EFFECTIVE VENTILATION

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Paper 4

# DETERMINATION OF VENTILATION EFFICIENCY BASED UPON SHORT TERM TESTS

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## SYNOPSIS

A short term testing methodology is developed to evaluate the performance of ventilation systems with respect to control of indoor air pollutants. Two efficiency measures, displacement efficiency and removal efficiency, are defined based upon analysis of mass transport into and out of a specified control volume. The displacement efficiency measures the ability of the ventilation system to supply ventilation air to a room without short-circuiting to the return duct. The removal efficiency measures the ability of the ventilation system to remove indoor pollutants from a room before they mix with room air. Both efficiencies are based upon short term measurements taken during the time that one volume change is supplied by the ventilation system to the room. Because these efficiency measures are based upon control volume analysis, they have well defined limits as $t \to \infty$ that can be used to calibrate experimental measurements. These new efficiency measures are applied to the analysis of a ceiling based ventilation system and comparisons are made with age of air and pollutant removal effectiveness concepts.

## LIST OF SYMBOLS

$c$ concentration ($kg/m^3$)
$Q$ ventilation rate ($m^3/s$)
$q$ volumetric pollutant source strength ($m^3/s$)
$s_a$ air stratification factor, nondimensional, equation (7)
$s_p$ pollutant stratification factor, nondimensional equation (12)
$V$ room volume ($m^3$)

Greek

$\eta_d$ average room displacement efficiency nondimensional, Figure 5
$\eta_r$ average room removal efficiency nondimensional Figure 12
$\eta_p$ Pollutant delivery efficiency, nondimensional, equation (9).
$\tau$ nominal room volume replacement time, V/Q (s)

Subscripts

| | |
|---|---|
| ent | entrainment |
| o | condition at t=0 |
| in | supply |
| out | return |
| s | pollutant source |
| oz | occupied zone |

Superscripts

| | |
|---|---|
| l | local |
| rel | relative, (local)/(overall average) |
| oz | occupied zone average |

## INTRODUCTION

Increased awareness of the potential health risks associated with indoor air pollutants [1-4] has stimulated interest in improving our understanding of how ventilation air is distributed and how pollutants are transported in buildings. The task of predicting the pollutant transport produced by ventilation systems is not a simple one. Pollutant transport depends in general upon building geometry, pollutant source characteristics, and thermo/fluid boundary conditions such as flow rate, thermal stratification, duct location, and diffuser characteristics. If the air in the room is well mixed, then the concentration can be predicted based upon knowledge of the room ventilation rate, the pollutant source strength, and the concentration in the supply air (Figure 1). In situations where the well mixed assumption does not apply, one must determine in addition the percentage of ventilation air that is supplied to the occupied zone and the percentage of the pollutant source that is directly removed by the ventilation system before mixing with air in the occupied zone . A flow chart showing the level of detail that is required for various situations is included in Figure 1.

The mitigation of indoor air quality problems depends upon maintaining an adequate balance between ventilation rate and pollutant source strength . This balance is shown graphically in Figure 2 for the case of a volumetric source in a perfectly mixed room. The horizontal axis is the ratio of ventilation flow rate to source flow rate and the vertical axis is the concentration of room concentration to inlet concentration. For a fixed source concentration $c_s$, the magnitude of the ventilation ratio Q/q determines the

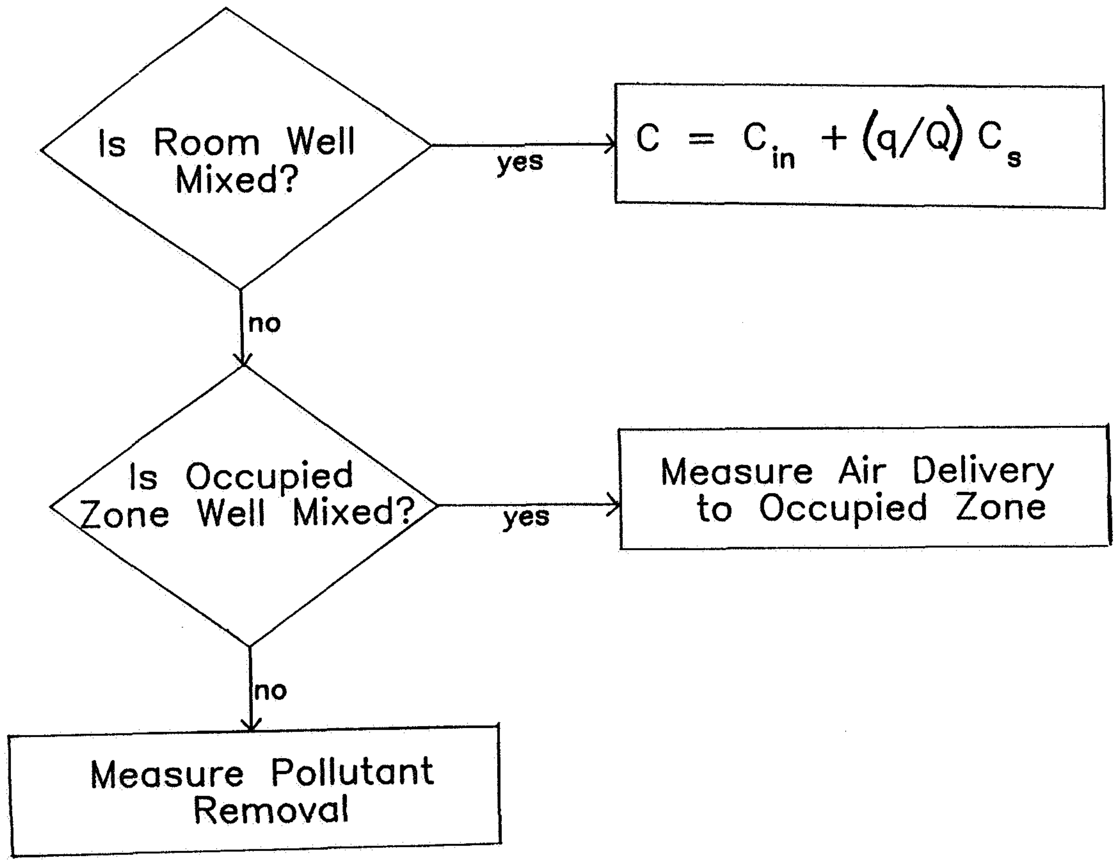



Figure 1 Knowledge Required to Predict the Pollutant Transport Performance of a Ventilation System. All pollutant sources are assumed to be located in the occupied zone.

concentration in the space. This ratio is adjusted in practice either by increasing the ventilation rate or by reducing the source strength. It can be seen in Figure 2 that the ventilation rate plays an important role in determining pollutant concentrations, especially at low ventilation ratios. Even if an acceptable room concentration can be achieved at low ventilation ratios, the corresponding sensitivity of concentration to flow nonuniformities (local variations in Q) can produce localized areas with unacceptably high concentration levels. As a result, a detailed knowledge of source characteristics and ventilation system performance is required to insure that the ventilation system provides pollutant control at reasonable ventilation rates.

The control of indoor air pollutants by ventilation is not necessarily a straight forward task. Short circuiting between supply and return ducts and other flow nonuniformities can produce localized regions that are not well ventilated even if the airflow measured at the supply diffuser appears to be adequate. A number of different ventilation efficiency/effectiveness measures have been proposed to provide a basis for ventilation

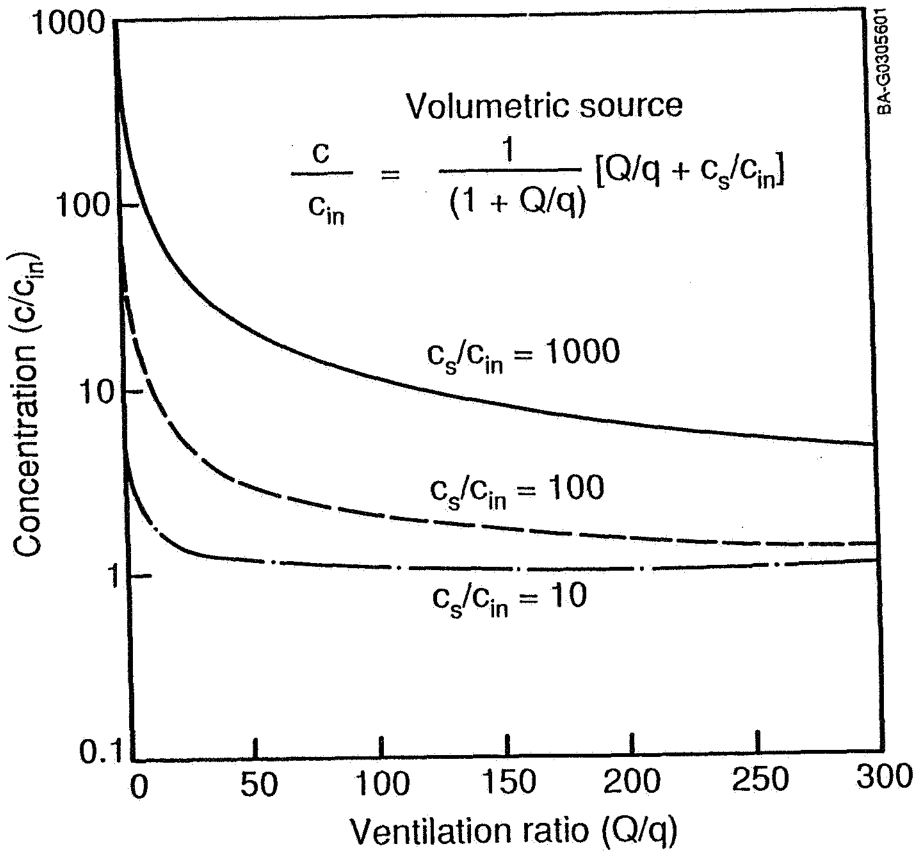



Figure 2 Sensitivity of Concentration to Ventilation rate for volumetric source in perfectly mixed room with specified $c_s/c_{in}$.

system design. These definitions can generally be categorized within the three dimensional matrix shown in Figure 3. The y-axis in Figure 3 defines the physical meaning attached to the definition (ventilation air delivery or pollutant removal), the x-axis defines the building subsystem that the definition is applied to, and the z-axis indicates whether the definition is based upon lab measurements, field measurements, or numerical calculations.

If source strengths are known and the occupied zone is well mixed, then the concentration in the occupied zone can be predicted provided that the rate of delivery of ventilation air is known. Janssen and co-workers[5,6] have developed a method of calculating the fraction of outside air that is delivered to the occupied zone, based upon knowledge of the system recirculation rate and knowledge of the fraction of air entering the room that short circuits directly to the return duct. This method accounts for the portion of outside air that is delivered to the occupied zone after recirculating through the system, even though it initially short circuits to the return duct without being delivered to the occupied zone. Meckler and

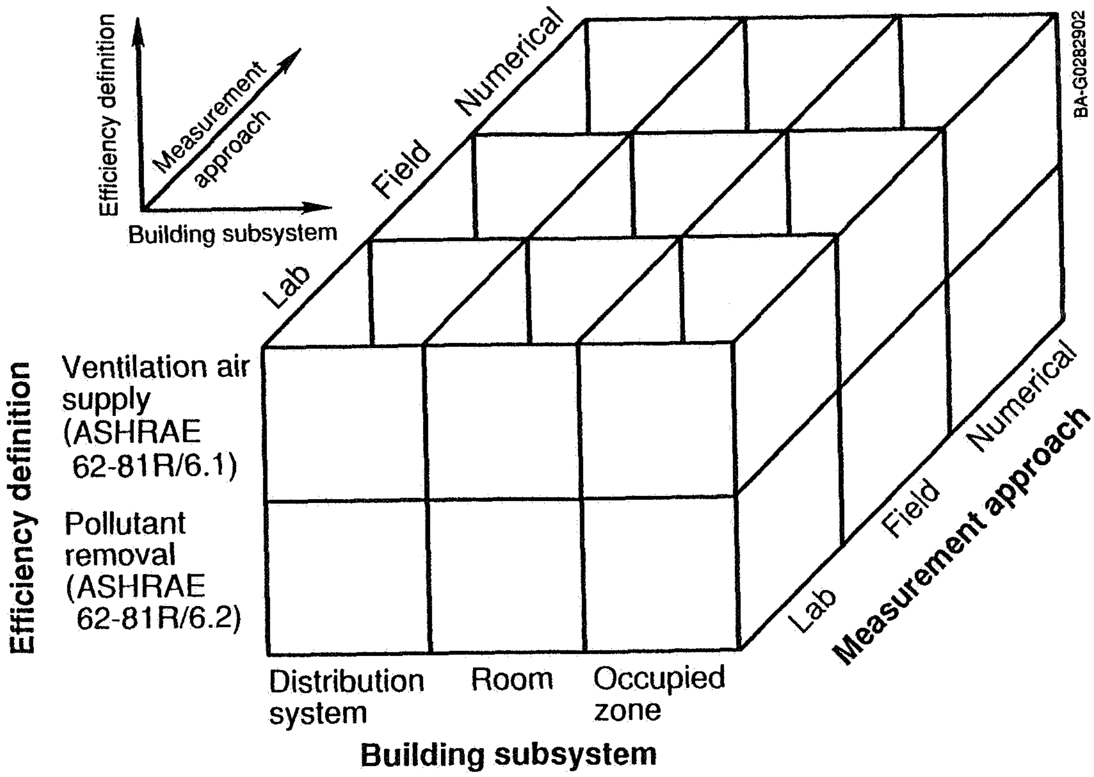



Figure 3 Major Applications of Ventilation Efficiency Measures

Janssen[7] have extended this method to calculate the amount of outside air that is required when air cleaners are used. Tracer gas techniques based upon measurement of the exponential decay time constant can be used to determine the short circuiting factor, provided the occupied zone is well mixed[8].

Building on previous work by Danckwerts[9,10], Spalding[11], and others, Sandberg and Sjoberg[12] used statistical methods to describe the age distribution of air in a room. Age of air methods can be used to detect spatial variations of air distribution by comparing the age of the air as a function of room location. When normalized with respect to the shortest possible residence time, the spatial average age of room air can be used to provide a measurement of air exchange efficiency[13].

If pollutants are not uniformly distributed, then the interaction of the ventilation system with the pollutant source cannot be neglected. Systems that directly remove pollutants before they mix with room air will have higher average concentrations in the exhaust than in the room. Systems that are not very efficient at removing pollutants will have lower average concentrations in the exhaust than in the room. To quantify this effect, Rydberg and Kulmár[14] defined removal effectiveness to be the ratio of the concentration in the exhaust to concentration in the room at steady state. This ratio is one for a perfectly mixed system and can range in value from zero to infinity for systems that are less efficient or more efficient than perfect mixing.

Recent reviews of ventilation efficiency/effectiveness definitions and measurement techniques have been given by Liddament[15] and Skaret[16]. These reviews provide an excellent overview of the current state of the art of ventilation performance measurements.

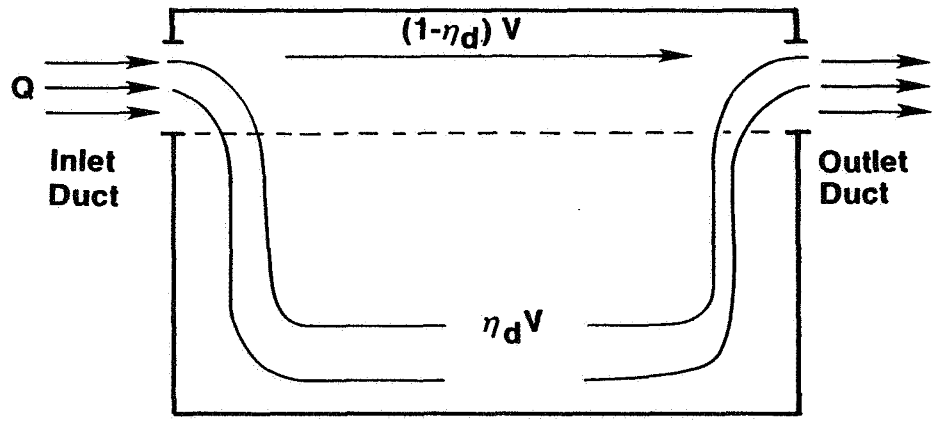



Figure 4 Control Volume Showing Physical Meaning of Displacement Efficiency, $\eta_d$.

## SHORT TERM MEASUREMENTS OF VENTILATION EFFICIENCY

The ventilation efficiency and effectiveness concepts described above have both strengths and weaknesses. The short circuiting analysis developed by Janssen and co-workers provides a much needed link between ventilation system parameters and ventilation performance, but little information is currently available for determination of short circuiting factors. Rydberg's definition of pollutant removal effectiveness requires that measurements be made after steady state conditions have been achieved. The age of air techniques provide powerful tools for analysis of ventilation performance, but require long time integrals that may be difficult to evaluate[10] and lose physical meaning when interpreted in terms of local ventilation rates[12].

The ventilation analysis method that is used in the present study was developed based upon the following criteria:

1. The method must allow performance evaluations based upon short term measurements so that the method is cost effective and easy to use,

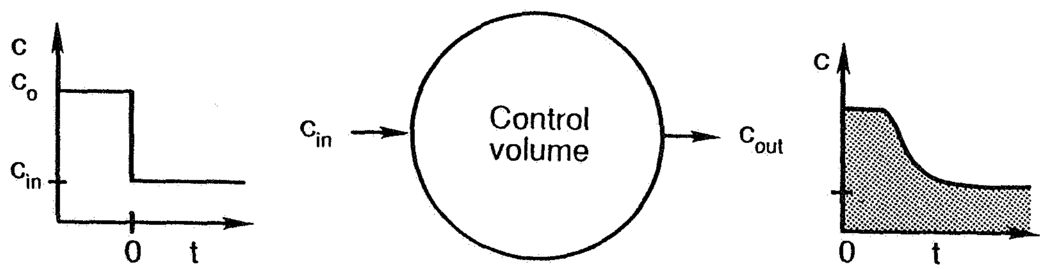
2. The method must be self calibrating so that results can be interpreted based upon knowledge of the experimental errors,

3. The method must be applicable to testing conducted under both laboratory and field conditions, and

4. The method must have direct physical significance so that results can be used as diagnostic tools to determine appropriate mitigation strategies for systems with low performance.

## Displacement Efficiency

The displacement efficiency, $\eta_d$, is defined to be the fraction of the control volume air that is replaced during the time, $\tau$, that one volume change of air has been supplied to the room by the ventilation system (Figure 4). The maximum value of $\eta_d$ that can be achieved by a ventilation system is 1.0, corresponding to 100% replacement. The displacement efficiency provides a direct measurement of the fraction of ventilation air that is delivered to a room relative to the delivery provided by a perfect displacement flow.




$$\eta_d = \frac{\text{(actual system)}}{\text{(perfect system)}} = 1/\tau \int_0^{\tau} \frac{C_{out} - C_{in}}{C_o - C_{in}}\, dt$$

$$\tau = V/Q$$

Figure 5 Determination of Average Displacement Efficiency, $\eta_d$, Based on Knowledge of Flow and Concentration on Boundaries of Control Volume.

A local value of the displacement efficiency, $\eta'_d$, can be calculated based upon knowledge of the local concentration at elapsed time $t=\tau$ after a step change in concentration has been applied to the air which is supplied to the control volume,

$$\eta'_d = (c-c_o)/(c_{in}-c_o) \text{ at } t=\tau \tag{1a}$$

$$c=c_o \text{ for } t<0 \tag{1b}$$

$$c=c_{in} \text{ for } t>0 \tag{1c}$$

In equation (1a), $\tau$ refers to the time scale associated with the overall ventilation rate and volume of the room, not the time scale associated with the local ventilation rate and local volume element.

An overall value for $\eta_d$ can be calculated by averaging the local value $\eta'_d$ over the room volume, or by integrating the concentration with respect to time in the exhaust duct (Figure 5). A relative measure of displacement efficiency $\eta^{rel}_d$ can be determined by calculating the ratio of the local displacement efficiency to the room average displacement efficiency.

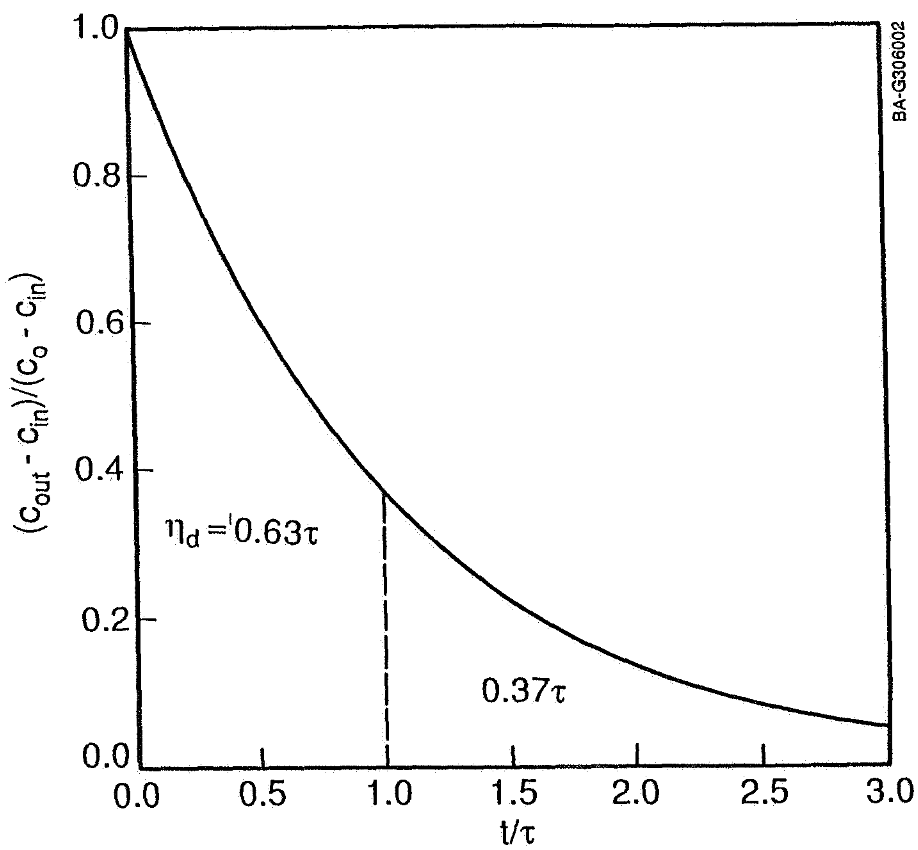



Figure 6 Average $\eta_d$ for perfectly mixed flow.

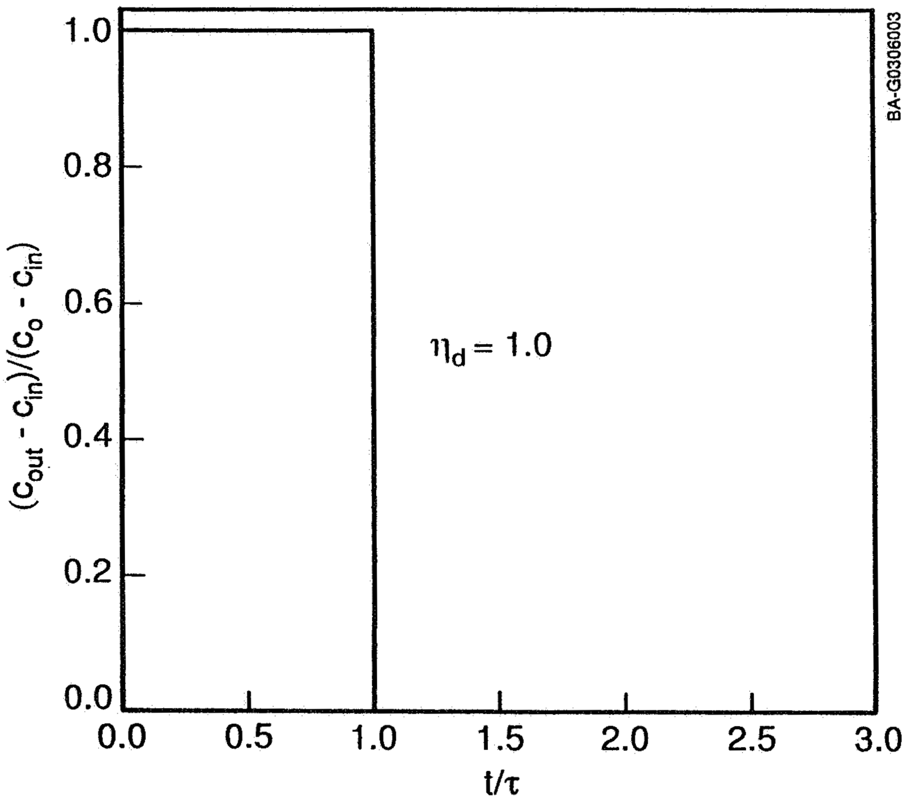



Figure 7 Average $\eta_d$ for perfect displacement flow.

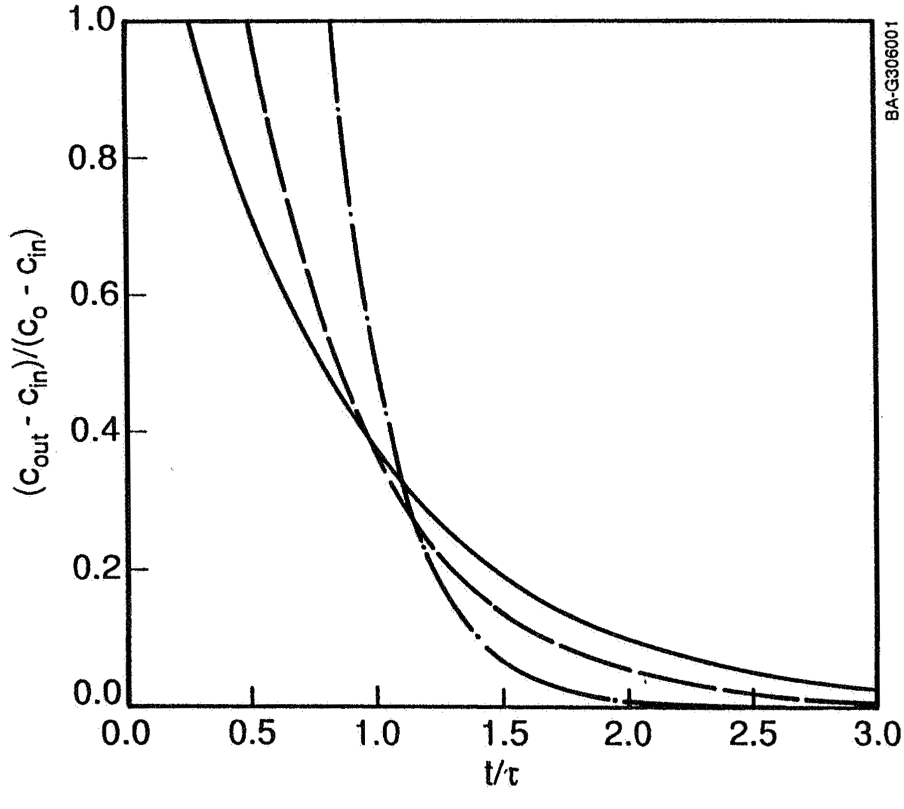



Figure 8 Average $\eta_d$ for real flows.

Limiting values of $\eta_d$ for perfectly mixed and perfect displacement flows are shown in Figures 6 and 7. Real flows include a combination of displacement and mixing, with the displacement fraction being determined primarily by the time of flight between the supply diffuser and exhaust duct (Figure 8).

Values of $\eta_d$ can also be calculated for room subvolumes. The displacement efficiency $\eta^{oz}{}_d$ is the efficiency obtained by averaging $\eta^l{}_d$ over the occupied zone. It is important to note that the integral approach shown in Figure 5 can not be used to calculate local values of $\eta_d$ unless the local time history of concentration and velocity distributions are known.

If the integral method of calculating $\eta_d$ is extended to the upper limit $t \to \infty$, it is equivalent to the definition of local age of air[13,17,18] divided by $\tau$. The theoretical limiting value of the integral as $t \to \infty$ is 1.0. When $\eta_d$ measurements are being used in field studies, this limiting value can be used during initial calibration tests to determine the errors associated with unspecified interzonal airflows and infiltration. If these sources of error are too large, they can be corrected for or controlled.

## Using $\eta_d$ Measurements to Calculate Flow Short Circuiting

One of the primary problems associated with the modeling of HVAC system performance is determining the fraction of air provided at the supply diffuser that is actually delivered to a given room location. Multizone mixing models have been used by several authors to differentiate between performance in different room subvolumes[5,19,20]. In this section a modified two zone analysis will be used to demonstrate the relationship between $\eta_d$ and short circuiting between the supply and return ducts in ceiling based systems (Figure 4) where the return duct is located in the jet mixing zone.

Because one of the primary objectives of diffuser design is to provide adequate mixing of the ventilation jet before it enters the occupied zone[21], it is convenient to divide the room into two zones: the jet mixing zone with volume $V-V_{oz}$, and the occupied zone with volume $V_{oz}$. The jet produces mixing by entraining air from the occupied zone at the rate $Q_{ent}$. By continuity, this is also the rate at which air is supplied to the occupied zone. If $(V-V_{oz})/(Q+Q_{ent}) \ll V_{oz}/Q_{ent}$ then a steady state approximation can be applied to the jet mixing zone, resulting in a concentration at the return duct equal to

$$c_{out} = (Qc_{in}+Q_{ent}c_{oz})/(Q+Q_{ent}) \quad (2)$$

For the system shown in Figure 4, this is also the concentration of the air that is delivered to the occupied zone. If we assume that the occupied zone is well mixed, then the differential equation describing the rate of change of concentration in the occupied zone is

$$dc_{oz}/dt=(1/V_{oz})[Q_{ent}Q/(Q+Q_{ent})]\{c_{in}-c_{oz}\} \quad (3)$$

This is identical to the equation that would result if the ventilation jet was added directly to the occupied zone with the ventilation rate

$$Q_{ent}Q/(Q+Q_{ent}) \quad (4)$$

If $Q_{ent}/(Q+Q_{ent})$ is not equal to $V_{oz}/V$, $\eta^{oz}{}_d$ will differ from 0.63 even though the occupied zone is well mixed. Solving equation (3) one finds

$$\eta^{oz}{}_d = 1-\exp(-\tau/\tau_{oz}) \quad (5a)$$

$$1/\tau_{oz} = (1/V_{oz})Q_{ent}Q/(Q+Q_{ent}) \quad (5b)$$

Equation (5a) provides a method for calculating $\tau/\tau_{eff}$ if $\eta^{oz}{}_d$ is known from short term experimental measurements. Evaluating equation (5) we find

$$\tau/\tau_{oz} = -\ln(1-\eta^{oz}{}_d) \quad (6)$$

A graph of equation (6) is shown in Figure 9. The fraction of ventilation air that short circuits to the return duct relative to what would have been supplied to the occupied zone if the entire room was well mixed is

$$s_a = (1-\eta^{oz}{}_d/0.63) \quad (7)$$

## Removal Efficiency

The removal efficiency, $\eta_r$, provides a measure of the ability of a ventilation system to remove pollutants before they mix with room air, and is based upon the same physical reasoning used in the definition of $\eta_d$. The removal efficiency is defined to be the fraction of a pollutant source that is directly removed by the ventilation system during the time that one volume change is supplied to the control volume. Schematic and mathematical definitions of room average values of $\eta_r$ are included in Figures 10 and 11. The removal efficiency

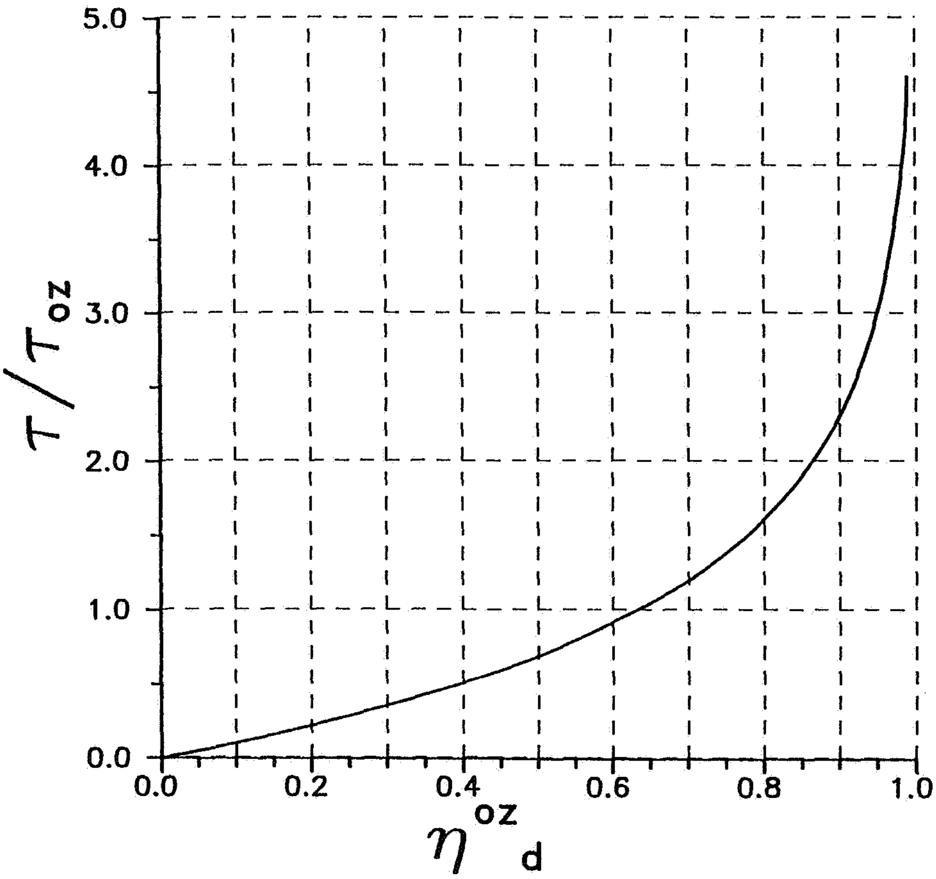



Figure 9 $\tau/\tau_{oz}$ as a function of $\eta^{oz}{}_d$

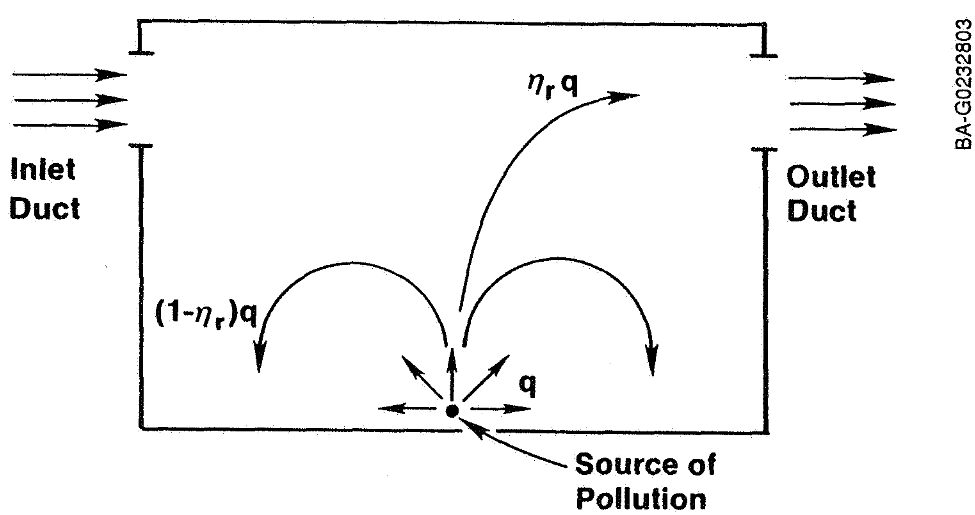
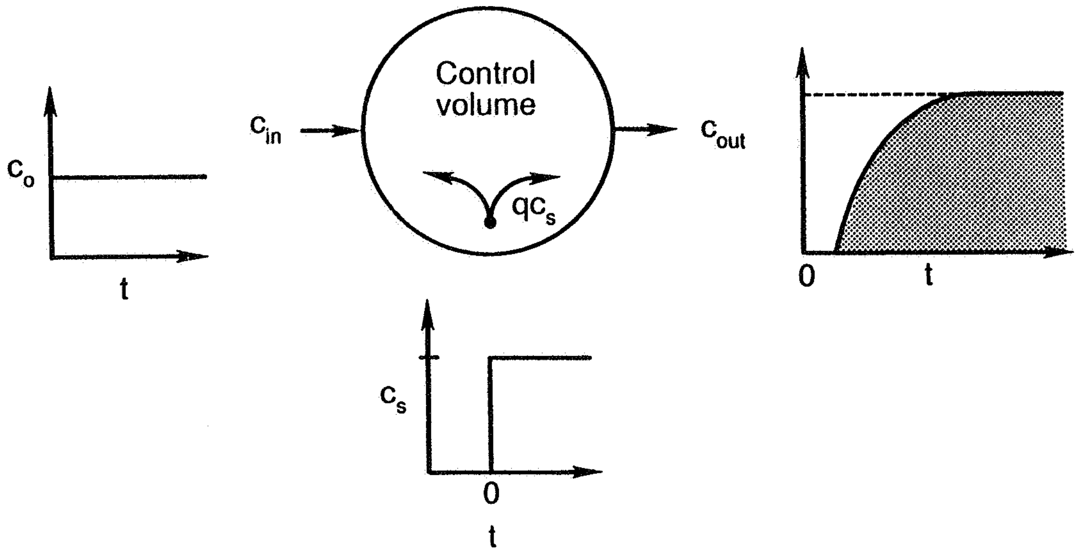



Figure 10 Schematic showing physical meaning of $\eta_r$.




$$\eta_r = \frac{\text{(actual system)}}{\text{(perfect system)}} = 1/t \int_0^t \frac{(Q+q)\,c_{out} - c_{in}Q}{qc_s}\,dt$$

Figure 11 Calculation of the average room value of $\eta_r$.

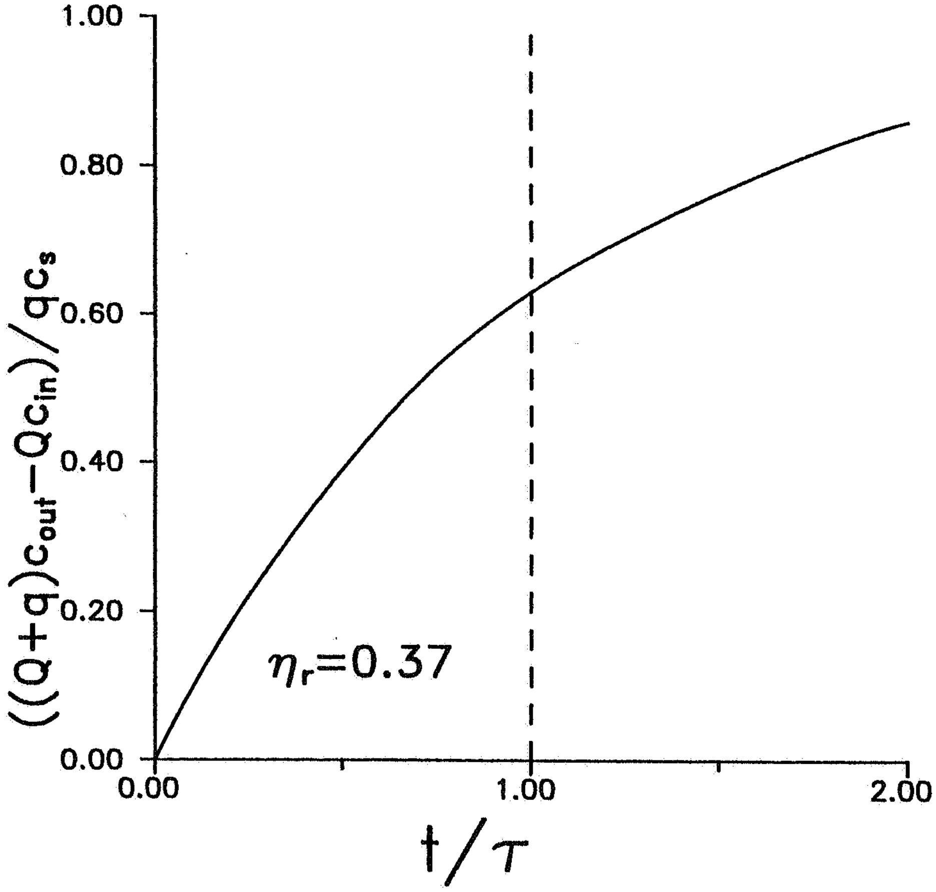



Figure 12 Removal efficiency for perfectly mixed flow.

is measured by maintaining a constant concentration at the supply, turning on the source at t=0, and performing the integral shown in Figure 11 based upon concentration measurements made in the return duct. The limiting value of the integrand shown in Figure 11 is 1.0 as $t \to \infty$. This limit can be monitored during initial calibration tests to insure that the measurements are providing the expected mass balance. Examples of $\eta_r$ calculations for perfect mixing and perfect displacement flows are shown in Figures 12 and 13. As in the case of $\eta_d$, $\eta_r$ calculations are based short term measurements taken during the time it takes to supply one volume change to a room.

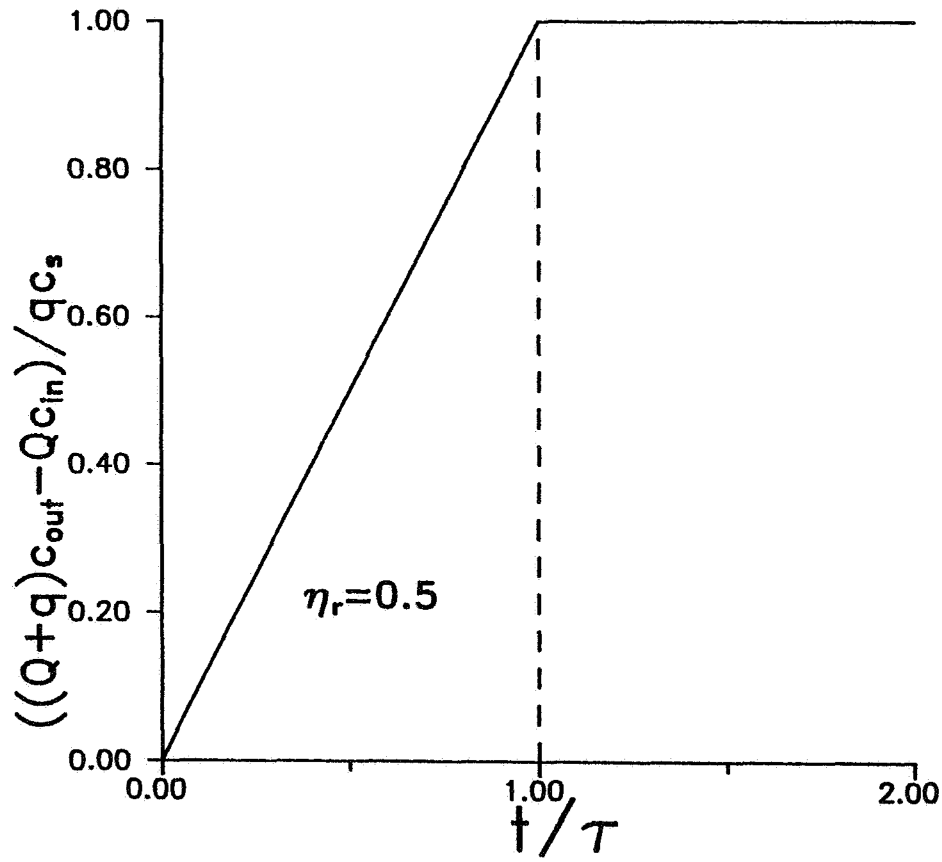



Figure 13 Removal efficiency for perfect displacement flow.

The removal efficiency does not make physical sense when applied to subvolumes of a room which do not contain pollutant sources. However, it is possible to define a pollutant delivery efficiency $\eta_p$, which measures the fraction of a pollutant source which is added to a room subvolume during the time that one volume change is supplied to the room. The pollutant delivery efficiency for a room is

$$\eta_p = 1-\eta_r = (c-c_o)Q/qc_s \quad (8)$$

where $c$ is the average concentration in the room at $t=\tau$.

The pollutant delivery efficiency for the occupied zone is

$$\eta^{oz}_p = [(c_{oz}-c_o)Q/qc_s](V_{oz}/V) \qquad (9)$$

In equation (10), $c_{oz}$ is the average concentration in the occupied zone at time $t=\tau$. For a room in which the entire volume is perfectly mixed,

$$\eta^{oz}_p = 0.63(V_{oz}/V) \qquad (10)$$

For a ventilation system with the same two zone structure as was used in the derivation of equation (5),

$$\eta^{oz}_p = (\tau_{oz}/\tau)[1-\exp(-\tau/\tau_{oz})] \qquad (11)$$

As in the case of air delivery. a stratification factor can be defined for pollutant delivery that measures the the effective pollutant source strength in the occupied zone relative to the source strength for a perfectly mixed flow.

$$s_p = (1/0.63)(V/V_{oz})\eta^{oz}_p \qquad (12)$$

Solving for the steady state concentration in the occupied zone for the two zone flow described above and simplifying with the use of equations (7), (11), and (12) produces the result

$$(c_{oz}-c_o)Q/qc_s = s_p/(1+s_a) \qquad (13)$$

Equation (13) demonstrates that $s_p$ and $(1+s_a)$ provide a direct measure of the effective source strength and the effective ventilation rate relative to a room that is perfectly mixed.

## CONCLUSIONS

Two new ventilation efficiency definitions, the displacement efficiency ($\eta_d$) and the removal efficiency ($\eta_r$), have been used to analyse the performance of a ventilation system with ceiling based supply and return ducts. Comparisons are made with age of air and removal effectiveness concepts. These new ventilation efficiency definitions have a number of advandages over previous methods including being on based short term measurements and having well defined limits which can be used to determine the magnitude of experimental errors. The ventilation efficiency definitions are suitable for both laboratory and field studies, and can be interpreted in terms of effective ventilation rates and pollutant source strengths, thereby providing direct physical insight into ventilation system performance.

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Discussion

Paper 4

D. Harrje (Princeton University, USA) Would you place recirculation in perspective with relation to short circuiting, perfect mixing and displacement flow, when in many cases 4/5 of supply air may be recirculated?

R. Anderson (Solar Energy Research Institute, USA) The work by Janssen and Woods referenced in the paper makes it possible to determine an "effective" short circuiting value for the ventilation system, as a function of the room short circuiting level and the recirculation rate. Because part of the short circuited air is re-supplied to the room, systems with high recirculation proportions are less sensitive to short circuiting at the room level than systems which use 100% outside air. Additional research is required to compare the relative performance of displacement and mixing systems that use recirculation, but it seems clear that recirculation will tend to smooth out concentration non-uniformities in both cases.

R. Grot (National Bureau of Standards (USA) (a) How often is ventilation effectiveness important - is this a real or imaginary problem? (b) How rigorous were the similarity relationships which you used for your scale tests?

R. Anderson (Solar Energy Research Institute, USA) (a) An adequate balance between ventilation and indoor air quality is required to maintain acceptable indoor air quality. The objective of ventilation efficiency analysis is to produce a quantitative measure of ventilation performance with respect to air delivery and pollutant removal. Measurements to date suggest that there are significant variations in performance as a function of ventilation system design. (b) Our scale experiments exactly reproduce the flows in a full scale room with the same boundary conditions during isothermal tests. Ventilation jet and source buoyancy effects are modelled with an accuracy of +/-10 to 20%. During our tests we did not attempt to model thermal sources, such as heaters.

W. Raatschen (Dornier Systems, W. Germany) (a) Is there a difference between your definition of displacement efficiency and the commonly defined "air exchange efficiency" (Sandberg, Skaret etc.)? (b) How can you draw conclusions from measuring tracer gas concentrations in the exhaust on the concentrations in the occupied zone? Don't you obtain information about the whole volume of air passing through the room?

R. Anderson (Solar Energy Research Institute, USA) (a) Yes. Displacement efficiency is based upon control volume analysis over the time that one volume change is supplied to the control volume. Air exchange efficiency is the ratio of local age of air to the age of air for a perfect displacement system. (b) Conclusions about the occupied zone were based upon local concentration distributions. Concentration measurements taken in the exhaust were used to determine room average values.

W. Fisk (Lawrence Berkeley Laboratory, USA) Your ventilation efficiency definitions are attractive because the practising engineer may be able to understand them. Have you thought about procedures for measuring these parameters in real commercial buildings, where the nominal time constant is not known in advance? There are usually multiple air handling units and air flow may vary with time.

R. Anderson (Solar Energy Research Institute, USA) Our ventilation efficiency analysis requires knowledge of the ventilation rate, which can be measured using standard pressure drop or anemometry techniques. The efficiency measurements have well defined limits that can be used to determine the magnitude of experimental error. As with any experimental measurement, the errors are expected to be larger in the field than in the laboratory.