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# VENTILATION STRATIFICATION AND AIR MIXING

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## Abstract

Minimizing ventilation for energy conservation in buildings requires that ventilation efficiency be high. The common practice of locating supply outlets and return inlets in or near the ceiling creates an opportunity for air to bypass from the supply to the return without mixing in the occupied space. Equations are derived for calculating efficiency and strtification factor from tracer gas decay measurements.

## Introduction

Dilution of the contaminants in indoor air with less contaminated outdoor air is the main mechanism for controlling indoor air quality. The ASHRAE Ventilation Standard[1] assumes that all of the outdoor air brought into a building is effective in diluting the contaminants. Tracer gas tests[2,3] have revealed incomplete mixing. The common practice of locating the ventilation supply outlets and return inlets in or near the ceiling of a room invites short circuiting of air from the supply directly to the return. When the exhaust is taken from the return air system some outdoor air can be inducted, short circuit to the return and be exhausted without ever mixing at the occupied level.

## Ventilation Models

### Stratification Model

A model for ventilation efficiency can be derived by considering a typical HVAC air handling system as shown schematically in Figure 1. It is possible that a fraction, s, of the supply air may bypass directly to the return inlet without mixing at the occupied level (i.e. below the dotted line in Figure 1).

The flow returned from the space is $Q_{21}$, and the total return flow is $Q_{21} + sQ_s$. A fraction, r, of this return flow is recirculated and the remainder, 1-r, is exhausted. We can write a material balance for a quantity of outdoor air, $Q_{10}$, that enters the system. We will assume there is no infiltration, i.e. $Q_{02} = Q_{20} = 0$.

The amount of this outdoor air that bypasses the occupied space and is exhausted is:

$$Q_{10-s} = s(1-r)Q_{01}\ [1 + rs + (rs)^2 + \ldots] \qquad (1)$$

$$\frac{Q_{10-s}}{Q_{01}} = \frac{s-sr}{1-sr} \qquad (2)$$

The ventilation efficiency can be defined as:

$$\eta_v = \frac{Q_{01} - Q_{10-s}}{Q_{01}} = \frac{1-s}{1-sr} \qquad (3)$$

Equation (3) defines the efficiency with which the outdoor air is circulated to the occupied space in terms of a stratification or mixing factor s, and the recirculation factor, r. If there is no exhaust flow, r=1 and the efficiency is 100%. If there is no stratified or bypass flow, s=0, the efficiency is also 100%. If however, there is both stratified flow and recirculation, outdoor air can pass through the system without ever being used to dilute contaminants at the occupied level. This ventilation loss also represents an energy loss.

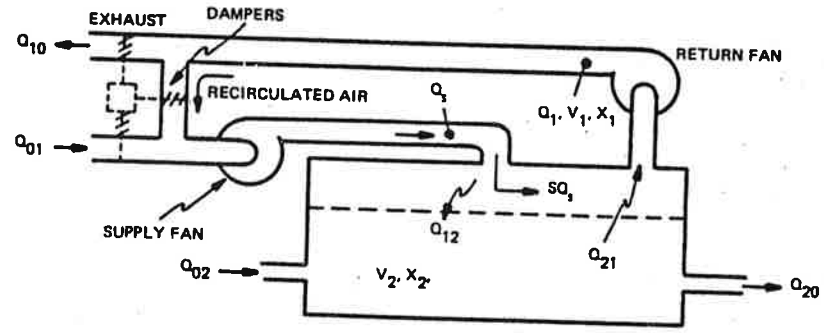


Figure 1. Typical Air Distribution System

## Two Chamber Model

Alexander[6], Sandberg[7], and Skarret[8] have used a two chamber model to develop ventilation efficiency equations. The ductwork and upper or unoccupied part of a room can be considered as one chamberwith a volume, $V_1$, and the lower, or occupied part of the room can be considered the second chamber with a volume, $V_2$.

If a tracer gas is injected into the supply duct (Chamber 1) at a rate, $\dot{N}$, let the concentration of the tracer gas be $X_1$ in Chamber 1 and $X_2$ in Chamber 2. The rates of change of concentration of the tracer gas in the two chambers are:

$$V_1 \frac{dX_1}{dt} = \dot{N} - Q_{10}X_1 - Q_{12}X_s + Q_{21}X_2 \qquad (4)$$

and,

$$V_2 \frac{dX_2}{dt} = Q_{12}X_s - (Q_{21} + Q_{20})X_2 \qquad (5)$$

Note that: $X_s = rQ_1X_1/Q_s$ (6)

$Q_1 = Q_{10}/(1-r)$ (7)

$Q_s = Q_{12}/(1-s)$ (8)

Using equations (6), (7) and (8), equations (4) and (5) can be reduced to the form,

$$dX_1/dt = \dot{N}' - bX_1 + aX_2 \quad (9)$$

$$dX_2/dt = gX_1 - hX_2 \quad (10)$$

where: $a = Q_{21}/V_1$ (11)

$b = (Q_1/V_1)\ (1-rs)$ (12)

$g = (Q_1/V_2)\ (1-s)r$ (13)

$h = (Q_{21} + Q_{20})/V_2$ (14)

$\dot{N}' = \dot{N}/V_1$ (15)

Equations (9) and (10) can be integrated to find the tracer concentrations, $X_1$ and $X_2$, in each volume.

$$X_1 = \frac{h\dot{N}'}{bh-ag} + C_1e^{\lambda_1 t} + C_2e^{\lambda_2 t} \quad (16)$$

$$X_2 = \frac{g\dot{N}'}{bh-ag} + \frac{C_1}{a}(\lambda_1 + b)e^{\lambda_1 t} + \frac{C_2}{a}(\lambda_2 + b)e^{\lambda_2 t} \quad (17)$$

$$\lambda_1 = 1/2\ [-(b+h) + \sqrt{(b+h)^2-4(bh-ag)}] \quad (18)$$

$$\lambda_2 = 1/2\ [-(b+h) - \sqrt{(b+h)^2-4(bh-ag)}] \quad (19)$$

Figure 2 shows a plot of equations (16) and (17) for an assumed set of conditions.

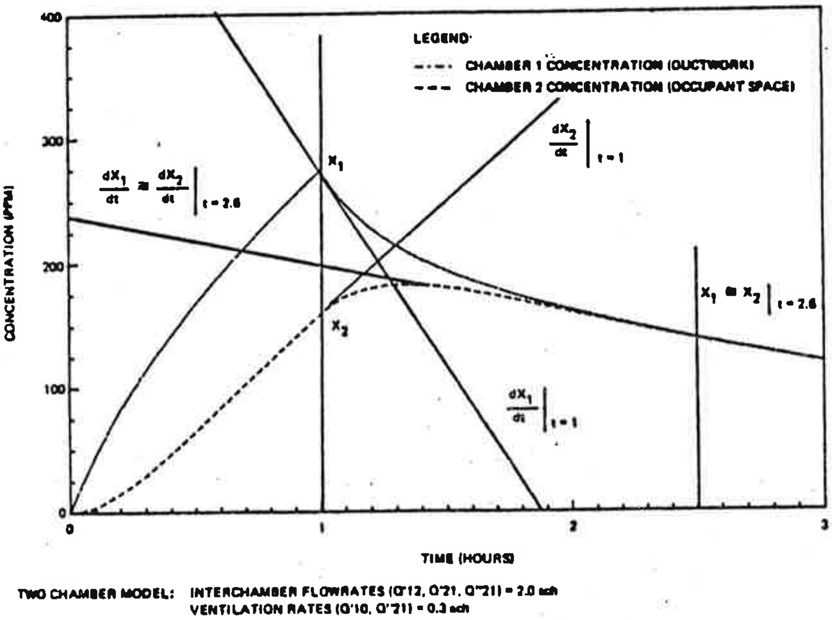


Figure 2. Tracer Concentration Buildup Decay

During a tracer decay period $\dot{N}=0$ and equation (9) and (10) can be solved for the values of a, b, g and h if tracer gas concentrations are measured in each chamber to get a set of curves similar to those in Figure 2. The slope of the decay curves, dX/dt, and the concentrations in each chamber can be measured at two different times. This will provide 4 equations from which the four coefficients can be calculated. The ventilation efficiency then can be written as:

$$\eta = (ga/hb)\,(1/r) \tag{20}$$

It would appear from equation (20) that the efficiency becomes infinite when r=0. Note, however, that g/r is proportional to (1-s). Thus, the minimum efficiency is a function of (1-s) and occurs when recirculation is small.

Equation (3) shows that the efficiency is 100% when r=1. Under the assumed conditions, however, (i.e. $Q_{02}=Q_{20}=0$) there would be no ventilation. It is seen that a high circulation rate with respect to the outdoor air flow rate in chamber 1 improves ventilation efficiency. Unfortunately as the outdoor air flow rate is increased to respond to a greater ventilation requirement, the efficiency falls. It is desirable, therefore to locate supply outlets and return inlets so that bypassing does not occur. Separating the exhaust from the recirculation system also avoids the mixing loss problem if the exhaust is taken from the occupied space, chamber 2.

## Special Case Model

Under certain conditions, the ventilation efficiency can be estimated from tracer decay measurements in chamber 1 only. Increasing the tracer gas feed rate, $\dot{N}$, with respect to the other flow rates will increase the initial difference in concentration in the two chambers. Then if $X_1 >> X_2$, equation (9) becomes,

$$dX_1/dt \simeq -bX_1 \tag{21}$$

or

$$b \simeq I_o \tag{22}$$

Thus, b is approximately equal to the initial slope of the decay curve on a semi-log plot. Also, if the ventilation rate is substantially greater than the exfiltration from chamber 2, i.e. $Q_{10} >> Q_{20}$, and sufficient time has elapsed, the tracer gas concentration in the two chambers will be nearly equal and will be decaying at the same rate as shown in Figure 2. Then equation (9) becomes:

$$dX_1/dt = (a-b)X_1 \tag{23}$$

and,

$$a-b \simeq I_\infty \tag{24}$$

Note that when the infiltration loss from chamber 2 is small compared with the ventilation rate, $Q_{20} << Q_{10}$, equation (14) is:

$$h \simeq Q_{21}/V_2 \tag{25}$$

and,

$$g/h \simeq r \tag{26}$$

Thus, the ventilation efficiency equation (20), under these conditions is approximated by:

$$\eta \simeq a/b \qquad (27)$$

Using equations (26) and (28), (31) becomes,

$$\eta = \frac{I_o - I_\infty}{I_o} \qquad (28)$$

Thus, under the assumed conditions ventilation efficiency can be estimated from tracer gas decay concentrations measured in the return air duct. It would appear that minimum stratification with good mixing would reduce the difference between the initial tracer decay rate, $I_o$, and the final rate, $I_\infty$. This would make the ventilation efficiency as defined by equation (28) go to zero. Note however, that equation (22) was based on poor mixing, i.e. $X_2 << X_1$ at t=0. Thus, care must be exercised in using equation (28).

Figure 3 is a tracer gas decay curve measured in a school room. The air supply outlets were located near the ceiling on one side of the room and the return inlet was also near the ceiling on the opposite side of the room. Thus, the air tended to flow across the ceiling and did not mix well at the occupied level. Substituting the values from Figure 3 in equation (32) gives,

$$\eta \simeq \frac{0.60 - 0.32}{0.60} = \frac{0.28}{0.60} = 0.47 \qquad (29)$$

This low ventilation efficiency was approximately confirmed by energy balance calculations.

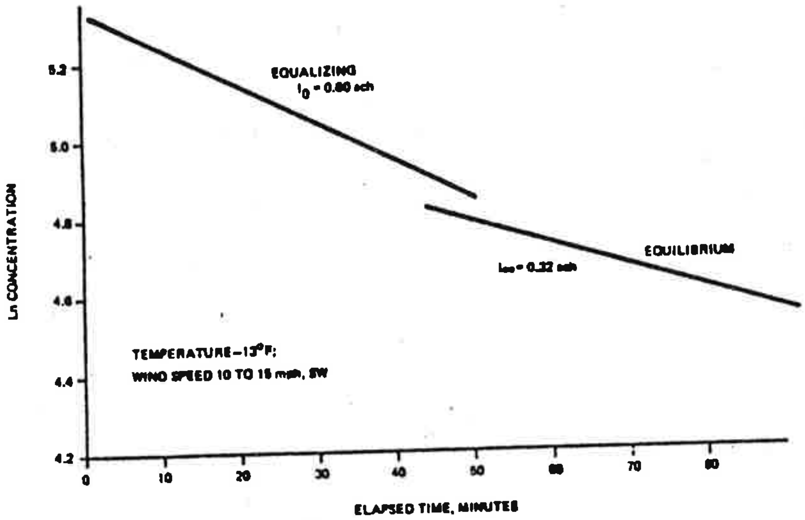


Figure 3. Measured Tracer Decay in Chamber 1.

## Conclusions

A tracer gas decay model for a two chamber system shows that ventilation efficiency and stratification or mixing factors can be calculated from tracer gas decay measurements. Under certain conditions estimates can be made from measurements in only one chamber. This measurement technique appears useful for evaluating the mixing characteristics of ventilation systems.

## References

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