dt$$

$$= \int_0^\infty [1-C_e(t)/(\dot{m}/Q)]dt. \tag{14}$$

τ_t is referred to as the "turnover" time of the contaminant. After a sufficiently long period of time T, $C_e(t)/(\dot{m}/Q)$ will approach one and $\mu_f^{(1)}$ can be determined by

$$\mu_f^{(1)} = T - [\int_0^T C_e(t)dt\ ]/C_e(\infty). \tag{15}$$

$C_e(\infty)$ is the equilibrium concentration of tracer in the exhaust duct and equals $\dot{m}/Q$. Thus, from the values of $C_e(\infty)$ and $\dot{m}$, one can determine the ventilation airflow rate Q. The integral in eq (15) is simply the average exhaust air concentration from 0 to T, and can be determined with an air sample container. By relating the turnover time τ_t to the turnover time under conditions of perfect mixing, $\tau_n = V/Q$, one obtains a pollutant removal efficiency

$$\varepsilon_r = \tau_n/\tau_t. \tag{16}$$

Values of ε_r greater than one correspond to more effective pollutant removal than would occur under conditions of perfect mixing. Because of additional airflow through the room, $\dot{m}/C_e(\infty)$ will equal the ventilation airflow Q plus other incoming air leakage. There is no way to distinguish between the supply airflow and air leakage from outside or from other rooms. Application of this experiment to a large zone or whole building would require one to inject the tracer gas uniformly throughout the entire space, which may be difficult.

In the second experiment a pulse of tracer gas m is released into the room to again determine $\mu_f^{(1)}$. In this case,

$$\mu_f^{(1)} = \int_0^\infty tC_e(t)/(m/Q)\, dt. \tag{17}$$

This integral must be determined numerically from measurements of exhaust concentrations. Exhaust air concentrations made roughly every minute should be sufficient to evaluate the integral in eq (17), however one still needs to know the value of Q to determine $\mu_f^{(1)}$ and τ_n. Q may be determined from the equality of (m/Q) and the integral of C_e over time. Again, the value of Q determined in this way includes airflows other than that through the ventilation system. Application of this experiment to a large zone would be extremely difficult because it would require the synchronization of the tracer gas pulses in each of the constituent zones. Thus, this second procedure is probably most appropriate for a smaller zone which is as isolated as possible from the rest of the building and the outside.

The third experiment is designed to measure the room average of the internal air age $\mu_\phi^{(1)}$ and the average internal air age at a point J $\mu_{\phi_J}^{(1)}$ by injecting tracer at a constant rate $\dot{m}$ into the supply air duct. $\mu_\phi^{(1)}$ is determined by measuring the exhaust air concentration according to

$$\mu_\phi^{(1)} = (1/\tau_n) \int_0^\infty t[1- C_e(t)/(\dot{m}/Q)]\, dt. \tag{18}$$

The integral must be determined numerically from measurements of $C_e(t)$. The equilibrium exhaust air concentration $C_e(\infty)$ is equal to $(\dot{m}/Q)$, and can be used to determine Q. $\mu_\phi^{(1)}$ can then be used to determine the air-diffusion efficiency $\langle\varepsilon_a\rangle$ according to eq (8). The local mean internal air age $\mu_{\phi_j}^{(1)}$ can be determined by measuring the concentration at point J $C_j(t)$,

$$\mu_{\phi_j}^{(1)} = \int_0^\infty [1- C_j(t)/(\dot{m}/Q)]\ dt. \tag{19}$$

This integral can be evaluated by using an air sample container which is filled until equilibrium is established. Thus, one can determine $\mu_\phi^{(1)}$ by monitoring the exhaust concentration during the test, and determine $\mu_{\phi_j}^{(1)}$ at several locations from air sample containers filled during the test. This technique is applied to a particular zone by injecting the tracer into the supply duct for that zone.

The fourth experiment yields the same information as the third by turning off the tracer gas injection after equilibrium has been reached during the previous experiment. During this "step-down" or decay test,

$$\mu_\phi^{(1)} = (1/\tau_n) \int_0^\infty t\ C_e(t)/C_e(0)\ dt. \tag{20}$$

and

$$\mu_{\phi_j}^{(1)} = (1/C_j(0)) \int_0^\infty C_j(t)\ dt. \tag{21}$$

The value of τ_n in eq (20) can be determined from the values of $C_e(\infty)$ and $\dot{m}$ before the decay begins. Equation (20) requires continuous monitoring of C_e to be evaluated, while eq (21) can be evaluated through the use of air sample containers. Skåret and Mathisen (1985) point out that the results obtained in the decay regime are probably more relaible than those obtained during the concentration buildup when building envelope air leakage occurs. This is because when there is leakage not all of the incoming air can be tagged with the tracer gas.

All of the above age distribution measurement techniques are complicated by the existence of airflows other than those through the ventilation system. Because of these other airflows, the equations used to determine Q are no longer appropriate.

5.3 Multi-Zone Approach

The single tracer measurement techniques are complicated by the fact that the spaces are subject to airflows other than those through the supply and exhaust air vents. These additional airflows prevent straightforward relations between the tracer gas measurements and the airflows of interest. Multiple tracer gas techniques can be used to overcome the limitations of the single tracer techniques, although they involve more complex tracer gas measuring equipment.

Figure 7 is a schematic of a three-zone model of the ventilation of a single office. The office itself is divided into two zones. The lower, occupied zone is #1 and the upper zone is #2. The rest of the building interior is referred to as zone #3. Each zone is assumed to be uniformly mixed. There are a total of twelve different airflows between each of the zones and the outside, and these flows characterize the ventilation of the office in question. The measurement of these different airflows with several tracer gases is discussed earlier. The details of injection and sampling for each zone depend on the building's floor plan and air distribution system. Regardless of which tracers are used, for each gas and each zone there is a tracer gas mass balance, for a total of nine equations. There are also three independent mass balances of the airflows Q_{ij}, providing twelve equations to determine the twelve airflow rates shown in figure 7. The values of Q_{ij} are not used in existing definitions of ventilation effectiveness, but they provide a complete characterization of the ventilation of the office in question.

6. CONCLUSIONS

We have reviewed several approaches to evaluating ventilation effectiveness in mechanically ventilated offices and office buildings. Two basic approaches which employ a single tracer gas, concentration efficiencies and age distribution measurements, were examined in detail. The steady-state relative ventilation efficiency ε_j is in general most appropriate to isolated zones, while the transient ventilation efficiencies, ε_t and ε_t, can also be applied in larger zones and whole buildings. Four different age distribution measurement procedures are described. The first two yield values of the pollutant removal efficiency ε_r and are most appropriate to isolated zones. The third and fourth procedures provide estimates of the air diffusion efficiency $\langle\varepsilon_a\rangle$ and the local air exchange indicator ε_a and can be applied to large zones and whole buildings. These single tracer approaches have been applied to test rooms in which air enters and leaves only through well defined locations.

Real offices have additional uncontrolled air leakage through windows and doors to the outside and adjoining offices. These additional airflows complicate the application of concentration and age distribution efficiencies such that airflows and other quantities of interest cannot be measured. Ventilation effectiveness can still be measured, but the results no longer the ventilation system performance. Regardless, single tracer measurements of ventilation effectiveness are useful because of their simplicity, and in some cases may provide an indication of what is occuring in the ventilated space. To completely characterize the airflows in and out of an office space, multiple tracer gas techniques must be used. These techniques are more complex, but they provide all the information required to evaluate the ventilation of an office space.

7. ACKNOWLEDGMENTS

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9. APPENDIX: EXPERIMENTAL DETAILS

In this section, experimental details are presented for ventilation effectiveness measurements. These details include tracer gas injection rates and strategies, sampling locations and other information, and are presented for isolated zones, large zones, and whole buildings. A multi-tracer measurement procedure ia also discussed.

A1. Isolated Zone

The details of ventilation effectiveness measurements in an isolated zone are presented for the room shown in figure A1. This is a small office (53.1 m^3) with a supply vent located under the window and an exhaust vent located above the door. The exhaust vent is simply a grill that opens into the hallway, which is exhausted through a return duct. In the experiments described below, the door is assumed to be closed. Without making the measurements, we do not know the ventilation flow rate through the room. This information is sometimes available from mechanical equipment specifications, but these can be different from the actual airflow rates. We assume the room is ventilated at 3 air changes per hour, which equals 0.044 m^3/s.

Concentration Efficiencies

To measure the steady-state relative ventilation efficiency, we use the two-zone approach outlined earlier. The tracer gas, sulfur hexafluoride (SF_6), is injected at a constant rate $\dot{m}$ into the working space. The injection rate can be estimated from eq (12) assuming a steady-state exhaust concentration C_e equal to 100 ppb. As stated above $Q = 0.044\ m^3/s$, and therefore $\dot{m} = 0.26$ cc/min of SF_6. This is a very low flow rate to measure and control. If one uses a 0.1% mixture of SF_6 in air, then the injection flow rate is 260 cc/min, which is much more manageable. If the actual ventilation flow rate is very different from the assumed value, one can adjust $\dot{m}$ as needed. If one wishes to inject the gas diffusely within the occupied zone, this can be done with a perforated tube running across the floor of the room, as depicted by the dotted line in figure A1. If one is simulating a pollutant emitted by people, than a single point source for each person is appropriate. After the injection starts, one monitors the SF_6 concentration at the exhaust vent to determine when steady-state conditions have been achieved. Once equilibrium exists, one fills several air sample containers at table-top or breathing zone height to obtain values of the steady-state concentration at several locations in the occupied zone C_j. These containers can be filled from outside the room through tubes which run under the door to avoid disturbing the airflow patterns within the room. The containers can be filled over a period of time on the order of 10 minutes to obtain average values of C_j. During this same period, one monitors C_e to determine its average value. From C_e, $\dot{m}$ and the room volume V, one determines the ventilation flow rate Q from eq (12). For each value of C_j, one can determine a mixing parameter β and a relative ventilation efficiency ε_j from eq (11) and (13). Because there will be airflow in and out of the room through windows, doors and other leakage locations, the estimate of Q will not be exact, nor will the estimates of β and ε_j.

To measure either of the transient ventilation efficiencies ε_t or ε_t', one must start with a uniform tracer concentration within the room. This can be achieved by injecting SF_6 into the supply vent at a constant rate. To begin with 200 ppb throughout the room, one can determine the injection flow rate $\dot{m}$ by setting $\dot{m}/Q$

equal to 200 ppb. For Q equal to 3 air changes per hour, the injection rate is 0.53 cc/min. Again, with a 0.1% mixture of SF_6 in air, the injection rate is 530 cc/min. After the injection is started, C_e should be monitored to determine when steady-state has been achieved. At this point, the injection is stopped and the measurement begins. To determine the integral ventilation efficiency ε_t', one needs the average value of C_e from t=0 until C_e has decreased to zero. The average values of C_e and C_j over this period can be obtained using air sample containers. To determine the instantaneous ventilation efficiency ε_t, one needs average values of C_e and C_j for shorter time periods, after the concentrations have begun to decay at the same rate.

Age Distribution

No. 1

The first experiment involves the injection of tracer into the room at a constant rate $\dot{m}$ to simulate a pollutant and to determine the mean residence time of the contaminant leaving the room $\mu_f^{(1)}$. In this experiment, one can use the same injection arrangement for measuring the steady-state relative ventilation efficiency and the same dilute mixture of SF_6. One monitors the exhaust concentration C_e starting when the injection starts and ending when steady-state is achieved. The value of $\mu_f^{(1)}$ is calculated over the monitoring period from eq (15). A sample container is used to obtain an average value of C_e, but one must still monitor C_e during the test to assure that equilibrium has been established. To determine the pollutant removal efficiency, one also needs the value of $\tau_n = V/Q$. τ_n can be determined from the equality of $C_e(\infty)$ and $\dot{m}/Q$.

No. 2

This experiment involves the release of a pulse of tracer gas into the room to simluate a pollutant and again yields a value of $\mu_f^{(1)}$. One monitors C_e throughout the test and determines $\mu_f^{(1)}$ from eq (17). To obtain a value of Q for determination of τ_n, one employs the equality of m/Q to the area under the curve of C_e vs time. One can obtain an approximate value for the tracr gas pulse volume by assuming C_e = 25 ppb and that it takes two hours for C_e to decrease to zero. In this case, m = 8 cc of SF_6. This gas should be released over a time period which is very short compared to τ_n = 20 min. Choosing a 30 sec injection time, the injection rate must be 16 cc/min. One must be certain to get all of the tracer into the room.

No. 3

In the third experiment, one injects tracer into the supply duct at a constant rate $\dot{m}$ to obtain estimates of $\mu_\phi^{(1)}$, the room average interior air age, and $\mu_{\phi j}^{(1)}$, the average internal air age at a point J. $\mu_\phi^{(1)}$ is determined with eq (18) and requires continuous monitoring of the exhaust concentration. $\mu_{\phi j}^{(1)}$ can be determined at several locations in the occupied zone by filling sample containers until C_e attains its equilibrium value (eq (19)). In this experiment one can use the same injection rate, 260 cc/min, and the same dilution mixture of SF_6, 0.1%, as in the determination of ε_j. To determine τ_n one requires Q, which can be obtained from the equality of $C_e(\infty)$ and $\dot{m}/Q$.

No. 4

This experiment takes place during the decay in concentration after the injection in No. 3 is stopped. $\mu_\phi^{(1)}$ is determined from continuous monitoring of the exhaust C_e and eq (20). The values of $\mu_{\phi_i}^{(1)}$ are obtained by filling containers in the occupied zone and using eq (21).

A2. Large Zone

The large zone for which ventilation effectiveness measurements are described below is shown in figure A2. It is a large office area with permanent walls enclosing the area shown in the figure. The left and bottom walls are on the outside of the building and have windows where noted. The volume is 327 m^3. There is a 1 m high return air plenum above the ceiling, which contains the supply ductwork. The room is ventilated by six 1.5 m slots, 0.6 m of which provide supply air. The other 0.9 m is a return air vent which simply opens into the return air plenum above the dropped ceiling. Assuming that the zone is ventilated at 3 air changes per hour, then Q equals 0.27 m^3/s and the value of τ_n for the zone is 20 min.

Concentration Efficiency

The steady-state ventilation efficiency measurement is very similar to the one described above for a single room, except this large zone has a more complex exhaust system. The tracer gas injection rate $\dot{m}$ required to yield a steady-state exhaust concentration of 100 ppb is 0.26 cc/min. Therefore, a 0.1% mixture of SF_6 in air will require an injection rate of 260 cc/min. One possible injection strategy is indicated in figure A2, where perforated tubes (denoted by dotted lines) are distributed around the room. Other injection schemes may be used, depending on the nature of the pollutant one is trying to simulate. Six workplace sampling points are shown for the measurement of C_j with sample containers. The six exhaust vents also need to be sampled individually with containers and the resultant concentrations averaged to determine C_e for the zone. One cannot simply measure C_e in the plenum space, because such a measurement will in general not provide a representative value of C_e for the space. One should monitor some of the exhaust concentrations during the test to determine when steady-state exists, and when to begin filling the sample containers.

To measure the transient ventilation efficiency one needs to begin with a uniform concentration of tracer throughout the zone. An initial concentration of 200 ppb can be obtained by injecting SF_6 at a constant rate into the main supply duct and waiting until the tracer gas concentration is uniform within the space. In this case, the SF_6 injection rate is based on the airflow rate through the supply duct. By monitoring the concentration at the various workplace locations, one can determine when a uniform tracer gas concentration has been achieved. At this point the supply duct injection is stopped, and the measurement begins. During the experiment one samples the concentrations at all six exhaust vents and at workplace locations of interest. To measure the integral transient ventilation efficency ε_t', one fills air sample containers at the different locations, starting when the injection stops and ending when all the concentrations decrease to zero. The instantaneous transient ventilation efficiency is determined from short term average concentrations at these same locations after the tracer gas decay rate is uniform at all the locations.

Age Distribution

No. 1

In this test one injects tracer at a constant rate to simulate a pollutant source in the occupied space using the same flow rate and dilute SF_6 mixture that was suggested for measuring the steady-state ventilation efficiency. One monitors several of the exhaust concentrations during the test to determine when steady-state has been achieved. During this period one fills air sample containers from the exhaust, starting when the injection begins and ending after steady-state exists, to determine the average exhaust concentration during the period. As in the case of ε_i, it may be difficult to inject the tracer uniformly throughout larger zones with complex layouts.

No. 2

In this test one releases a pulse of tracer gas into the occupied zone, and can use the injection scheme already mentioned. Assuming an average SF_6 concentration of 25 ppb over a 2 hour period and an airflow rate through the room of 0.27 m^3/s, one obtains a tracer pulse volume of 50 cc. This experiment requires continuous monitoring of the exhaust concentration, and since this zone has six exhaust vents, this may present a problem. It takes one minute to measure the SF_6 concentration with electron capture detectors, therefore each exhaust location can be sampled only once every six minutes. If this measurement frequency is not sufficient to evaluate the integral in eq (17), one may sample a mixture of the air from all six exhaust locations. The value of Q is determined from the equality of m/Q and the integral of C_e over time.

No. 3

This experiment requires a constant injection of SF_6 into the supply duct at the same rate and dilution as in the measurement of the steady-state relative ventilation efficiency. The injection must be made into the supply duct before it branches off to the six supply vents for this zone. However, if this supply duct also serves other areas then this injection location is inappropriate. In addition, the tracer gas must be well-mixed with the supply air before it reaches the supply vents. If a well-mixed injection can be made into the supply duct of this room, then one continuously monitors the exhaust air concentrations to determine the room average internal air age from eq (18). One uses air sample containers to determine local mean internal ages at locations within the workplace using eq (19). The exhaust concentrations are monitored and the containers are filled until equilibrium is attained in the zone. The value of Q is determined from the fact that $C_e(\infty) = \dot{m}/Q$.

No. 4

This experiment is the decay in concentration after the injection in experiment No. 3 is stopped. Continuous exhaust concentrations and average workplace concentrations are measured as in experiment No. 3. The measurement continues until all the concentrations decrease to zero.

A3. Whole Building

To demonstrate the techniques which can be used for whole building ventilation effectiveness measurements, we consider an office building with a volume of about 1.25×10^5 m^3. The whole building is served by a single supply fan that feeds into a large supply duct that handles all the floors. The return air from each floor flows into a large return duct that flows up to a return air fan. The building employs ceiling return air plenums.

Concentration Efficiency

The measurement of the steady-state ventilation efficiency on a whole building scale is not discussed due to the potential difficulty of injecting the tracer gas uniformly throughout all the workplace locations throughout the building. This measurement is generally practical only for individual offices or large zones of manageable size.

To achieve the desired initial conditions of uniform tracer gas concentration throughout the building for measuring the transient relative ventilation efficiency, one must inject tracer at a constant rate into the supply air duct for the whole building. At 3 air changes per hour, the injection rate should be about 1.25 l/min to obtain a concentration of 200 ppb. By sampling the air at each floor's opening into the return air duct, one can determine when steady-state exists. At this point the tracer gas injection is stopped and the measurement begins. One samples workplace and exhaust concentrations for any office or zone as described earlier using sample containers. If one has sufficient containers, and can control all of them, one can determine an average floor concentration and an average transient ventilation efficiency for the floor. Similarly, a total building average transient ventilation efficiency can be determined from an average concentration determined over the total building workplace. Some questions exist concerning timing since after the tracer injection is stopped in the penthouse, it takes different amounts of time for the 0 ppb supply air to reach different floors. One could account for this delay when filling the sample containers on different floors, but the delay time is short compared to the characteristic time of the system, and therefore this is probably an insignificant effect.

Age Distributions

No. 1

This experiment requires a constant, uniform injection of tracer gas throughout the building workspace which may be difficult to accomplish, as mentioned for the steady-state ventilation efficiency. Therefore, this experiment is generally inappropriate for a whole building.

No. 2

As in experiment No. 1, it would be very difficult to inject a pulse of tracer uniformly throughout a building at one time. Again, this experiment is probably inappropriate for a whole building.

No. 3

This experiment requires a constant injection of SF_6 into the main supply duct at about 0.6 l/min to obtain an equilibrium concentration of about 100 ppb. One can determine the average internal air age for the building by monitoring the building return air concentration using eq (18), and the same age for a floor from the floor return air concentration. Again, these exhaust concentrations must be monitored continuously, and the sampling frequency required to evaluate the integral in eq (18) determines how many floors can be studied in one experiment. Also, the value of $\mu_{\phi}^{(1)}$ for each floor can only be compared to the whole building τ_n because one does not know the value of m for individual floors. Local mean internal ages can be determined with eq (19) using air sample containers filled at workspace locations, starting at the injection time and ending when the equilibrium concentration has been obtained.

No. 4

This test is simply the decay in concentration after the injection of No. 3 has stopped. One must measure the floor and whole building exhaust (return) continuously to determine $\mu_{\phi}^{(1)}$ using eq (20). Again, one must use τ_n for the whole building from No. 3 since one cannot determine τ_n for individual floors. The values of $\mu_{\phi j}^{(1)}$ for workspace locations are determined from containers filled starting when the injection stops until the concentration decreases to zero.

A4. Multi-Tracer

In this section an example is outlined of a multi-tracer experiment involving the zone in figure A2 as part of the whole building discussed in section A3. This experiment involves three zones, as shown in figure 7, in which zone #1 is the workspace of the test area and zone #2, referred to as the ventilation zone, corresponds to the upper zone of a two-chamber model of an office area. Zone #3 refers to the rest of the building. In this experiment a different tracer gas is injected at a constant rate into each of the three zones and the equilibrium concentrations of each gas in each zone are measured. Due to the large building volumes and the cost of the tracers, measurements in the ppb range are desirable. Various refrigerants can be used as tracers with analysis times on the order of five minutes per sample. A wide range of measurable concentrations are required, particularly for tracers A (zone #1) and B (zone #2). Because the volume of zone #3 is in general much larger than #1 and #2, the concentrations of tracers A and B will be much lower in zone #3 than in the other two zones.

The injection and sampling arrangements for this test will depend on the zone volumes, the ventilation system design, and the building zoning arrangement. The injection of tracer gas A into zone #1 should be a diffuse arrangement as discussed earlier. It is difficult to estimate the injection rate without knowing the airflow rates which are being measured. An estimation can be made based on the total room volume (327 m^3) and an assumed ventilation rate of 3 air changes per hour. If the maximum measurable concentration of tracer A is 500 ppb, then the injection rate should be 1.3 cc/min. The actual concentration in zone #1 will be different than 500 ppb due to two opposing influences. Mixing between the room and the rest of the building will tend to decrease the concentration, while a lack of mixing between zones #1 and #2 will tend to increase the zone #1 concentration. The air samples in zone #1 should be taken at occupied locations of interest which are not too close to the tracer gas injection points.

Tracer gas B is injected in zone #2 and should be released into the supply air stream. The injection rate should be estimated just like the injection rate of tracer gas A, but using the maximum measurable concentration of tracer B. This injection can take place in the supply duct before it splits off into the six outlets which serve the room, but only if this duct serves no other rooms. Otherwise, the injection must be split proportionately among the six outlets. The air for zone #2 should be sampled at the six exhaust vents, either separately at each vent or from a mixture of air from all the vents.

The injection on tracer gas C into the rest of the building is the most complicated. This injection should be uniform, in terms of tracer flow rate per unit volume, throughout the building except for the room being tested. On all the floors except for the floor containing the test room, the tracer can be injected into the supply duct for each floor. The injection rate should be based on the floor volume, an estimate of the air exchange rate, and a target concentration of about 75% of the maximum measureable concentration of tracer gas C. On the floor containing the room, the tracer should be injected at branches in the supply duct such that the entire floor receives the gas except the test room. This may require several injection points, and each injection rate should be sized according to the same target concentration and based on the volume of the floor section served by the duct branch which is receiving the injection. The tracers in this test can be injected using passive emitters similar to those employed in the PFT infiltration measurement technique (Dietz et al 1984).

After the injections are begun, one samples the air at each location to determine when equilibrium has been established. Once equilibrium has been achieved, an average value of each of the three tracer concentrations in each of the three zones is measured. Using eqs (10) and their versions for the other two tracers, one solves for the twelve flows shown in figure 7. The solution also requires the mass balances of the airflows for each zone.

Table 1 Age Distributions Obtained from Different Injection Procedures (Sandberg 1983)

INJECTION POINT → / LOCATION OF MEASURING POINT → / INJECTION PROCEDURE ↓	SUPPLY DUCT: EXTRACT DUCT	SUPPLY DUCT: IN THE ROOM	IN THE ROOM: EXTRACT DUCT
PULSE m $[m^3]$	$f(\tau) = \frac{c_e(\tau)}{\int_0^\infty c_e(\tau)d\tau} = \frac{c_e(\tau)}{(m/Q)}$	$\phi_P(\tau) = \frac{c_P(\tau)}{\int_0^\infty c_P(\tau)d\tau} = \frac{c_P(\tau)}{(m/Q)}$	$f(\tau) = \frac{c_e(\tau)}{\int_0^\infty c_e(\tau)d\tau} = \frac{c_e(\tau)}{(m/Q)}$
STEP-UP $\dot{m}$ $[m^3/s]$	$F(\tau) = \frac{c_e(\tau)}{c_e(\infty)} = \frac{c_e(\tau)}{(\dot{m}/Q)}$	$\phi_P(\tau) = \frac{c_P(\tau)}{c_P(\infty)} = \frac{c_P(\tau)}{(\dot{m}/Q)}$	$F(\tau) = \frac{c_e(\tau)}{c_e(\infty)} = \frac{c_e(\tau)}{(\dot{m}/Q)}$
STEP-DOWN	$1 - F(\tau) = \frac{c_e(\tau)}{c_e(0)}$	$1 - \phi_P(\tau) = \frac{c_P(\tau)}{c_P(0)}$	$1 - F(\tau) = \frac{c_e(\tau)}{c_e(0)}$
POPULATION →	AIR LEAVING THE ROOM	LOCAL POPULATION OF AIR AT POINT P	CONTAMINANT LEAVING THE ROOM

Table 2 Summary of Age Distribution Measurement Techniques

No.	Injection	Concentration	Calculation	Age
1	Constant rate into room	$C_e(t)$	Time average	$\mu_f^{(1)}$
2	Pulse into room	$C_e(t)$	Integration	$\mu_f^{(1)}$
3	"Step-up" Constant rate into supply duct	$C_e(t)$	Integration	$\mu_\phi^{(1)}$
		$C_j(t)$	Time average	$\mu_{\phi_j}^{(1)}$
4	"Step-down" (No injection)	$C_e(t)$	Integration	$\mu_\phi^{(1)}$
		$C_j(t)$	Time average	$\mu_{\phi_j}^{(1)}$

$\mu_f^{(1)}$ = mean residence time of contaminant leaving the room.

$\mu_\phi^{(1)}$ = room average of the internal air age.

$\mu_{\phi_j}^{(1)}$ = mean age of the internal air at point J.

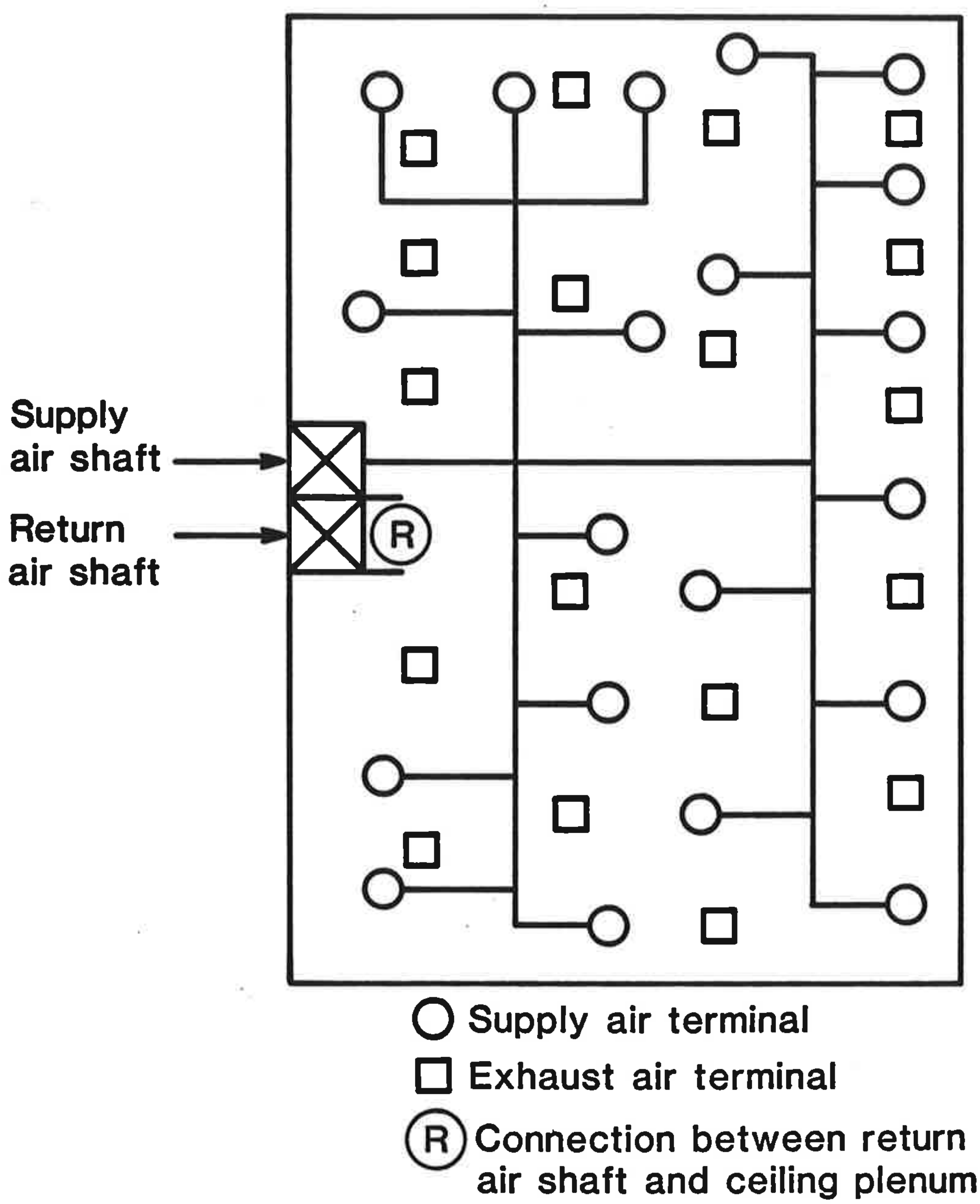


Figure 1 Example of an Air Distribution Network

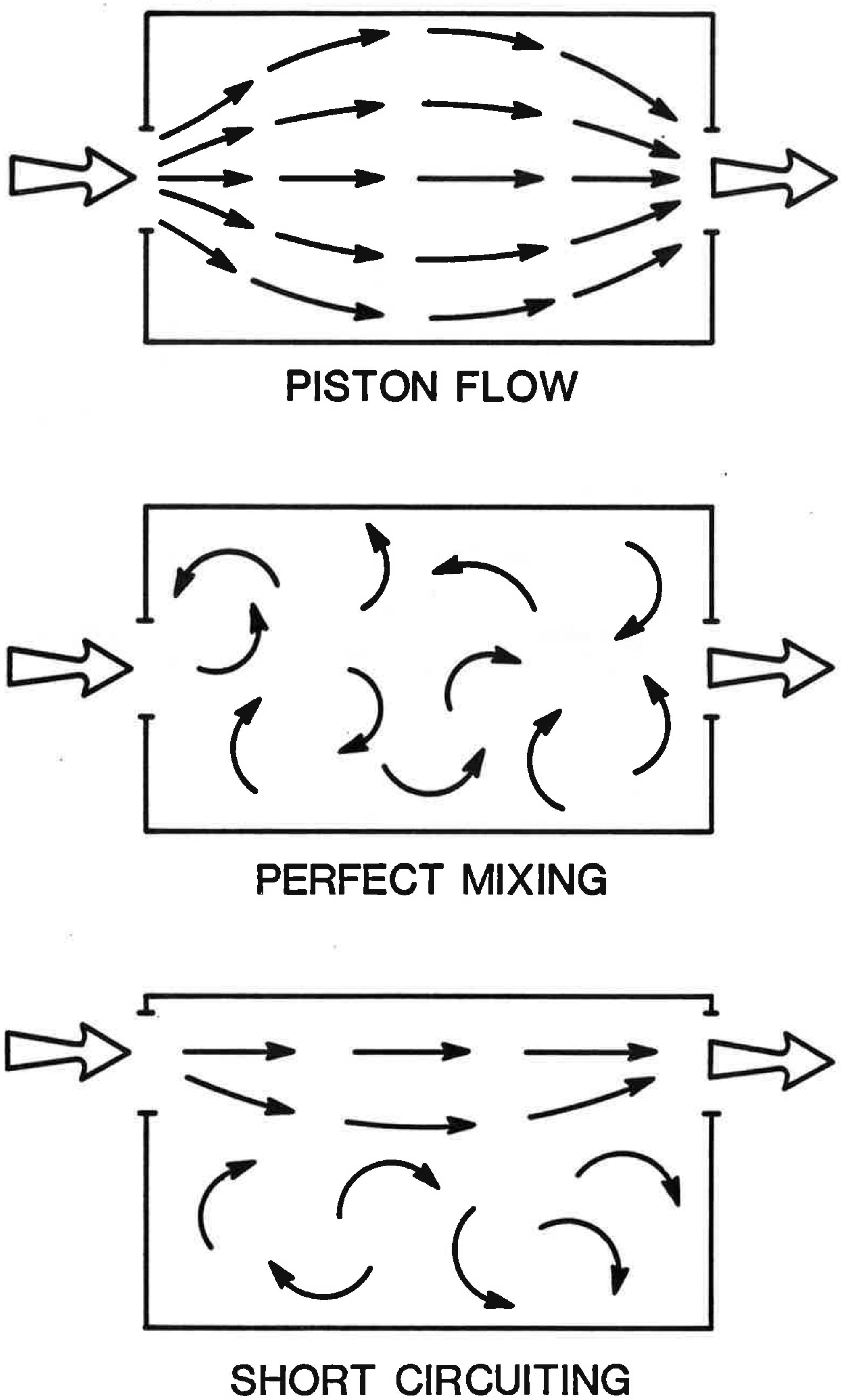


Figure 2 Representative Examples of Ventilation Air Movement

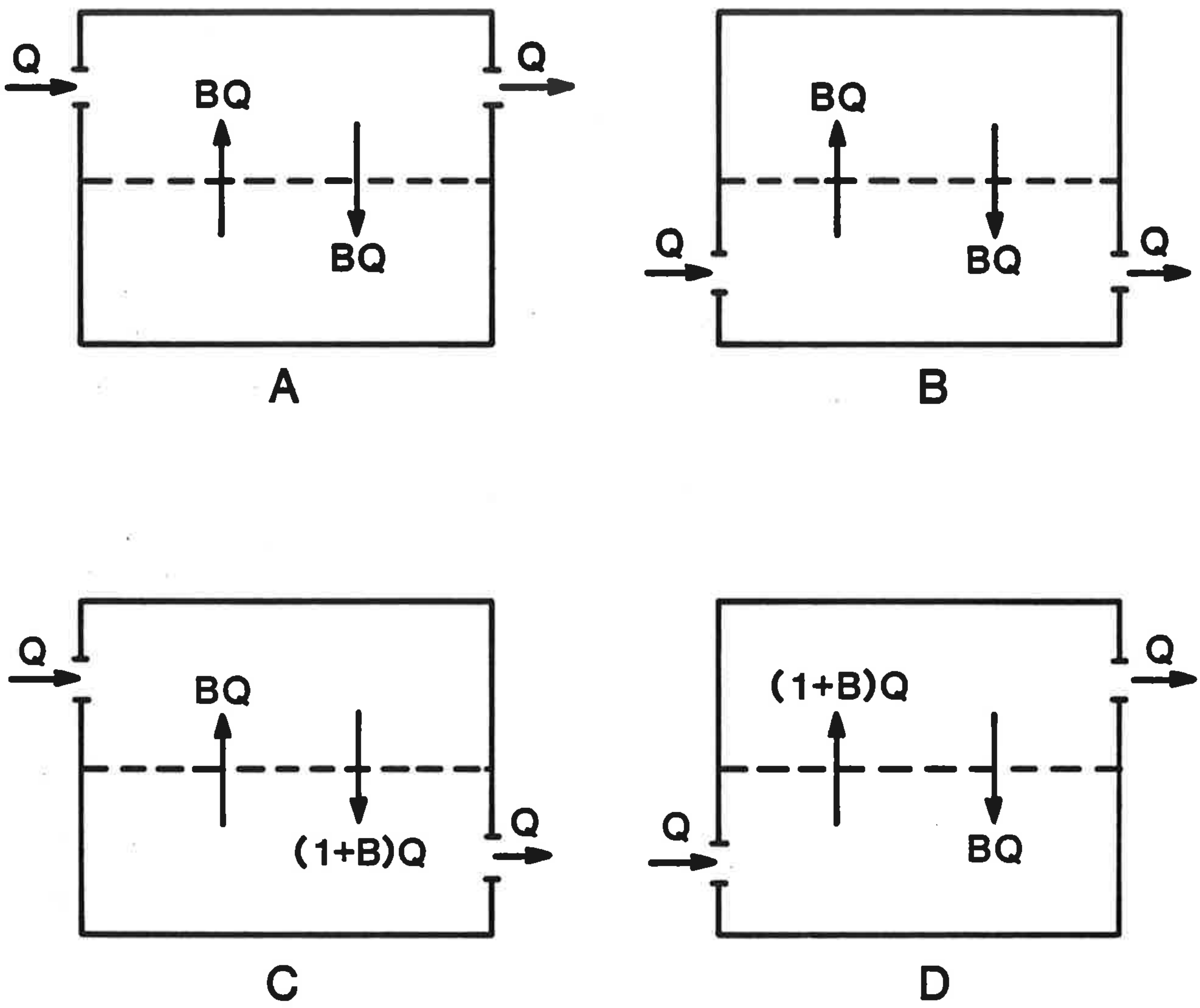
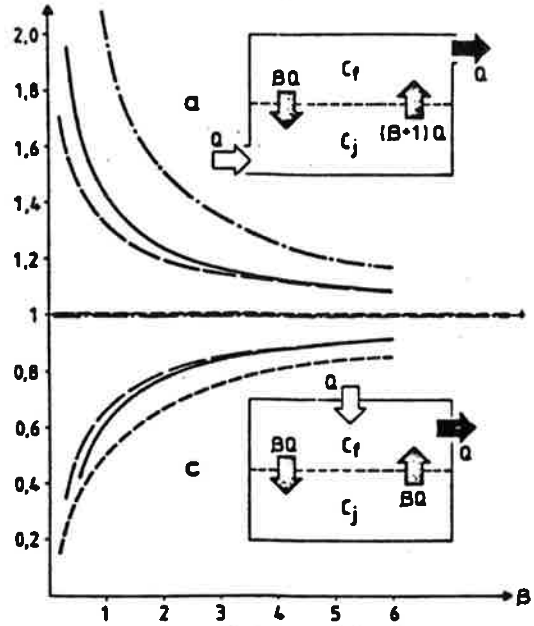


Figure 3   Flow Diagrams of Two-Zone Models



Case D in Figure 3

Case A in Figure 3

———— instantaneous transient relative ventilation efficiency

– – – – – – steady-state relative ventilation efficiency with a pollution source in the upper and lower zones

- - - - - - - - steady-state relative ventilation efficiency with a pollution source in the lower zone

—·—·—·—·— steady-state relative ventilation efficiency with a pollution source in the upper zone

Figure 4 Calculated Ventilation Efficiencies for Different Pollution Source Locations and Different Ventilation Systems (Sandberg 1981)

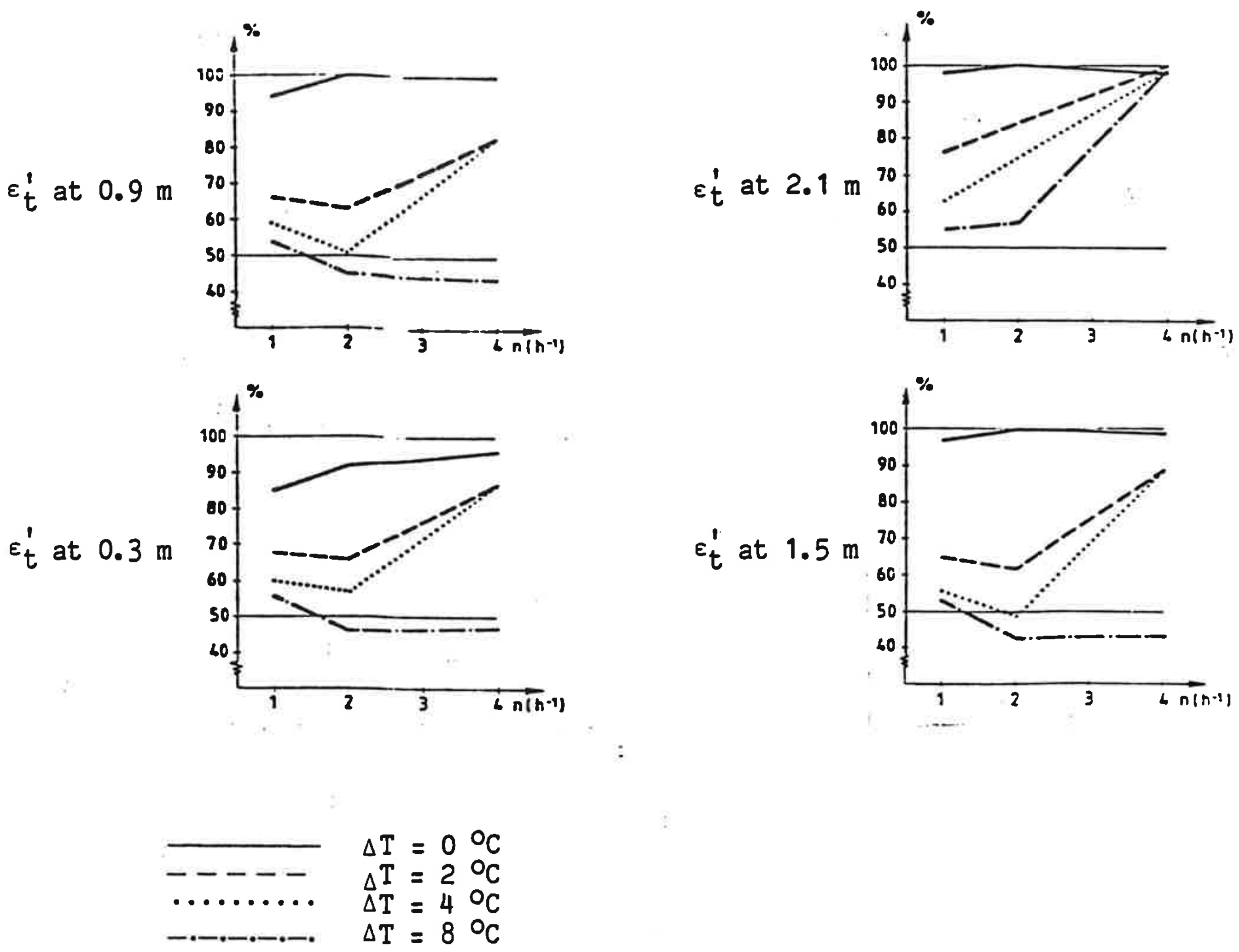


Figure 5 Measured Values of Integral Transient Relative Ventilation Efficiency at Different Room Heights under Various Conditions of Supply Air Overtemperature and Ventilation Rate (Sandberg 1981)

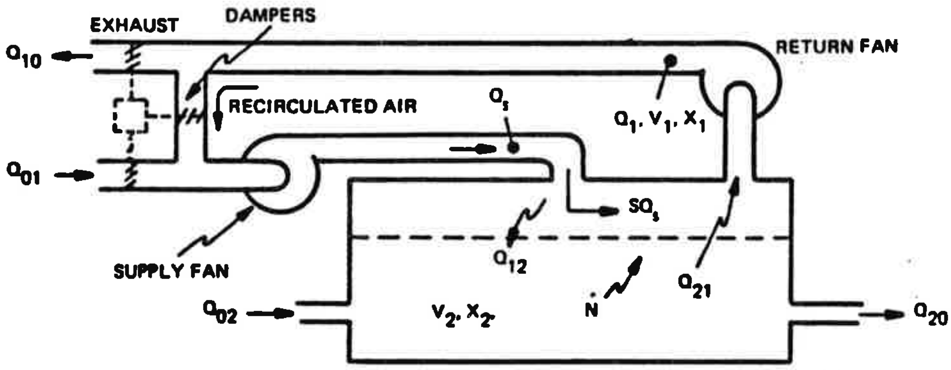


Figure 6 Ventilation System Schematic (Harrje and Janssen 1984)

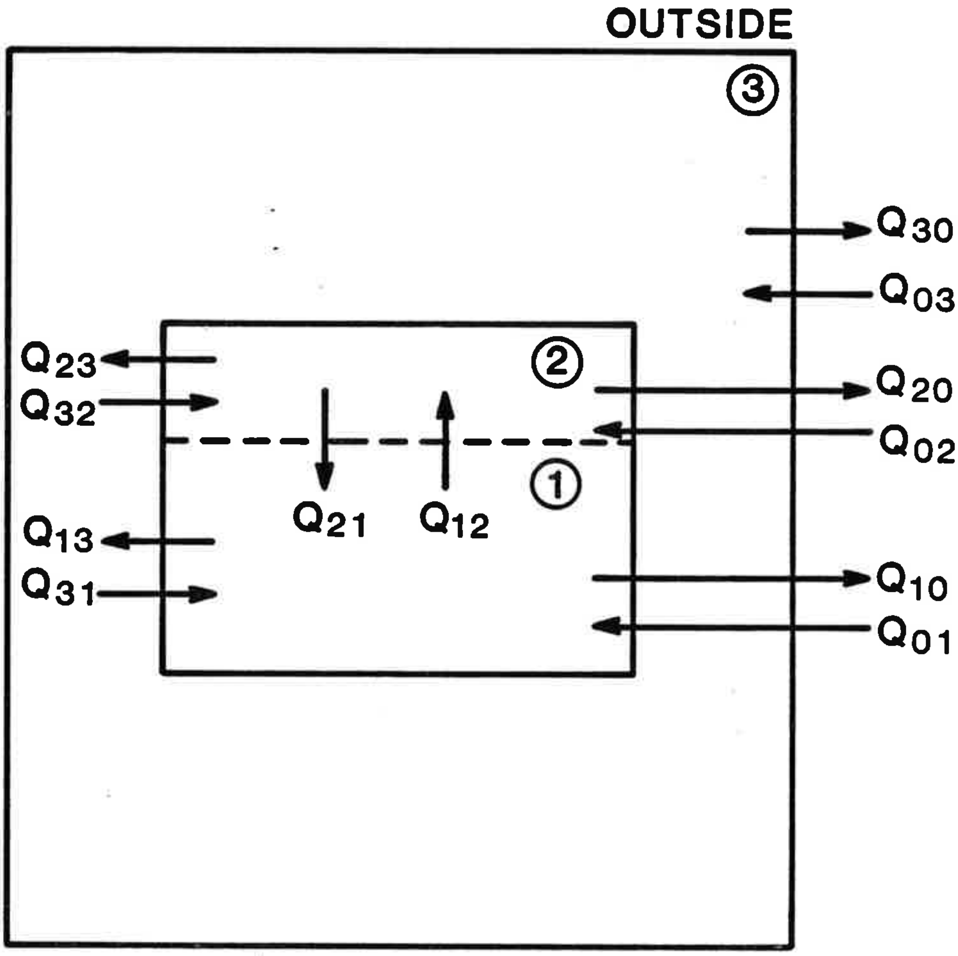


Figure 7 Schematic of a Three-Zone Model of Office Ventilation

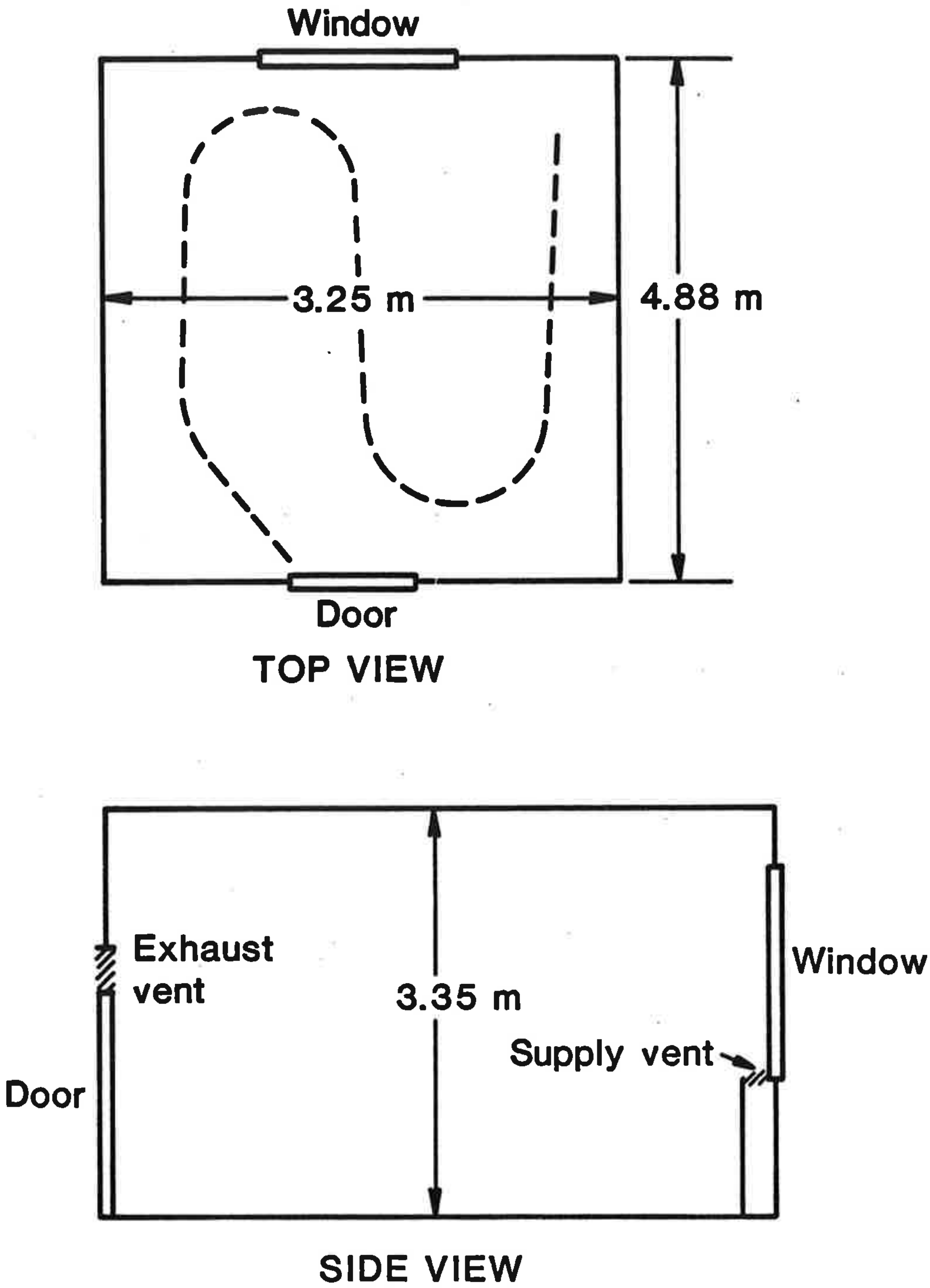


Figure A1 Example of an Isolated Zone

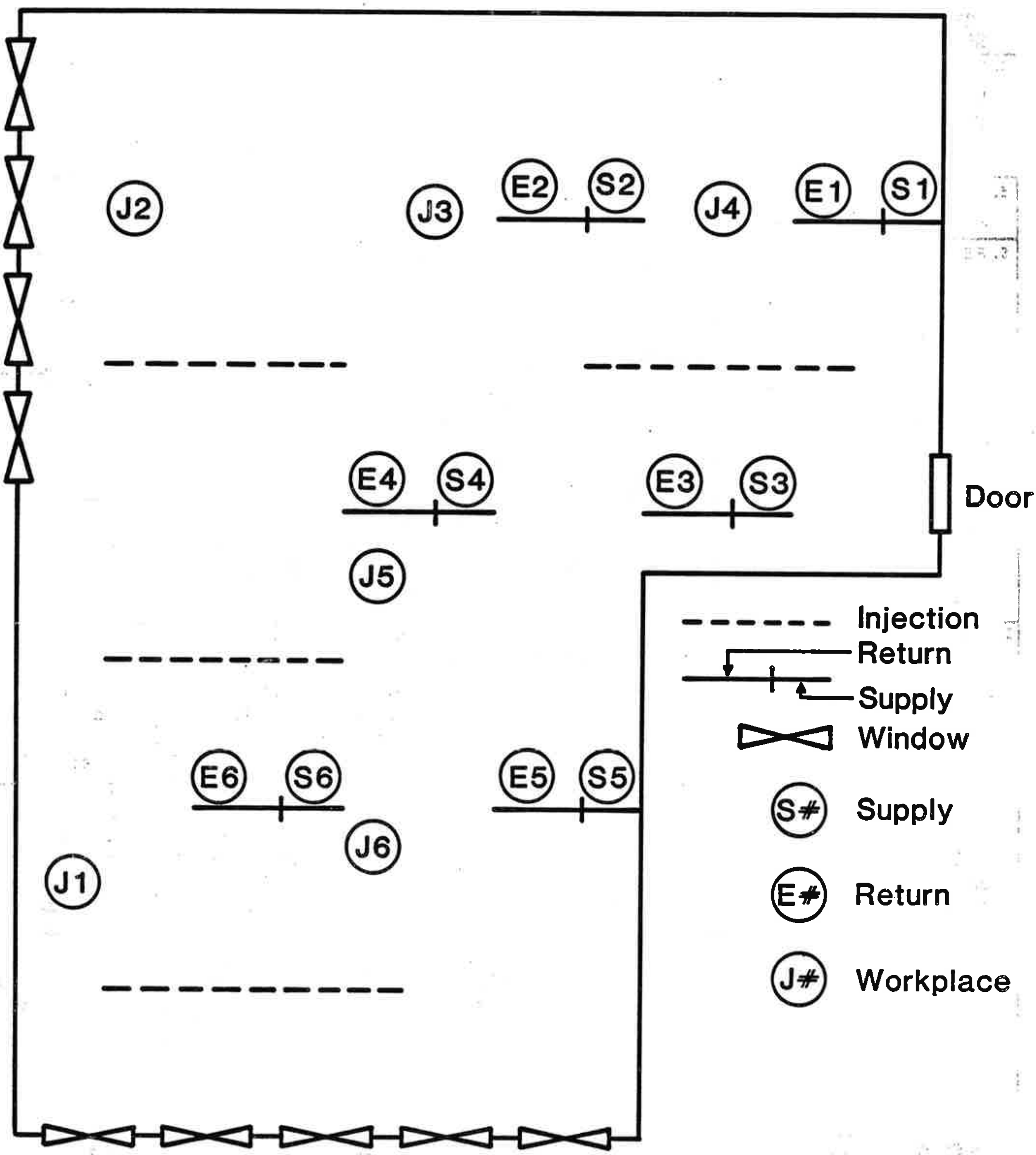


Figure A2 Example of a Large Zone

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Mechanical ventilation systems in large office buildings are designed to meet space conditioning loads and to maintain acceptable indoor air quality. In order to achieve acceptable air quality, the ventilation systems are designed to bring in a minimum amount of outside air whenever the building is occupied. In addition to minimum outside air intake levels, there must also be adequate distribution of this air within the building. Although the net ventilation rate of a building or room may be sufficient, poor air distribution may lead to some areas within the space being inadequately ventilated. The concept of ventilation effectiveness has been developed to quantify the air distribution characteristics of a ventilated space. This paper examines several definitions of ventilation effectiveness and associated tracer gas measurement techniques. Techniques for making ventilation effectiveness measurements in mechanically ventilated office buildings are discussed with reference to building and mechanical equipment design and tracer gas instrumentation. Specific strategies are proposed for measuring ventilation effectiveness on different scales ranging from individual rooms to whole buildings.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

air infiltration; building ventilation; mechanical ventilation; office building ventilation; ventilation; ventilation efficiency, tracer gas measurement

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