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Effect of room air recirculation delay on the decay rate of tracer gas concentration

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Summary: *Tracer gas measurements are commonly used to estimate the fresh air exchange rate in a room or building. Published tracer decay methods account for fresh air supply, infiltration, and leaks in ductwork. However, the time delay associated with a ventilation system recirculating tracer back to the room also affects the decay rate. We present an analytical study of tracer gas decay in a well-mixed, mechanically-ventilated room with recirculation. The analysis shows that failing to account for delays can lead to under- or over-estimates of the fresh air supply, depending on whether the decay rate calculation includes the duct volume.*

Keywords: *tracer decay rate, recirculating ventilation.*
Category: *Indoor air quality.*

Introduction

Tracer gas measurements are used to estimate the flow rate of fresh air into a room or building [1]. These methods commonly account for the decay of tracer gas concentration as the result of ventilation air supply and infiltration, using a well-mixed model of the space. Some researchers also have considered the effect of leakage in the ventilation ductwork [2], [3].

This paper considers the effect of recirculation through ventilation ducts on the calculated fresh air supply rate. Transport delay in the ducts can significantly alter the time evolution of tracer concentration, and hence alter the estimated air change rate.

This result could be important when interpreting experimental measurements of tracer gas decay in a space with recirculating ventilation. For instance, transport delays longer than ten minutes have been observed due to low airspeeds in a ceiling return plenum [4]. This paper shows that such long delays can have a significant impact on the estimated building air change rate.

Method

In a typical tracer decay test, a pulse of tracer is injected into a room, and its concentration measured over time. Fitting the observations to a model of the well-mixed concentration in the room yields an estimate of the supply rate of fresh air to the room.

Consider a room of volume V_R, with a volume flow rate Q_{OA} of clean outside air into the room. The same flow leaves the room, carrying with it tracer gas at a volume concentration C_R. A well-mixed model of the room gives the rate of change of tracer mass in the room as

$$V_R \frac{dC_R(t)}{dt} = -Q_{OA} C_R(t). \tag{1}$$

Starting from an initial room concentration C_0, equation 1 has a solution

$$C_R(t) = C_0 e^{-\lambda_R t} \tag{2}$$

where

$$\lambda_R = \frac{Q_{OA}}{V_R}. \tag{3}$$

Classical decay rate practice finds the outside air exchange rate, λ_R, and hence the fresh air supply, Q_{OA}, that best fits equation 2 to the measured tracer data $C_R(t)$ [1].

Now consider how a building's recirculating ventilation system affects the tracer concentrations. The ventilation system may run during the experiment, for example to determine the amount of fresh air it supplies, to assess duct leakage, or because the building operation does not permit leaving the space unconditioned.

Figure 1 shows the new situation. The ventilation system supplies air to the room at a total volume flow rate Q_T. This supply air comprises a flow rate Q_{OA} of clean outdoor air, plus a recirculated flow $Q_T - Q_{OA}$ of air removed from the room some time τ earlier. Define the recirculated air fraction as

$$f = \frac{Q_T - Q_{OA}}{Q_T}. \quad (4)$$

Then, assuming no diffusion in the duct, the ventilation system adds tracer mass to the room at a rate $Q_T f C_R(t - \tau)$. Assuming instantaneous mixing, a mass balance on tracer in the room yields

$$V_R \frac{dC_R(t)}{dt} = Q_T \big(f C_R(t-\tau) - C_R(t) \big). \quad (5)$$

When $f C_R(t-\tau) > C_R(t)$, the ventilation system recirculates enough tracer back to the room to temporarily increase its well-mixed concentration. This suggests that long transport delays, and large recirculation fractions (small intakes of fresh air), can introduce errors in the decay rate procedure.

Imagine taking experimental data from such a system and, following equation 2, trying to fit a decay rate

$$C_R(t) = C_0 e^{-\lambda_\tau t}. \quad (6)$$

Substituting in equation 5, and noting that $dC_R(t)/dt = -\lambda_\tau C_R(t)$, gives

$$\begin{aligned} \lambda_\tau &= \frac{Q_T}{V_R}\left(1 - f e^{\lambda_\tau \tau}\right) \\ &= \frac{Q_{OA}}{V_R}\left(\frac{1 - f e^{\lambda_\tau \tau}}{1 - f}\right). \end{aligned} \quad (7)$$

This result reduces to equation 3 when the duct delay $\tau = 0$, or when the recirculation fraction $f = 0$. For nonzero recirculation, on the other hand, the apparent decay rate, λ_τ, differs from λ_R. Thus, calculating Q_{OA} without regard for transport delays can lead to incorrect estimates of the fresh air exchange rate.

We stress that equation 6 does not solve the tracer mass balance for all time. In particular, this assumed solution does not account for the startup period, during which tracer from the room fills the duct. Nor does it account for intermediate periods when the duct may deliver tracer at a higher concentration than in the room. However, some time after releasing the tracer, the duct and room should reach a dynamic equilibrium, for which equation 7 describes the rate of tracer decay in the room.

In order to check these results, we simulated the system of figure 1 numerically. The Integrated Indoor Transport Model (IITM) solves stiff differential systems arising from coupled well-mixed zones [5]. We treated the room as a single zone, and partitioned the duct into n smaller zones, following a "tanks in series" formulation. During simulation, n was increased until the solution no longer changed; for the cases considered here, $n = 100$. The volume of each duct subzone was set to $Q_T \tau / n$, in order to match the desired transport delay. Thus, the numerical simulation reflects the same assumptions as equation 5, except that numerical diffusion between duct segments allows minor amounts of tracer to "break through" to the end of the duct before the full delay τ elapses.

Results and Discussion

Figure 2 shows the tracer decay predicted by numerical simulation, for a room with an outside air exchange rate $Q_{OA}/V_R = 1.6h^{-1}$. The ventilation system has $f = 0.6$, and a nine-minute transport delay, $\tau = 0.15h$.

For times $t < \tau$, the ventilation air entering the room carries no tracer, and the room concentration falls off rapidly. However, most of the tracer does not leave the system, but is only stored in the duct. For $t > \tau$, the observed rate of decay decreases as the stored tracer makes its way back into the room.

The figure also shows the concentrations predicted using three estimates of the decay rate. These curves all start from the same initial condition, at $t = 0.4h$, which might correspond to the first sample of a tracer experiment. The first decay curve uses

$$\lambda_R = Q_{OA}/V_R = 1.6h^{-1}.$$

The second decay rate estimate, like λ_R, ascribes the tracer decay entirely to dilution by outside air. However, it adds the duct volume, V_D, to that of the room:

$$\lambda_D = \frac{Q_{OA}}{V_R + V_D} = 1.0h^{-1},$$

since $V_D = Q_T\tau = Q_{OA}\tau/(1-f)$. The third curve uses equation 7 to find

$$\lambda_\tau = 1.149h^{-1}.$$

As figure 2 shows, the best match to the simulated concentrations comes from λ_τ. By contrast, calculating λ_R with the correct value of Q_{OA} overestimates the rate of tracer decay. This implies that fitting equation 2 to experimental data taken in a system with significant recirculation would underestimate the actual supply of fresh air.

To explore these relationships more fully, consider the dimensionless forms of the decay constants. Defining $\nu \equiv \lambda V_R/Q_{OA}$ yields nondimensional decay rates

$$\nu_R = 1, \tag{8}$$

$$\nu_D = \frac{1}{1+R}, \tag{9}$$

$$\nu_\tau = \frac{1 - fe^{\nu_\tau(1-f)R}}{1-f}, \tag{10}$$

where R is the duct volume ratio

$$R = \frac{V_D}{V_R} = \frac{Q_T\tau}{V_R}. \tag{11}$$

Figure 3 plots ν_τ as a function of R, for various values of f. In the figure, $f = 0$ gives $\nu_\tau = 1$ no matter what the duct volume. Zero recirculation implies that only outside air enters the room, making $\lambda_\tau = Q_{OA}/V_R$, and hence $\nu_\tau = \nu_R = 1$. Thus equation 8 places an upper bound on ν_τ.

As recirculation increases, the dimensionless decay rate decreases. For a given system, R is fixed, and increasing f corresponds to, for example, reducing the outside air flow for a fixed total duct flow. In this case, the decrease in ν_τ may be attributed to the lower rate at which clean outside air replaces tracer-laden air from the room.

On the other hand, increasing f also corresponds to increasing the total flow Q_T for a fixed Q_{OA}. In this case, exhaust air leaves the system at the same rate, Q_{OA}, as before, but carries with it a lower tracer concentration (thus reducing the decay rate). The lower concentration results from the fact that increasing Q_T shortens the delay time, thus reducing the amount by which the concentration in the duct can exceed that in the room.

In a sense, increasing the total recirculation flow causes more of the duct volume to participate with the room volume in diluting the tracer. Indeed, figure 3 shows that as f approaches 1, ν_τ approaches the value $\nu_D = 1/(1+R)$ established by equation 9, which simply lumps the duct volume together with that of the room. However, equation 10 does not admit $f = 1$, because for full recirculation, no fresh air enters the system. With $Q_{OA} = 0$, the tracer simply mixes until the room and duct have a uniform, non-decaying, concentration.

Note that equation 10 depends on the relation $\tau = V_D/Q_T$, which implicitly asserts that the delay results from passing the recirculating flow through the entire duct volume. In fact, a large fraction of the volume of a ventilation return system may consist of plenum spaces. A large plenum above a room effectively adds volume to the return duct, without adding a corresponding delay (since well-mixed tracer in the room does not, on average, need to traverse the entire plenum in order to enter the recirculation duct).

Because equation 10 adds another assumption to the well-mixed and plug flow approximations already made, we recommend using equation 7 when finding Q_{OA} for a room or building with a recirculating ventilation system. In addition, the total flow and delay should be measured or estimated independently, possibly with a second tracer test, since they affect the calculation of the fresh air intake.

Conclusion

We have demonstrated that transport delays in recirculating ventilation systems affect the decay rate of tracer in the spaces served by that system. The actual decay rate, λ_τ, is less than would be estimated based on the room volume alone, but greater than would be estimated based on adding the duct and room volumes together (λ_D). After fitting an exponential tracer decay curve to tracer concentration data, the calculation of the outside airflow should account for the delay, as well as for the room and duct volumes.

Nomenclature

C_0	Initial indoor concentration (g/kg)
C_R	Well-mixed tracer concentration in room (g/kg)
f	Fraction of Q_T that recirculates back to room (1)
Q_{OA}	Makeup-air volumetric flow rate (m^3/h)
Q_T	Ventilation flow rate to and from room (m^3/h)
V_R	Room volume (m^3)
t	Time (h)
τ	Transport delay in recirculation system (h)
λ	Exponential decay rate of tracer ($1/h$)

Acknowledgements

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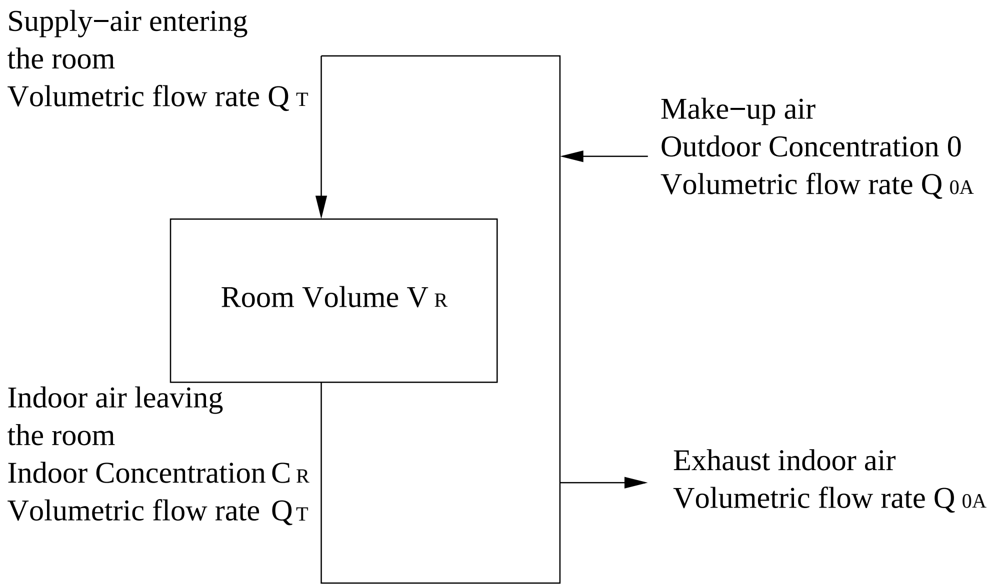

Figure 1: Ventilation system for an indoor-outdoor model.

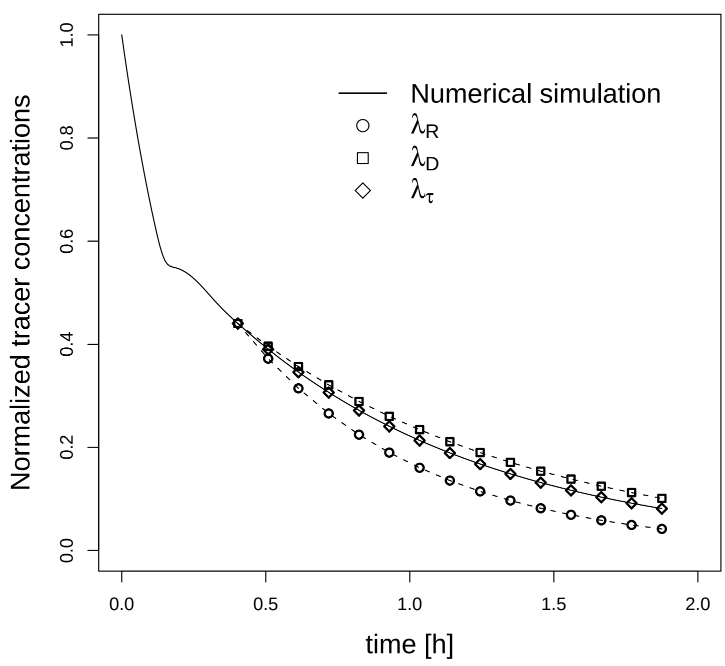

Figure 2: Simulated tracer concentration in a well-mixed room with 1.6 room volumes per hour of clean outside air, recirculated air fraction $f = 0.6$, and a duct transport delay of 9 minutes.

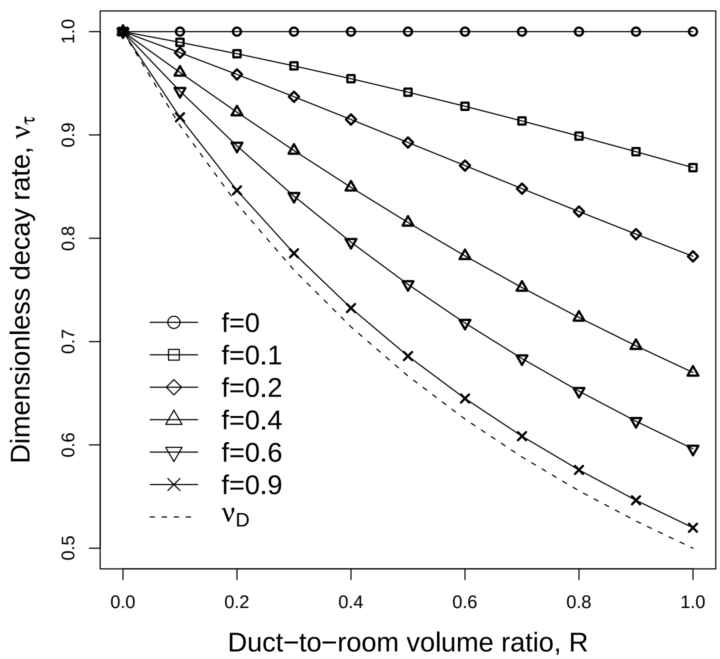

Figure 3: Dimensionless decay rate, ν_τ, as a function of R and recirculation fraction f.