MODEL SCALE AND NUMERICAL EVALUATION OF TRACER GAS DISTBRIBUTION DUE TO WIND-FORCED NATURAL VENTILATION

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Abstract

This study investigates the simulated wind-forced natural ventilation rates of a rectangular, single-cell low-rise building as observed with tracer decay and continuous tracer release tests. A 1:25 scale model is used in a boundary-layer wind tunnel to provide ventilation rates as a function of tracer test method and approach wind speed. Simultaneously, a commercial computational fluid dynamics (CFD) package is used to recreate the flow field and the tracer gas distribution of the wind tunnel cases. The conclusion shows that the high volume of naturally ventilated air is not uniformly mixed with the room air, resulting in a consistent bias of observed ventilation rates depending on tracer gas test method and location of tracer gas sampling and release equipment in the room.

1. INTRODUCTION

Although most modern buildings are designed with a highly sealed envelope, the benefits of utilizing wind-driven ventilation have long been known. Especially in mild climates, natural ventilation can be used as an inexpensive cooling source for the building occupants, the structure and the mechanically conditioned air. Resulting room air motion due to wind-forcing can save mechanical forcing costs as well. Natural ventilation as a component of overall building design also generally has a positive effect on perceived comfort and indoor air quality.

Naturally ventilated air is driven by pressure gradients across the surfaces of the building envelope and the momentum of approaching wind. The wind's stagnation and wake effects along with the ambient temperature field govern the exterior surface pressure distribution, while interior pressures are controlled by the location and quantity of openings, indoor temperatures and background leakage. For this study and most mild climate natural ventilation cases, thermal (stack) effects are small compared to wind effects. Many summarizing accounts of wind-driven air exchange are available in the literature; e.g. Dick (1950), Givoni (1969), Baturin (1972), Aynsley et al (1977), and ASHRAE (1993).

Model scale fluid simulation is a reliable tool for observing the wind-forced ventilation behavior of potential designs or existing construction in a well-controlled environment. Early efforts by Smith (1951), Caudill et al (1951), and Van Straaten (1967) use scale models in conjunction with flow visualization. Internal velocity and pressure field measurement techniques are illustrated in Cermak et al (1982), Chandra et al (1986), Ernest et al (1992), and Dutt et al (1992). Cockroft et al (1976), Etheridge et al (1979), and Cermak et al (1982) present potential approaches for effective model scale tracer gas investigations.

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The history of computational solutions for wind-forced indoor air motion characteristics is generally more recent. Present numerical efforts include the indoor flow interaction with building exterior flow studies provided by Kato et al, (1991) and Tsutsumi et al (1992).

2. BACKGROUND

Full-scale room air exchange rates can be determined by observing tracer flux from the building volume according to ASHRAE (1993). By controlling the release of a detectable tracer into the airspace, the fresh air introduction rate, Q, can be evaluated according to the following mass balance.

$$V\left(\frac{dc}{dt}\right) = F(t) - Q(t)c(t) \tag{1}$$

Where, $Q(t)$ = infiltration rate, $[L^3/T]$,
V = volume of space being tested, $[L^3]$,
$c(t)$ = tracer gas concentration at time t,
dc/dt = time rate of change of concentration, $[T^{-1}]$,
$F(t)$ = tracer gas injection rate at time t, $[L^3/T]$ and
t = time, [T].

This equation assumes that the exterior concentration of tracer is zero, there are no unknown sources or sinks of tracer gas and the density differences across the envelope are negligible. Equation (1) also implies that the tracer concentration can be represented by a single point value. It is assumed that the test volume is uniformly mixed at all times. An imperfectly mixed airspace can introduce significant uncertainties as discussed in Lagus et al (1985).

As shown in the present work, the above mass balance can be applied to naturally ventilated air spaces. However, when compared to mechanical ventilation, wind-forced air is especially prone to mixing problems due to a relative lack of temporal directional and volumetric control. A typical lack of diffusing hardware also significantly contributes to mixing deficiencies. This study tests the uniformly mixed room assumption in the context of strong wind-driven natural ventilation rates.

3. APPROACH

3.1 Full Scale Case

Present wind tunnel and computational simulations investigate a single-cell, low-rise building with no nearby exterior flow obstructions or windbreaks. The approach wind conditions and building geometry are modeled after those at the Wind Engineering Research Field Laboratory (WERFL) at Texas Tech University (TTU) as illustrated in Chok (1988) and Yeatts (1992). Boundary layer characteristics include a power-law exponent of $0.14 \leq \alpha \leq 0.17$ and a roughness length of 7 mm $\leq z_o \leq$ 38 mm. For all flow parameters in this work, the reference height, h, is the building or eave height.

The full-scale building is considered with one windward window (0.85 m x 0.85 m) opening, one leeward door (2.13 m x 0.91m) opening, a relatively unobstructed interior flow field and a normal approach wind direction. The WERFL is a rectangular building (13.7 m x 9.1 m) with a single-tiered, low pitch roof of h equal to 4.0 m.

3.2 Physical Modeling Apparatus

The Industrial Aerodynamics Wind Tunnel (IAWT) of Colorado State University's Fluid Dynamics and Diffusion Laboratory (FDDL) is used for the wind tunnel simulations of this work. The IAWT is a large boundary-layer wind tunnel with a long upwind approach. The interior of the test volume measures (1.8 m x 1.8 m x 18 m). With the model placed on the center of the turntable 16.8 m from the entrance of the test section, the blockage is approximately 3%.

The wind field parameters, α and z_o, of the IAWT profile are matched to the characteristics of full scale profile through the use of an array of vertically-stacked and staggered vortex generators as in Birdsall (1993). The 1:25 scale power law exponent, α, is 0.15 and the roughness length, z_o, is 15 mm. The turbulence intensity profile and longitudinal length scales of the scale flow in the region of the building are comparable to the full scale.

The 1:25 scale model (55 cm x 37 cm x 16 cm) used in this study is a modular design with an internal space frame. One endwall has a (3.4 cm x 3.4 cm) window opening, and the other endwall has a (3.7 cm x 8.6 cm) door opening. The model is sealed so that a small background gap is the only path for air exchange other than the two dominant openings. After assembly, V is 28,350 cm^3. The exterior dimensions of the model are illustrated in Fig. 1.

Inside the building, a Gow-Mac (#10-133) thermal-conductivity (TC) probe is used to continuously monitor helium tracer levels. The detector is a heated tungsten wire resistor carrying a constant current. A Gow-Mac (#40-002) power supply unit provides the balancing resistances for the bridge and a corresponding output voltage. The TC probe and a solenoid tracer release valve are each installed inside the model and assumed to not physically affect the interior flow field significantly. The locations of the release and sampling probe are illustrated in Fig. 2.

3.3 Numerical Modeling Apparatus

Numerical simulation of tracer transport phenomena through the TTU building with two openings is accomplished with a commercially-available fluid modeling package. FLUENT Version 3.03 is installed on a Digital Equipment Corporation (DECstation 5000/120) workstation at Colorado State University's Engineering Research Center (ERC). The FLUENT model domain includes the entire full scale TTU building with window and door open and the immediately local exterior wind field.

The inlet flow velocities and turbulent intensities are specified to match the WERFL test site results. The inlet velocity vectors have no lateral or vertical components; their magnitudes are discretized to the center-point of each vertical cell according to an α value of 0.15. The reference height, h, is the eave height of 4.0 m.

The computational grid encloses a full scale volume of (29 m x 13 m x 7 m) and includes 24,725 (25 x 43 x 23) grid cells. The domain begins 0.8h upwind and extends to 2.9h downwind, 0.8h above and 1.9h on either side of the building. It is designed with consideration to an upwind and downwind wall thickness of 15.2 cm and dense clusters of cells in the window and door openings. The boundary conditions prescribed to this domain provide a normal approach wind direction to the open-window endwall. The building dimensions enclose a space of $V = 508 m^3$. The extents of the domain are illustrated in Fig. 3. Tracer concentrations are evaluated at (11, 7, 17) to compare with the tracer concentrations evaluated at the corresponding location in the 1:25 scale model. Tracer is released in the continuous test at cell (13, 1, 31).

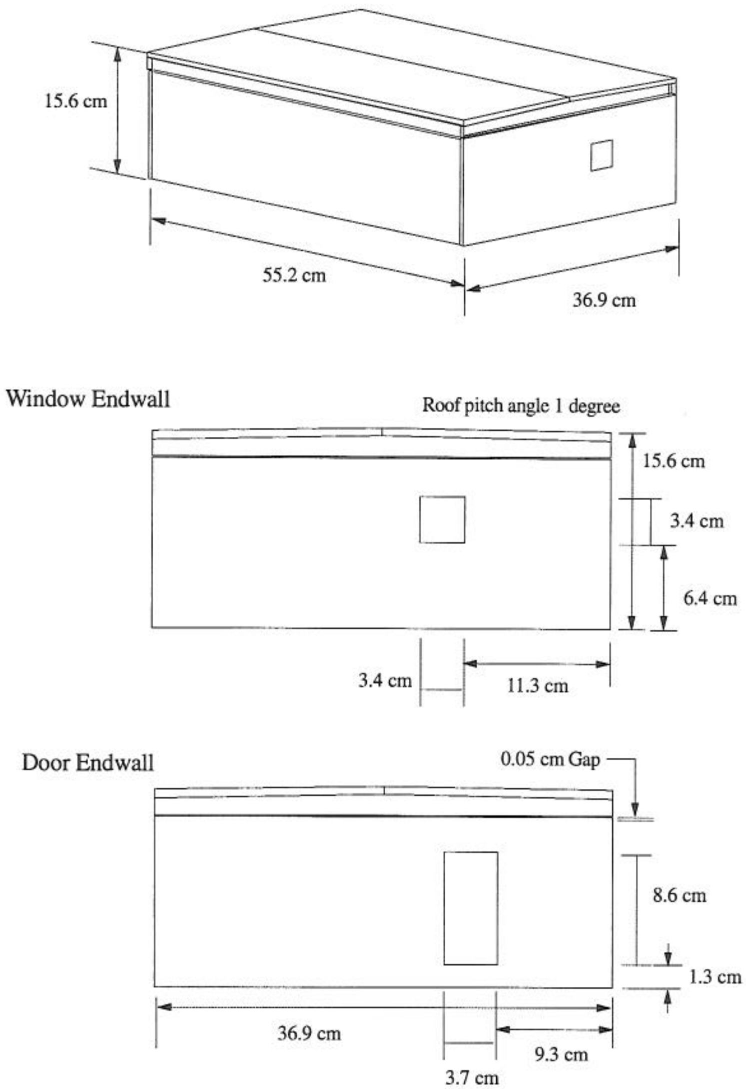


Figure 1. Exterior Dimensions of 1:25 Scale Model

3.4 Tracer Decay Method

The decay method specifies a uniform distribution of tracer at the beginning of the test and assumes no residual source or sink throughout the test. Therefore, the tracer source and sampling probe locations inside the building are chosen to not hinder the mixing process, see Fig. 2. Low probe sampling volumetric flowrates (1 cm^3/s) are used so that sink effects on the interior velocity field are minimal. The molecular decay rate of the tracer are observed to ensure that their effect is negligible. Helium is chosen as the tracer due to its high thermal conductivity.

The test begins with 100% helium tracer being released to reach a room concentration of $c \sim$ 500 ppmv. Once the measured level of tracer has stabilized, the source is cut off. The TC probe output signal is then sampled during the duration of decay and recorded for post-processing. Amplified, discreet voltages from the TC probe are converted to time-varying concentration levels, $c(t)$, and then normalized with the initial average concentration at the probe, c_o.

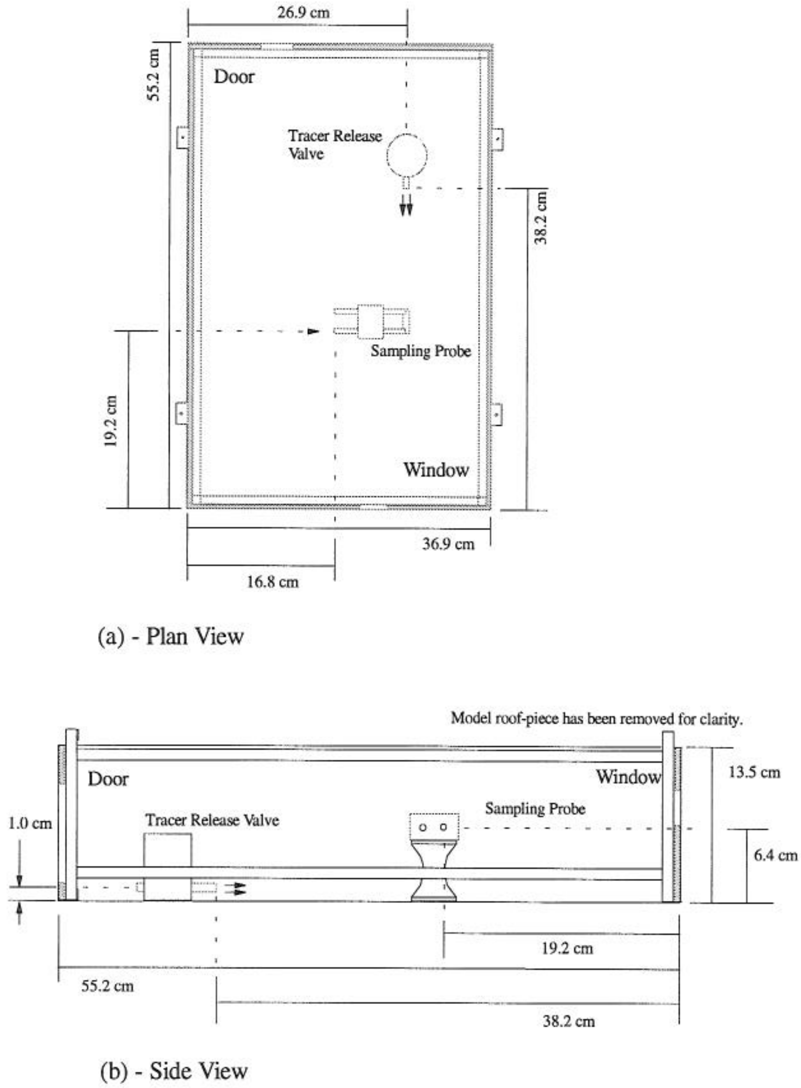
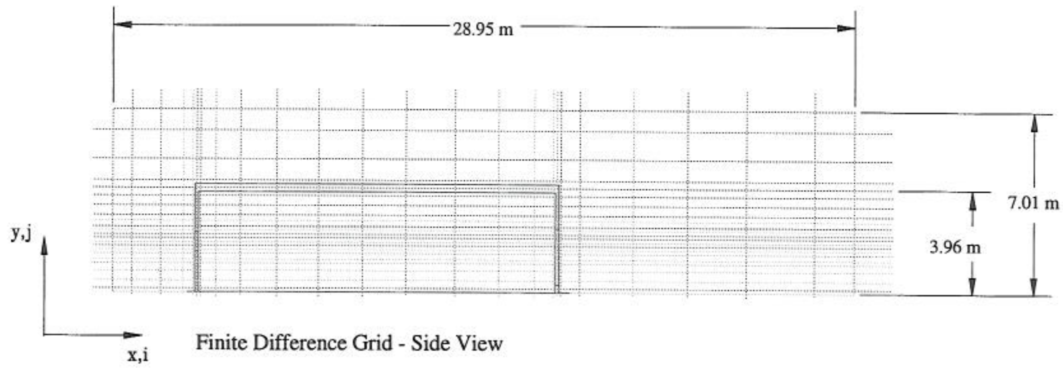


Figure 2. 1:25 Scale Model - Locations of Sample Probe and Release

For the computational simulation, once a converged velocity field solution has been developed, a uniform (0.1%) distribution of generic tracer is prescribed for all interior cells. This begins a sequential, temporally-incrementing, computation of the dispersion process. By recording the tracer concentration at one cell, the decay over time is normalized with the initial concentration of 0.1%.

The exponential behavior of tracer decay allows linearization by applying the natural logarithm to the normalized concentration. According to the tracer mass balance equation (Eq. 1), the slope of $\ln(c(t)/c_o)$ with time, t, is directly proportional to Q.

$$\ln\left(\frac{c(t)}{c_o}\right) = -\left(\frac{Q(t)}{V}\right)t \qquad (2)$$



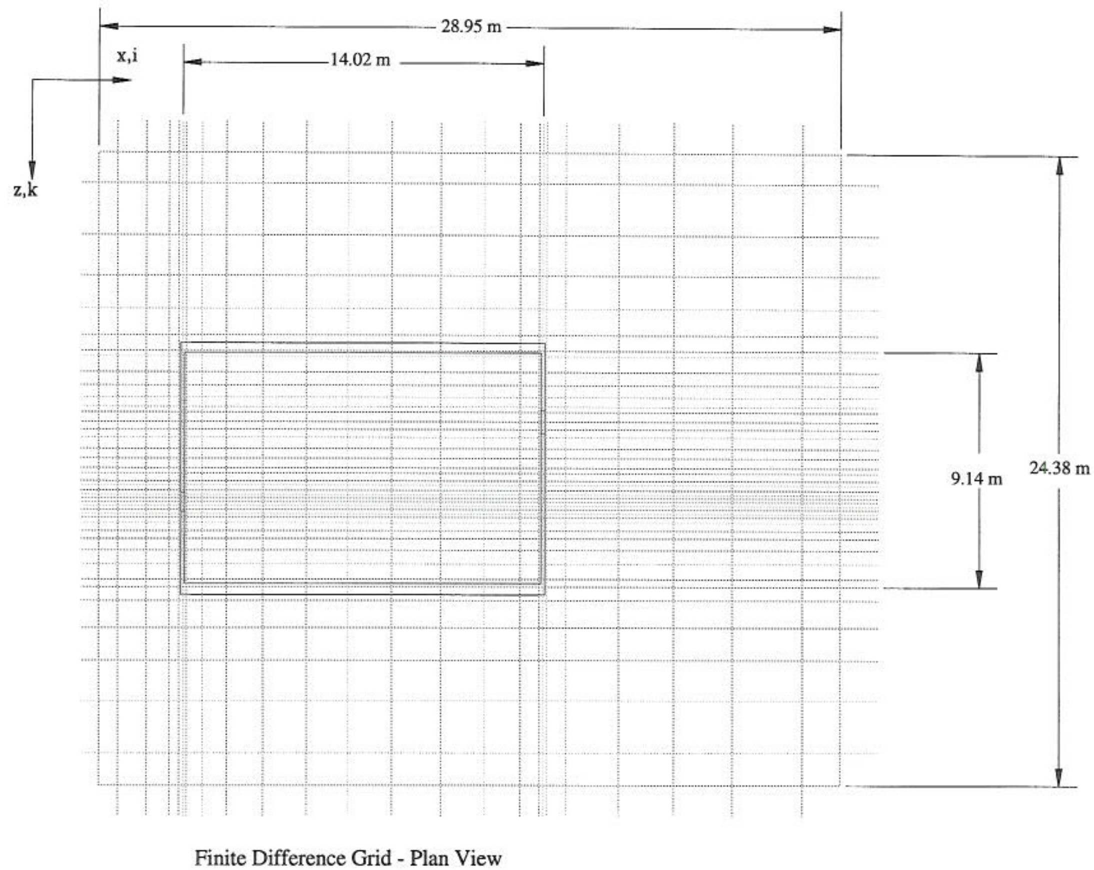


Figure 3. Finite Difference Analysis Computational Grid

The distinct advantage to using the decay procedure lies in the method's reliance on relative concentrations. This is especially helpful here because of the thermal conductivity instrumentation. Noting that the relation between voltage and concentration is linear, and concentration levels are self-normalized, intermediate uncertainties from possible bias in absolute concentration measurements are self-correcting.

3.5 Continuous Tracer Release Method

The continuous release method involves a constant release of tracer gas throughout the period of tracer measurement at the probe. For the 1:25 model, the TC probe and a remote-controlled solenoid is specified. As above, release and sampling probe locations (Fig. 2) and tracer introduction and sampling rates are chosen (each ~ 1 cm^3/s) to minimize sink or source effects on the interior flow field.

The scale test begins with a steady tracer introduction rate, *F*, providing an interior concentration level within the measuring range of the probe. The tracer flow rate remains known and stationary while acquiring samples, and the probe measures the absolute tracer concentration within the building, *c*(*t*). After a brief natural decay period, the tracer level will become stationary with time because the infiltration rate is stationary with time. The discretized concentration values from the probe are used to solve Eq. 3 for a time-averaged *Q*(*t*) through a post-processing root-solving code.

In the numerical simulation, 1.0% tracer is released at 0.3 m/s at the cell (13, 1, 31). The flow field is solved while maintaining this release to develop a steady-state distribution of the tracer plume throughout the room. The concentration at cell (13, 1, 31) is used with a large value for *t* to arrive at a steady-state value of *Q* Eq. 3

$$c(t)=\left(\frac{F}{Q(t)}\right)\left(1-e^{-(\frac{Q}{V})t}\right) \qquad (3)$$

One disadvantage to using the continuous method is the requirement that absolute concentration, *c*, and tracer introduction flow rate, *F*, be known. While not a concern during the numerical simulation, small uncertainties in calibrating the experimental equipment for *F* and *c* can lead to significant errors in the discreet values of *Q*(*t*).

3.6 Test Summary

Tracer decay and continuous release test results are presented for the 1:25 scale model at approach wind speeds, *U*(*h*), 1 m/s to 6 m/s. Exterior Reynolds number flow field invariance occurs above *U*(*h*) ~ 2m/s (Birdsall, 1993).

For the computational solution, three approach velocity profiles are specified, *U*(*h*) = 0.5, 0.9 and 5.6 m/s. Decay and continuous tests for *Q* are provided, and as an alternative solution source for *Q*, the window cross-section longitudinal velocity vector components are integrated to show the net flux of air into the room space.

4. VENTILATION RATES AND TRACER DISTRIBUTION

Wind tunnel testing for the overall ventilation rate, *Q*, as a function of tracer gas techniques and approach wind speeds yields Fig. 4, the values for *U*(*h*) versus *Q* are listed in Table 1. It is important to note the general trend; continuous tracer release methods provide consistently larger observed ventilation rates than tracer decay methods.

Table 1 introduces a new factor, Q^*. This is a non-dimensional flow factor which may be used to remove the influence of the approach wind speed, *U*(*h*), and distinguish the variance, if any, of *Q* as a function of measurement technique. It is defined in Eq. (4).

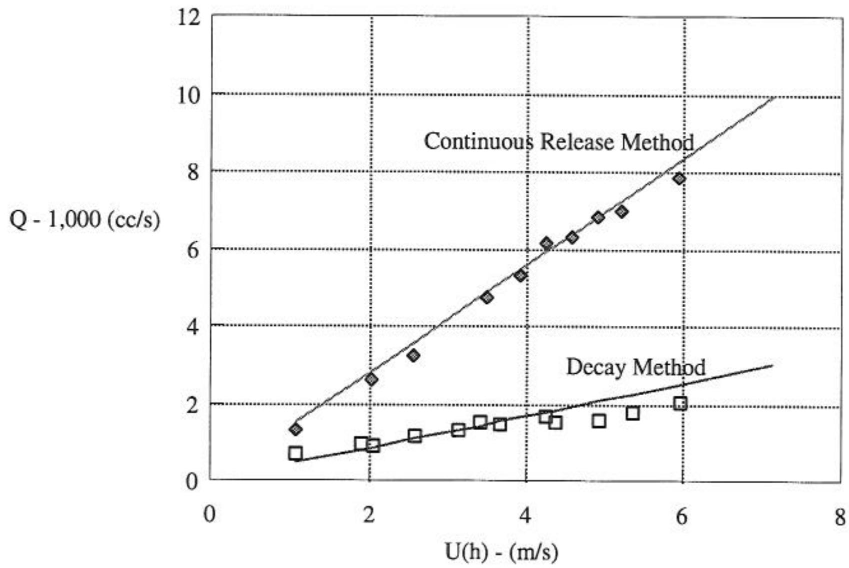


Figure 4. 1:25 Model Scale Ventilation Rates

$$Q^* = \frac{Q}{U(h)} \frac{1}{\mathrm{L}^2} \tag{4}$$

Where, L is the length scale of the model, relative to 1 m full-scale, [L].

If the flow through the window, room and door is considered to be predominantly momentum driven, i.e. of a turbulent nature, the large pressure gradient across the downwind length of the model allows the window and door to be each treated as an orifice. In such a case, the flowrate, Q, through each orifice becomes a function of the pressure gradient to the 1/2 power. Given that the mean internal and external pressure coefficients are invariant with $U(h)$, the absolute pressure difference across the opening is a function of $(U(h))^2$. Thus, the volumetric flow will be linearly related to $U(h)$, and the factor Q^* will be invariant with wind speed. This is shown to be the case by Table 1.

A high volume of ventilated air entering through the building's upwind opening and exiting quickly through the leeward opening causes a path of fresh air to unevenly distribute the tracer within the room. At the location of the sampling probe, a quantity of stagnant air exists. In the decay tests, poor mixing of this portion of the room air causes a lag in tracer concentration decay rates. This leads the decay test to under-estimate the actual room air exchange rate.

For the continuous test, the location of the tracer release valve within the building causes bias in the opposite direction. The release is located nearer to the leeward opening than the windward opening, on the downwind end of the model from the sampling probe. Therefore, a portion of tracer is introduced to the airspace and exhausted from the room before being measured at the probe. Since the room is not uniformly mixed, the probe reports a low concentration of tracer which over-evaluates the ventilation rate.

Table 1. Physical Simulation Ventilation Rates

$U(h)$ (m/s)	L (m)	Decay Method Q (cm^3/s)	Decay Method Q^*	Continuous Release Q (cm^3/s)	Continuous Release Q^*
1.08	1/25	671.8	0.389		
1.08	1/25			1333.2	0.772
1.90	1/25	951.5	0.313		
2.02	1/25			2605.5	0.806
2.06	1/25	912.7	0.277		
2.55	1/25			3226.9	0.791
2.58	1/25	1162.2	0.282		
3.13	1/25	1285.5	0.257		
3.41	1/25	1491.4	0.273		
3.50	1/25			4747.6	0.848
3.67	1/25	1441.4	0.245		
3.93	1/25			5319.0	0.846
4.24	1/25	1698.3	0.250		
4.26	1/25			6128.3	0.899
4.37	1/25	1492.4	0.213		
4.57	1/25			6312.8	0.863
4.90	1/25			6831.8	0.871
4.93	1/25	1588.5	0.201		
5.20	1/25			6968.8	0.838
5.37	1/25	1790.8	0.208		
5.93	1/25			7835.3	0.826
5.95	1/25	2038.8	0.214		

Numerical simulation of the tracer distribution support the wind tunnel results. Figure 5 is a horizontal cross section of a typical tracer distribution around and throughout the building during the tracer decay simulation. This shows very high concentration gradients around the plume of fresh air through the center of the room. Table 2 shows the results of computing ventilation rates within the numerical environment. Again, the continuous release method yields consistently high ventilation rates. The integrated sum of the velocity vectors across the window opening to the building airspace is reported in the last column. It shows that the two tracer approaches provide upper and lower measurable bounds for the actual volumetric flow of ventilated air through the room.

5. DISCUSSION

Tracer gas measurement of room ventilation rates in wind-driven naturally ventilated airspaces may face a major weakness when applying the assumption of a uniformly mixed tracer gas distribution. In this case, the high volume of fresh air entering and exiting the room through primarily unrestricted openings, without the aid of mechanical diffusion devices, does not distribute effectively through the bulk of the indoor air. As a result, the concentration of tracer gas and the ventilation rates observed by a conventional single-point sampling tracer analysis become a large function of measurement location within the room.

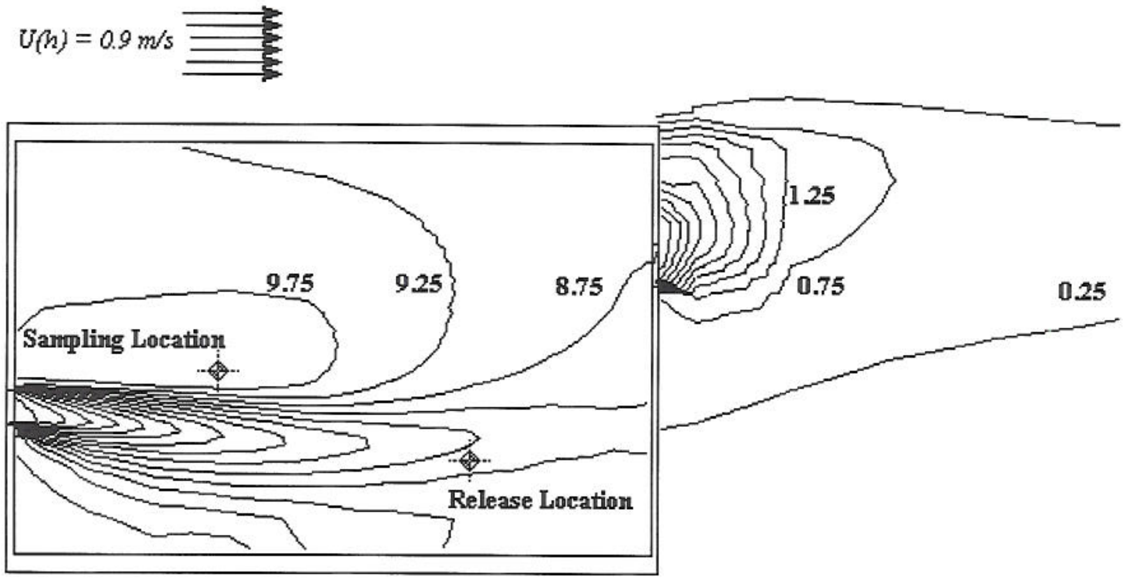


Figure 5. Example of Numerical Tracer Decay Test Results.
Horizontal slice of predicted tracer distribution 1 hour after source ceases. Plan view.

Table 2. Numerical Simulation Ventilation Rates

		Decay Method		Continuous Release		Integrated Solution	
U(*h*) (m/s)	L (m)	*Q* (m^3/s)	*Q**	*Q* (m^3/s)	*Q**	*Q* (m^3/s)	*Q**
0.50	1.00	0.038	0.075	0.533	1.066	0.273	0.546
0.90	1.00	0.062	0.069	0.695	0.772	0.511	0.568
5.60	1.00	0.423	0.076	-		3.130	0.559

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