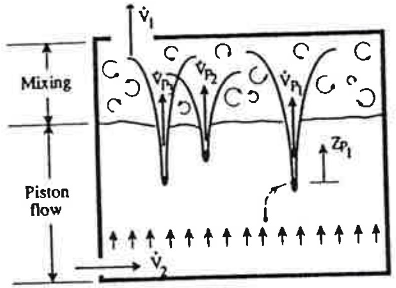


Figure 2. Schematic of two-zone model.

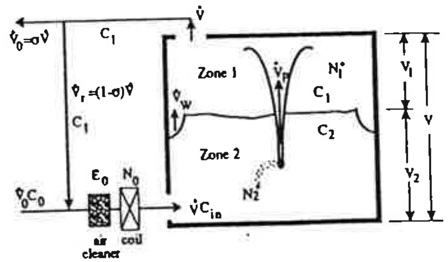


Figure 3. Diagram of test room and HVAC system model.

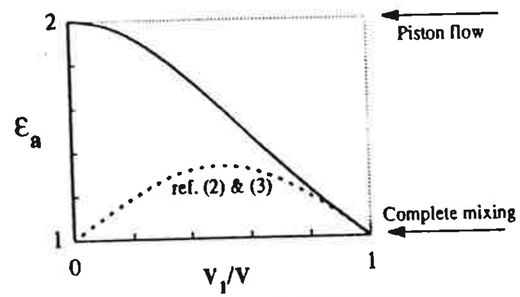
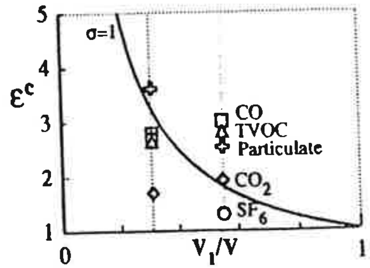


Figure 4. Predicted air change effectiveness.



(a) Comparison with measurements at $V_1/V = 0.31$ & 0.55, for $\sigma=1$.

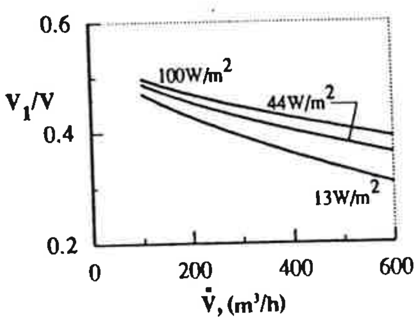
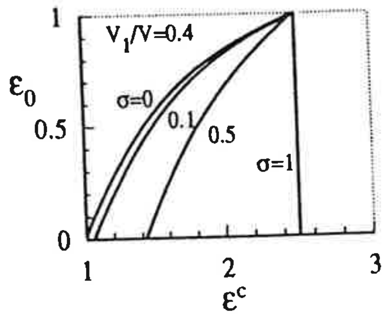


Figure 6. Predicted values of V_1/V as a function of the supply flow rate.



(b) Filter efficiency required for a specified σ and ε^c.

Figure 5. Predicted contaminant removal effectiveness.

COMPARISON OF DIFFERENT METHODS OF MEASUREMENT OF LOCAL VENTILATION PERFORMANCE

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ABSTRACT

A major determinant of exposure of workers in modern office buildings is the micro-environment of their worksite. This is determined by the dynamic relationship between local production of contaminants and their removal by mechanical ventilation. For this latter phenomenon, understanding is poor, definitions are controversial, and methods of measurement are not standardized. We have conducted a study using different methods to assess local ventilation performance at 28 worksites in 10 mechanically ventilated office buildings. SF6 tracer gas was released and the resultant concentrations at diffuser and respiratory zones during and after release were measured. The pattern of change of respiratory zone SF6 concentrations during and after local release did not differ significantly compared to central HVAC system release, nor following evening compared to afternoon release. Different patterns of respiratory zone SF6 concentrations during release were seen. A "plateau" was seen at 11 sites and was associated with open area concept worksites. This pattern of respiratory zone SF6 concentration was seen with lower diffuser output and lower theoretical air changes per hour (ACPH), but on the other hand was also associated with higher actual ACPH based on SF6 decay after release ended. Actual ACPH were very low at many sites, and varied considerably between sites. We conclude that measures of local ventilation performance at individual worksites is feasible using local SF6 release and results appear to be reasonably consistent and reliable. However, the relationship of these measures to other more traditional measures such as age of air as well as the relationship to symptoms and local contaminants concentrations remain to be determined.

INTRODUCTION

In modern office buildings with sealed windows, pollutants arising from indoor sources are generally removed by mechanical ventilation through exchange of contaminated indoor air with outdoor air. Although the cause(s) of sick building syndrome (SBS) remains unknown, there is widespread belief that symptoms of SBS result from increased concentrations of contaminants because of inadequate supply of outdoor air. Despite the lack of supportive scientific evidence this belief lead to changes in North American standards for outdoor air supply, in 1981 from 2 to 5 L/sec/person (1), and in 1989 from 5 to 9 L/sec/person (2). However in a recently completed randomized experimental double-blind study, increases in outdoor air supply from 14 to 28 L/sec/person were not associated with reduction in symptoms considered typical of SBS (3). In this study, there were significant differences in temperature, air velocity, and concentrations of certain contaminants between worksites, even those on the same floors in the same buildings; these between site differences were associated with between subject differences in symptom reporting (3).

The major determinants of the concentrations of contaminants at a worksite are the rate of production from local sources, and the rate of removal by the ventilation system. There has been considerable investigation into factors associated with local contaminant production, but the factors affecting contaminant removal remain poorly understood. Investigation of this

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phenomenon is complex, as it usually requires tracer gas release and measurement (4,5), and there is no consensus regarding the definition, nor methods of measurement. We planned to use tracer gas techniques to characterize the performance of the ventilation system in removal of contaminants, from the worksites of workers with symptoms typical of SBS, and matched controls. To address a number of methodological questions, we first conducted a pilot study comparing three methods of estimating local ventilation system performance, at 28 worksites.

MATERIALS AND METHODS:

Sites and Buildings: The pilot was conducted in 10 mechanically ventilated buildings. Two to three sites served by the same branch line of the supply air of one ventilation system within each building were selected. Sites were selected to provide a representative sample of the types of offices, and HVAC systems, found in these buildings.

Tracer gas release: To minimize potential building occupant concerns, we planned to release tracer gas after 6:00pm, and locally into or pre mixing box in the branch supply air duct serving the worksite to be studied. First, local vs central system releases and afternoon vs evening releases were compared in three enclosed offices, each with one diffuser, in a single building. For the remainder, local evening releases were conducted. For the system releases, pure SF6 was released into the main supply air duct at 1.0 L/min. For local releases, pure SF6 was injected at 200 mL/min into a branch supply air duct typically supplying 5 to 10 diffusers feeding an enclosed area, at a suitable injection point 3-5 metres 'upstream' from the site diffuser. SF6 was injected from a 15L polyethylene bag, for 10-13 minutes, using a volumetric pump.

Tracer gas measurement: At one site for each injection instantaneous measurements were made every minute using a photoacoustic multi-gas monitor equipped with a filter for SF6. Measures were made at respiratory zone alternating with diffuser zone. At all other sites being concomitantly measured, collections of air at diffuser and respiratory zones were made every minute into empty polyethylene bags using volumetric air pumps set at 4.0 L/min. The two measurement points were sampled at each site, one located at respiratory zone (1 meter above the floor) and the other at diffuser zone (directly in the diffuser) every minute during release of SF6, and every 2 minutes for up to 90 minutes after release ended, until SF6 concentrations were no longer measurable. The decay rate was constantly monitored to ensure a linear decay was occurring which is indicative of adequate mixing and uniform initial concentration. If adequate mixing was not occurring, the session was aborted. During local releases, enclosed offices were sampled under positive pressure with the door closed and the open concept sites sampled, were always in a largely enclosed area located in the supply zone of the system implicated and gas traced. This ensured minimal or no infiltration of untraced air.

Other measurements: Prior to the test the room dimensions were measured and volume calculated. Output from all diffusers in the room or open area was measured directly with a hot-wire anemometer. A surface grid of diffuser measures ,traverse measures of the ducts and the surface correction factors were utilized to calculate volumetric output of the diffusers. In some cases, the most recent balancing report was utilized.

Definitions and calculations:
1. Diffuser ratio: the ratio of the output of the diffuser for the site being measured - to - the average output for all diffusers in the room/open area.
2. Air changes per hour (ACPH) theoretical: total output from all diffusers -divided by - the room volume in cubic metres.
3. ACPH actual: Calculated from decay of log(SF6 concentrations) at respiratory zone (RZ).
4. ACPH theoretical: Calculated from total air supply from all diffusers -divided by - room volume.
5. ACPH ratio: ratio of ACPH actual - to - ACPH theoretical.
6. Ratio end SF6: the ratio of Respiratory Zone SF6 concentrations (RZ-SF6) to Diffuser Zone SF6 concentrations (DZ-SF6) during the last four minutes of tracer gas injection.
7. Ratio mid SF6 - the ratio of RZ-SF6 to DZ-SF6 in the middle three minutes of injection.
8. Pattern of SF6 rise at RZ: visual impression with regard to rate of rise in RZ-SF6, relative to DZ-SF6. "Plateau" defined as: RZ-SF6 concentrations significantly less than DZ-SF6 concentrations, without significant difference between Ratio-end-SF6 and Ratio-mid-SF6.

Analysis: These outcomes were correlated with each other. Average values of these outcomes grouped by characteristics of sites such as office of HVAC type, were compared by T-test or Analysis of Variance.

RESULTS:

As shown in Table 1, there were no differences in the pattern or rate of rise in RZ-SF6 during local or system (central) injection, although there were substantial, and unexplained, differences in the ACPH calculated from SF6 decay. There were minimal differences in the pattern, rate of rise and calculated ACPH between afternoon and evening local releases. At 7 worksites air was supplied from two different supply air ducts running to different diffusers. At these sites, tracer gas was injected into both supply air ducts simultaneously. However DZ-SF6 concentrations resulting from the two injections were often very different, with the result that RZ-SF6 concentrations varied widely, as did the mid-SF6 and end-SF6 ratios, making results from these sites difficult to interpret.

Table 1. Methodologic aspects of SF_6 measurements.

	(Number)	ACPH actual	ACPH ratio	Diffuser perform.	Ratio End SF_6	Ratio Mid SF_6
Type of release						
System	(3)	0.9	.05	100%	.75	.59
Local	(3)	2.7	.17	100%	.75	.57
Time of release						
Afternoon	(3)	2.7	.17	100%	.75	.57
Evening	(3)	2.1	.13	100%	.65	.50
No. of injections						
One	(27)	0.7	.12	97%	.66	.58
Two	(7)	0.7	.08	86%	.81	.65

As shown in Table 2, the ratio of RZ-SF6 to DZ-SF6 was positively correlated with the worksites' diffusers delivery of air relative to other diffusers in the same room, and negatively correlated with room size. These ratios were also positively correlated with theoretical ACPH, calculated from diffuser output and room volume. This could be interpreted as indicating that delivery of air from the DZ to the RZ is lower if the room is larger, and is better if the diffuser output is higher, at least relative to other sources of air supply in the room. On the other hand these ratios are, if anything, negatively correlated with ACPH calculated from RZ-SF6 decay after tracer gas injection was stopped. The more negative correlations with ACPH ratios is a reflection of the positive correlation of diffuser output, and theoretical ACPH, with these ratios.

Table 2. Correlation of different estimates of local ventilation performance.

	Ratio End SF_6	Ratio Mid SF_6	Ratio End Ln SF_6	Ratio Mid Ln SF_6	Room Vol.	Diff. Perf.	ACPH Actual	ACPH Ratio
Ratio End SF_6	1.0	.83	.94	.85	-.11	.40	-.14	-.45
Ratio Mid SF_6	1.0	.80	.93	-.22	.35	-.06	-.39	
Ratio end Ln SF_6			1.0	.93	-.11	.32	-.11	-.57
Ratio mid Ln SF_6				1.0	-.22	.28	-.01	-.49
Room Volume					1.0	-.33	-.02	.22
Diffuser performance					1.0	-.11	.04	
Actual ACPH							1.0	.75
Ratio ACPH								1.0

Table 3. Relationship of office and HVAC characteristics to estimates of local ventilation performance.

	(No.)	ACPH Actual	ACPH[1] Ratio	Diff.[2] Perf.	Ratio[3] end (ppb)	Ratio[4] mid(ppb)
Office type						
Closed	(24)	1.2	.10	97%	.70	.60
Open	(10)	0.8	.14	88%	.66	.59
HVAC type						
CAV	(25)	1.1	.08	95%	.70	.58
VAV	(9)	1.0	.20	96%	.67	.62
Pattern						
Plateau	(11)	1.2	.19	89%	.51	.47
No plateau	(15)	1.2	.08	98%	.73	.60
Infiltrations	(4)	1.3	.23	100%	.99	.86
Office/HVAC						
Closed/CAV	(18)	1.2	.07	98%	.75	.60
Closed/VAV	(4)	1.2	.24	93%	.50	.45
Open/CAV	(7)	0.8	.13	87%	.59	.55
Open/VAV	(5)	0.7	.15	99%	.81	.74

[1] ACPH Ratio : ACPH Actual / ACPH Theoretical
[2] Diffuser performance: Diffuser output/ Average diffuser output for room.
[3] Ratio end: $RZ-SF_6/DZ-SF_6$ at end of release.
[4] Ratio mid: $RZ-SF_6/DZ-SF_6$ at middle of release.

As shown in Table 3, there were substantial differences between office types or HVAC types in these different estimates of local ventilation system performance. The plateau phenomenon was seen in 55% of open concept offices, compared to only 28% of closed offices, yet the calculated ACPH were significantly higher in these open areas. This may have been because the decay in RZ-SF6 concentrations was due to mixing with air from other worksites in the open area, and not actual removal by dilution with air from the ventilation system. Actual air change rates were very low, considerably below the theoretical rates calculated from measured diffuser output.

The pattern of change in RZ-SF6 in response to SF6 release could be characterized as a plateau at 11 worksites, and not as a plateau at 15 sites. In Figure 1 are shown examples of these two patterns seen at two different sites. At four sites the RZ-SF6 concentrations exceeded the DZ-SF6 concentrations. These four sites were all supplied by VAV systems; differences in DZ-SF6 concentrations at the different diffusers in the same room were seen, and infiltration from sites with higher DZ-SF6 may have occurred.

DISCUSSION

In this study local release of SF_6 tracer gas after normal working hours provided similar measures of local ventilation performance as more standard techniques involving release in the central HVAC system (7). Even though SF_6 is safe at concentration many orders of magnitude greater that used in building ventilation studies, we have had to cancel tracer gas studies in the past because building occupants did not wish to be exposed to SF_6. Local injection performed in the evening is simpler, cheaper as it uses less SF_6, and does not expose any of the normal building occupants to the tracer gases. The effectiveness of the ventilation system in removing contaminants that are produced locally is considered to be an important determinant of environmental conditions at worksites (6). We have shown that environmental conditions vary widely between worksites within the same buildings, and that these between site differences are associated with between-worker differences in symptoms (3). In this study there were considerable differences between sites in both the theoretical and actual ACPH using standard methods (7). There were substantial differences between worksites in the response of SF_6 at respiratory zones during SF6 release. This has been labeled the "plateau" phenomenon (6), but would be better described as a slower increase or response. Slower response was associated with open concept offices, but not with other worksite characteristics. This phenomenon correlated well with the theoretical air changes per hour but not with the actual air changes per hour calculated from SF_6 decay.

Measurements of ventilation system performance are complex (4-7), and not standardized, nor is there a consensus regarding the definitions of terms such as ventilation efficiency and effectiveness. We conclude that a number of parameters of local ventilation system performance can be estimated using local SF_6 release with measurement of resultant increase and decay at the respiratory zone. However these parameters can not be interpreted without additional information regarding contaminant concentrations, and occupant health and well-being.

ACKNOWLEDGMENTS
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MODEL EXPERIMENTS FOR THE DETERMINATION OF AIRFLOW IN LARGE SPACES

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ABSTRACT

Model experimenting is one of the methods used for the determination of airflow in large spaces. This paper will discuss the formation of the governing dimensionless numbers. It is shown that experiments with a reduced scale often will necessitate a fully developed turbulence level of the flow. Details of the flow from supply openings are very important for the determination of room air distribution. It is in some cases possible to make a simplified supply opening for the model experiment.

INTRODUCTION

Large ventilated air spaces as shopping arcades, atria and exhibition buildings have grown popular in the last decade. The main purpose of designing the air distribution in such constructions is to obtain control of the energy flow and the temperature level. It is also very important to have a high ventilation efficiency in the occupied areas and a system which can handle this area without too large air exchange in the rest of the air volume. Smoke movements in case of a fire and necessary escape routes are other important subjects. It is also necessary to limit the air velocity in the occupied areas because people may work with restricted activity level in the shops and in open offices.

It is not possible to use full-scale experiments in the design of the air distribution system due to the large dimensions. It is also difficult to use simplified design methods as those based on throws of jets and penetration depths of non-isothermal jets. The cause of this is the complicated geometry which is present in many situations. Several sources for the air movement as for example diffusers, pressure difference around the construction, cold downdraft and thermal plumes make it also difficult to use simplified methods.

Computational Fluid Dynamics (CFD) and physical Model Experiments (ME) are two possible methods for the determination of the air distribution system and the latter will be discussed in the following.

Intensive work on air distribution in large spaces has just been initiated by the International Energy Agency Annex 26 programme "Efficient Ventilation of Large Enclosures". The programme will both contain field measurements, simplified methods, model experiments and CFD-methods (1).

GOVERNING EQUATIONS AND DIMENSIONLESS NUMBERS

The conditions for model experiments are formulated from the governing equations in a nondimensional form (2). The governing equations consist of the continuity equation, three Navier-Stokes' equations (one in each coordinate direction x, y and z) and the