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Distribution of Ventilation Air—Measurement and Spectral Analysis by Microcomputer

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Ventilation is a time-varying phenomenon which may be quantified using statistical methods and tracer gas techniques. For example, using spectral analysis of the concentration history of SF_6 introduced in the ventilation air, the major time scales for ventilation flows in rooms can be estimated. Experimental studies with a simple, PC-based data acquisition system in occupied laboratories in Waterloo, Ontario produced data records of contaminant concentration of up to 5 days' length with corresponding velocity records of ventilation and infiltration flows. Corresponding length scales can be estimated from spatial correlations of records from paired velocity probes.

NOMENCLATURE

σ_{xy}	covariance of x and y
ρ_{xy}	correlation of x and y
τ	lag period between samples
$c_{xx}(\tau)$	autocovariance at lag τ
$\rho_{xx}(\tau)$	autocorrelation at lag τ
$R_{xy}(\tau)$	cross-correlation coefficient of x and y at lag τ
G_{xx}	spectral density function
δ	data sampling interval
w	spectral window smoothing function

INTRODUCTION

NOW THAT research has identified the major air pollutants within buildings, successful measures to improve indoor air quality will depend on a better understanding of the ventilation flows themselves that are necessary to dilute and exhaust these contaminants. Much recent research has concentrated on the numerical modeling of contaminant concentrations and air flows in buildings. However, many of these models still require experimental verification. The work reported here illustrates the development of a microcomputer-based data acquisition and analysis system capable of performing such verifications.

The system was evaluated in field rather than in laboratory environments. As a consequence, the results are indicative of the sort of variability and randomness that characterize real ventilation flows.

A basic motivation of the research has been the desire to incorporate recent developments in spectral analysis for application to ventilation problems. Computational algorithms are available that allow simple and rapid calculation by personal computer of statistics of large sets of random data. The approach of the present work was to consider the concentration of a contaminant as a random variable which might reveal a statistical behavior that was characteristic of the space and the flow it contained.

Reviews of ventilation models and the concepts of ventilation are presented by Woods [1] and by Siurna [2]. The model that inspired the present project was a stochastic analysis of ventilation by Siurna and Bragg [3]. They proposed a probabilistic two-zone model to provide quantitative statistical predictions of system performance. That model assumed input variables and initial conditions to be either inherently random or quantifiable only with uncertainty, and therefore treatable as random variables.

The work of Niemela *et al.* [4], Barber and Ogilvie [5] and Sandberg and Blomqvist [6] are examples of experimental studies to verify other mixing models or to describe actual ventilation systems. However, other than recent work by Sandberg to determine power spectra of diffuser jet velocities, spectral analysis is new to ventilation research and not well represented in the literature.

SPECTRAL ANALYSIS OF VENTILATION DATA

Natural phenomena may be classified by their deterministic or random behavior when recorded over time. The movement of air can be described as a random process, whereby the record of air velocities and of the dispersion of contaminants being transported are viewed as a stochastic process. Since different sections of the record of a given ventilation flow may be similar only in their average or statistical behavior, it is necessary to describe such records in statistical terms.

Time-domain statistics used to describe the flows in the present project included the probability density function,

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mean, standard deviation and autocorrelation coefficients of the concentration signal and spatial correlations of pairs of velocity signals. Random data may also be analysed in the frequency domain to determine spectral functions and permit, for example, the investigation of the structure of turbulence. This may be useful in identifying where energy is transferred and in quantifying its dissipation. Detail not otherwise apparent in time-domain measurements may thereby be revealed by spectral analysis. Furthermore, correlation functions may be calculated more efficiently using new computational algorithms for power spectra, the distribution of power over frequency.

In the present project, the general questions asked about the technique and the flows were whether deterministic components could be detected within a given random signal, whether major time and length scales could be determined, and whether the flow was steady or unsteady in the time-scale of measurement. Accordingly, this was as much an experiment in evaluating spectral analysis and correlation techniques with ventilation flows as it was an investigation into the flows themselves. The objective was to explore realistic room behavior rather than a highly controlled situation.

Probability density distributions

A probability density distribution describes the frequency at which a signal will occur within a certain amplitude window. As the basic distribution function for any distributed quantity, it can express, for example, the nature of the fluctuations observed in steady-state concentration signals. The area under the frequency function curve between two concentrations equals the fraction of data whose concentrations fall within this interval. The area under the entire curve is always unity.

If the probability density function is observed to be skewed to the right and to cover a large range of values, as is common among aerosol particle sizes and other environmental distributions [7], a lognormal distribution may fit the observed distribution better than the normal distribution, and be more mathematically convenient for calculating weighted distributions and moment averages. Lognormal distributions are often the result of several independent random effects on a process, and it was hypothesized that concentrations of a contaminant introduced into ventilation air would also be lognormally distributed. Sandberg and Sjoberg [8] have reported that a lognormal distribution fit the concentration histories of single pulse injections of tracer gas in rooms.

The autocorrelation

The degree of linear dependence between two random variables x and y is calculated by the average product of $x-\mu_x$ and $y-\mu_y$. In the limit, this average product yields the covariance of x and y, defined as

$$\sigma_{xy} = \frac{1}{N}\sum_{i=1}^{N}(x_i-\mu_x)(y_i-\mu_y). \tag{1}$$

When x and y are positively linearly related,

$$\sigma_{xy} = \sigma_x\sigma_y = 1, \tag{2}$$

which is the largest possible value of the covariance between two random variables. σ_x and σ_y are the variances of x and y, respectively. Consequently, correlation can be expressed as

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x\sigma_y}, \quad -1 \leqslant \rho_{xy} \leqslant 1, \tag{3}$$

where ρ_{xy} is the correlation coefficient and assesses the linear dependence between two variables.

If observations $x(t)$, $(t = 0, 1, 2, \ldots, N)$ form part of a time series, then neighboring values will generally be correlated. Only in a purely random series will neighboring values be independent, i.e. $x(t)$ is not influenced by $x(t+\tau)$ where τ is the lag period between samples. For the present work the unbiased autocovariance is computed by [9]

$$c_{xx}(\tau) = \frac{1}{N-\tau}\sum_{t=1}^{N-\tau}(x(t)-\bar{x})(x(t+\tau)-\bar{x}), \tag{4}$$

where

$$\bar{x} = \frac{1}{N-\tau}\sum_{t=1}^{N-\tau}x(t), \tag{5}$$

and the autocorrelation by

$$\rho_{xx}(\tau) = \frac{c_{xx}(\tau)}{c_{xx}(0)}, \quad \tau = 0, 1, 2, \ldots, m, \tag{6}$$

where m is the maximum lag and $c_{xx}(0)$ is the variance.

Any periodic components in the signal will be indicated by local maxima in the autocorrelation function at the time scale of the periodic fluctuation. The autocorrelation coefficient is the inverse Fourier transform of the power spectra density function and can be computed from it rather than directly from the correlation function.

The cross-correlation

Where the two signals to be correlated are spatially separated, the cross-correlation coefficient is computed by

$$R_{xy}(\tau) = \frac{1}{T-\tau}\int_0^{T-\tau} x(t)y(t+\tau)\,dt \tag{7}$$

to reveal information about the large-scale fluctuations of the flow. If a series of coefficients is calculated for two velocity probes separated by different distances in the room and the resulting values expressed as a function of separation distance, any large eddies that exist should produce a maximum value of the coefficient at the corresponding separation distance. The cross-correlation coefficient is the inverse Fourier transform of the wave-number spectrum, and alternatively can be calculated from that spectral density estimate rather than from the direct correlation function.

The power spectrum

The spectral density function between two random signals is defined as the Fourier transform of the correlation function, and gives the distribution of the mean square of the signal over frequency. It is useful for identifying deterministic components of the signal and is also an efficient computational route to the correlation functions. The application of the power spectrum in this project is to identify the frequency of the major energy-containing eddies responsible for dispersion of ventilation air and contaminants in a space. It is expected that these spectra will have most of their power at low frequencies, as is characteristic of processes whose autocorrelation damps out smoothly with lag. This will be the case if the signal is free of large, high-frequency oscillations; indeed, the major fluctuations that are anticipated are those caused by varying weather-dependent infiltration patterns, occupancy activities and building operation, which may have time scales of hours or days.

The discrete estimation formula for the spectrum is

$$G_{xx}(f) = \delta \sum_{k=-(L-1)}^{L-1} w(k) R_{xx}(k)\, e^{-j2\pi f k\delta}, \quad -\frac{1}{2\delta} \leqslant f < \frac{1}{2\delta}, \quad (8)$$

where δ is the sampling interval of the data, $1/2\delta$ is the Nyquist frequency, $w(k)$ is a spectral window smoothing function, and L is the maximum number of lags [10]. Since the autocorrelation function is an even function of frequency, the one-sided spectrum can be computed according to

$$G_{xx}(f) = 2\left[R_{xx}(0) + 2\sum_{k=1}^{L-1} R_{xx}(k) w(k) \cos 2\pi f k\right], \quad 0 \leqslant f < \frac{1}{2}, \quad (9)$$

where the sampling interval $\delta = 1$. The spectrum is computed at values of f corresponding to $f = 0$, $1/F$, $2/F, \ldots, F/2F$ in which F is 2–3 times the maximum lag L. Here, this smoothed spectrum is computed by

$$G_{xx}(l) = 2\left[1 + 2\sum_{k=1}^{L-1} R_{xx}(k) w(k) \cos\frac{\pi l k}{F}\right], \quad l = 0, 1, \ldots, F, \quad (10)$$

with the Tukey spectral window

$$w(k) = 0.5(1.0 + \cos(\pi k/L)), \quad k = 1, \quad L-1. \quad (11)$$

As presented in [10] and [11], computation of the spectrum uses the following algorithm in BASIC:

```
  FOR I = O TO F
C = COS (PI * I/F)
V0 = 0
V1 = 0

FOR K = L-1 TO STEP -1
  V2 = 2*C*V1-V0+W(K)*R(K)
  V0 = V1
  V1 = V2
NEXT K
G(I) = 2*TIME*(R(0)+2*(V1*C-V0))
FREQ(I) = I/(2*F)
  NEXT I
  'F = # of frequency intervals (approx. 2 x L)
  'L = # of lags
  'R(K) = autocorrelation coefficient at lag K
  'G(I) = smoothed spectral density at
  frequency FREQ(I)
```

or:

$$G_{xx}(i) = 2\delta\left\{1.0 + 2\sum_{k=1}^{m-1} R_{xx}(k) W(k) \cos\frac{\pi k i}{NF}\right\}; \quad i = 0, NF. \quad (12)$$

EXPERIMENTAL EQUIPMENT

The data acquisition system utilised an IBM-XT type computer with 640K of RAM, 10MB of hard disk storage, a floppy disk drive, graphics adaptor, and a Metrabyte Dash-16 multifunction, high speed, A/D I/O expansion board. Labtech Notebook software was used to configure the Dash-16 files and provide real-time screen plots.

Sulfur hexafluoride was selected as a tracer gas for reasons of safety, good detectability, and the absence of any background interference. Concentration was measured continuously at a single location by a Miran 1A infrared spectrometer and a 10 s average recorded at 1 min intervals.

Air velocity was measured by Sierra Model 618 thermal anemometers which produce a 0–1 V DC signal. This was subsequently linearized by software. The measuring probes were directionally sensitive, responding to an included flow angle of 100° and optimally to an angle of <70°. Calibration of the probes was by laser Doppler anemometer in a low-flow wind tunnel at 0.06–0.27 m s^{-1} and utilizing software developed in-house [12].

To meter the flow of tracer gas, the SF_6 injection system relied on two relays and solenoid valves controlled by the digital output control system of the computer multifunction board. Two digital output channels sequentially opened and closed the valves to discharge controlled pulses of SF_6 to the supply air duct. Injection rate could then be varied by changing either the digital output signal, the length of the gas metering section, or the delivery pressure of the SF_6.

This tracer gas injection and data acquisition system was arranged as shown in Fig. 1. More complete design details are presented in [11].

EXPERIMENTAL PROCEDURES

All experiments were conducted in occupied rooms in the Mechanical Engineering building of the University of Waterloo, which were taken to be representative of typical industrial and institutional workplaces (Fig. 2). However the rooms were relatively "leaky", compared to high-rise commercial space, for example, and therefore likely to be more influenced by infiltration than many other situations of interest. Ventilation air was distributed with the conditioned air through a single overhead duct system.

The building heating, ventilating and air-conditioning (HVAC) system serving these rooms was normally in operation, with a setback mode reducing fan speed at times at night and on weekend. This velocity reduction would be expected to increase the concentration of SF_6 in the supply air, reduce the dispersion of the tracer gas and contribute to a corresponding daily and weekly

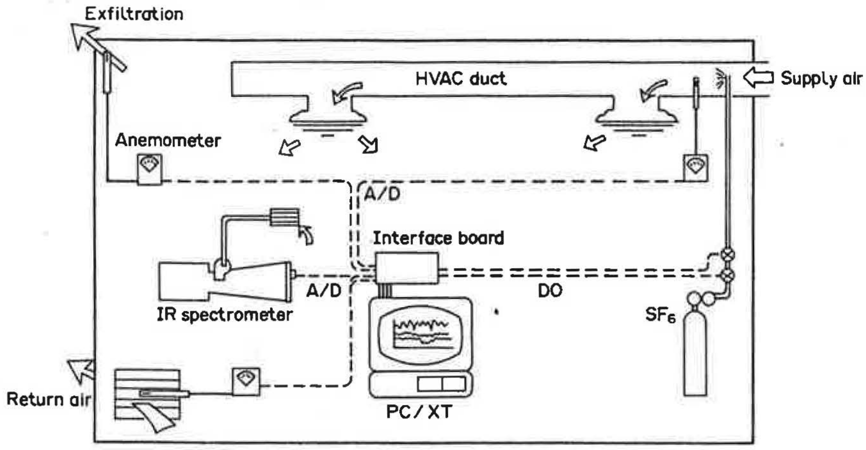

Fig. 1. Data acquisition and tracer gas injection system.

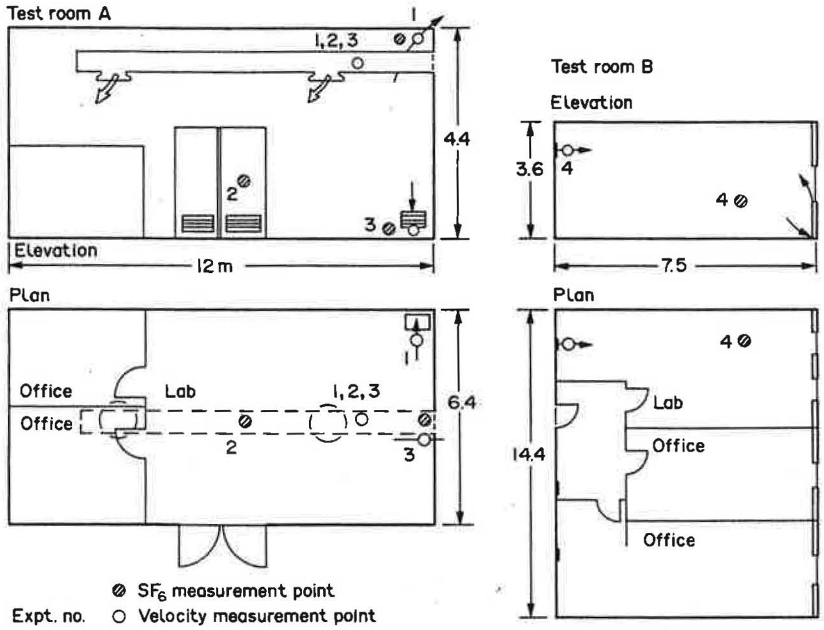

Fig. 2. Concentration and velocity measurement sites. Plan and elevation. (a) Mixed laboratory and office space, test room A. Experiments 1, 2 and 3. (b) Mixed office and laboratory space, test room B. Experiment 4.

signal in the power spectrum; however, unless the supply air was interrupted completely it would not affect the mass flow of tracer gas injected into the room. Supply air velocity was logged at 10 min intervals to monitor the HVAC operation.

Design outside make-up air was a constant 15% of total volume, except during the free cooling mode of 100% outside air. However, since the recirculated building air contained no measurable amount of SF_6, it had the same dilution effect on the tracer gas in the test rooms as did outside air. This meant that the concentration of the tracer gas could be considered to be independent of the make-up air settings of the HVAC system. In other words, concentration dilution was a function only of the total mechanical and infiltration flows and was independent of the source of dilution air.

Mechanical ventilation rates were modest, e.g. test room A had a nominal time constant of about 0.9 h.

Autocorrelations

SF_6 was introduced in pulses at a constant rate into the supply air duct or diffusers. This source concentration was typically 15–30 ppm and constant—depending on the ventilation rate—for the duration of each experiment.

The injection frequency of a pulse either every 5 or every 10 s was chosen so as to be considerably greater than any expected frequency of the factors driving the room air change and circulation. The injection rate of tracer gas, Q_{SF_6}, was measured by gasometer and could be used to determine the mechanical ventilation flow, given that the tracer gas concentration in the supply air was known.

Velocity measurements. In the power spectrum experiments, velocity was monitored primarily to identify the contribution of HVAC flows to fluctuations in contaminant level over the long term. Accordingly a single probe within the duct or at the diffuser face was used to measure the supply air velocity. A sampling interval of 10 min was adequate to detect major fluctuations, which were on the order of hours. Between these changes, which probably represented changes in HVAC fan speed, fluctuations in supply velocity were small and the flow uniform over the long term.

In some experiments, a second probe was placed in return air flows to determine the correlation of that signal to contaminant fluctuations. Whereas the supply flow represented only the mechanical ventilation rate, the return flows would also incorporate the effects of infiltration and other unintentional ventilation.

Cross-correlations

Figure 3 shows the layout of the test cell in which the spatial-correlation experiment was conducted, and the location of the velocity measuring points in a vertical plane along the mid-line of the room. The room was furnished but not occupied.

Two anemometer probes were positioned at a given distance above floor level and the cross-component of velocity measured at different cross-separation distances. Airflow was created by the normal building supply air from a high-wall register and by exhaust ventilation from two high-wall grills. A louvred equalising grill in the door provided the make-up air for this ventilation flow.

The velocity sampling rate and duration was determined in a manner similar to that in the tracer gas experiments. Assuming the longest length scale, L, to be 4 m and the slowest velocity scale, U, to be 0.1 m s^{-1}, then the time scale, T, would be about 40 s. Therefore the minimum measurement duration for the largest or slowest room-scale eddies would be twice this; a greater test duration of 150 s was conservatively chosen.

Assuming a maximum velocity, U, of 0.5 m s^{-1} and a minimum length, L, of 0.1 m, then the time scale, T, for these eddies would be 0.2 s. Therefore the sampling interval was set at 0.1 s (10 Hz).

Data was collected for $7\frac{1}{2}$ min then split into three records of 150 s for processing. At each measurement point, the spatial correlation was calculated as the average of three independent results.

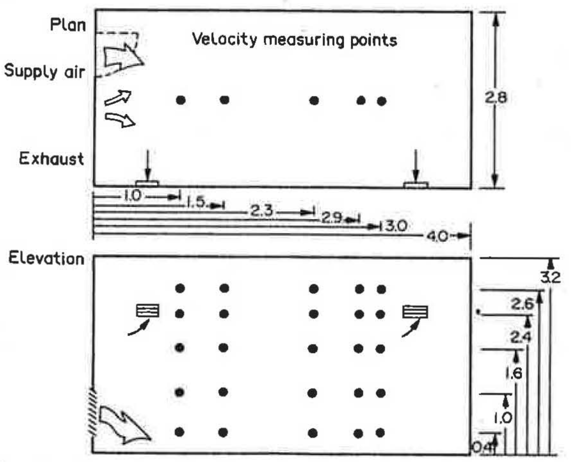

Fig. 3. Measuring sites in test cell for determining spatial correlation of air-flow velocities. Plan and elevation.

EXPERIMENTAL RESULTS

Times series records for tracer concentrations

Figure 4 is an example of the record of SF_6 concentrations sampled over 5 days at ceiling height in the Aerosol Lab, using a constant source of SF_6 injected into the supply air. The first noteworthy feature of this record is that there is no dominating steady-state condition that would apply to the whole record. Despite the constant generation rate, the contaminant experienced large fluctuations in concentration that did not diminish with time. Secondly, these lower frequency fluctuations were generally of greater amplitude than the higher frequency fluctuations. Portions of the record which appear to grow or decay exponentially over a period of hours suggest that step changes in either mechanical ventilation or infiltration have occurred.

The difficulty in proposing a strictly deterministic model to explain the concentration history is well illustrated by the record of ventilation flows superimposed on the concentration record in Fig. 5. Any correlation between the concentration and one particular exfiltration flow, measured at a wall-ceiling joint, is very poor, and neither record correlates with the HVAC supply flow. The lab was unoccupied for the early part of this record.

Supply air velocity was relatively constant over the 5 days, indicating that the night and weekend set-back mode of the HVAC system was not functioning in its normal mode. This supply air flow was originally recorded to help explain the large, long-term fluctuations that were observed in the concentration signal.

SF_6 concentration was measured at breathing level in a central location of the lab for two and one half days (Fig. 6). Activity in the room was light. Again, large and irregular growth and decay patterns which last several hours predominate over the finer scale fluctuations of the short term.

A comparison of the HVAC supply velocity with SF_6 concentration shows a poor correlation between concentration and mechanical ventilation. To test if wind was driving the flow in the room and if it could therefore be the explanation for the observed dilution, wind speed data from the local weather office is also plotted. It too indicates a poor correlation to SF_6 concentration.

Solar radiation may also contribute to a pronounced 12-h periodicity in infiltration flow, especially in spaces such as test room A having an industrial-type, metal deck roof/ceiling. However, insolation or the consequent heat transfer at the ceiling was not measured.

The 5-day record of SF_6 concentration at 40 cm from floor level was recorded to see if the behavior of the contaminant was significantly different from that observed at breathing level and at ceiling level (Fig. 7). Had the tracer gas not been completely mixed with the supply air, this might have been expected. SF_6 is about five times heavier than air and density effects have been observed by others. Air flows were monitored in the main supply duct and at the face of an equalising duct 45 cm from floor level and connecting to an adjacent lab which did have return air points.

The dotted line indicates the approximate range of these ventilation velocities. There is still no strong apparent dependence of SF_6 concentration on the recorded flows.

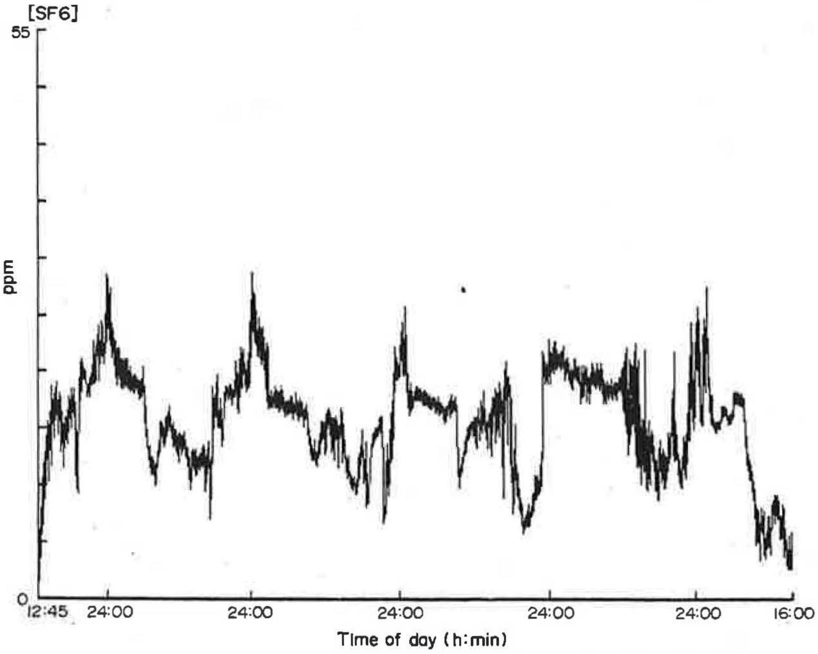

Fig. 4. Experiment 1. Concentration of SF_6 at ceiling level of test room A vs time. SF_6 injection typically started at time 0.

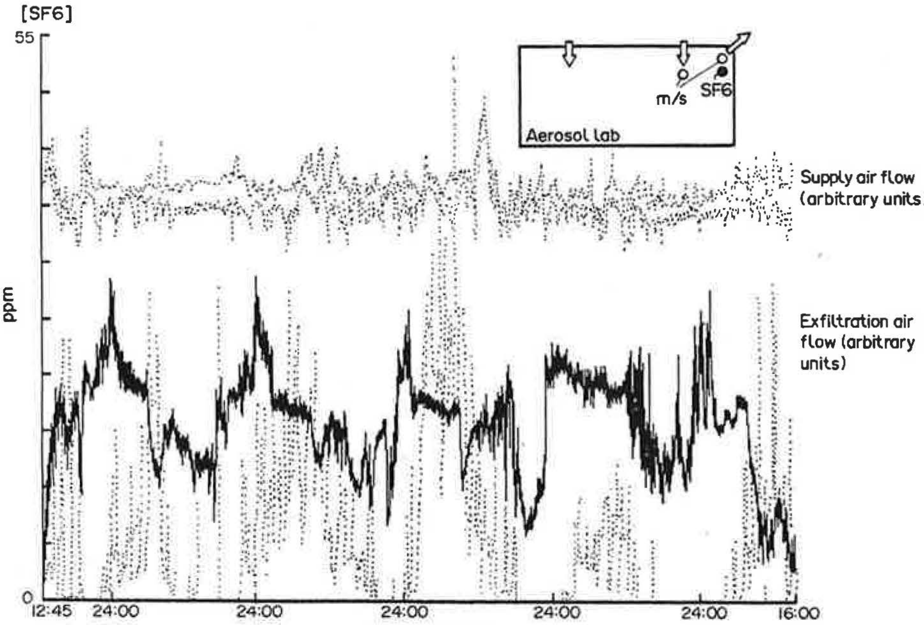

Fig. 5. Experiment 1. SF_6 concentration, supply air flow, exfiltration velocity for 5 days.

Figure 8 presents the 2-day data record from test room B. Here, night set-back of ventilation is complete, and does correspond somewhat to the major SF_6 fluctuations.

Autocorrelations and power spectra

Figure 9 shows the autocorrelation coefficients at lags up to 50 h for the SF_6 concentration records of Experiments 1–4 (described in Fig. 2), resampled at a 10 min interval. For Experiment 1, the quasi-periodic series is characteristic of a second-order, autoregressive process and resembles a sine wave with a period of about a day. The strongest positive correlation after the initial decay occurs at a lag of about 24 h, suggesting an influence by some cyclical component of the building mechanical system or of the building occupants. Even though the building HVAC fans were supposed to be operating on a 24 h cycle, this was not observed in the record of supply air flows in Fig. 5. The one measured exfiltration flow did however have an apparent periodicity of about 1 day. If this did prove to be the major cause of the 24 h period in concentration fluctuations, it would show that infiltration has a greater effect on general ventilation in that room than did mechanical ventilation. Somewhere in the building, a programmed fan may indeed have been

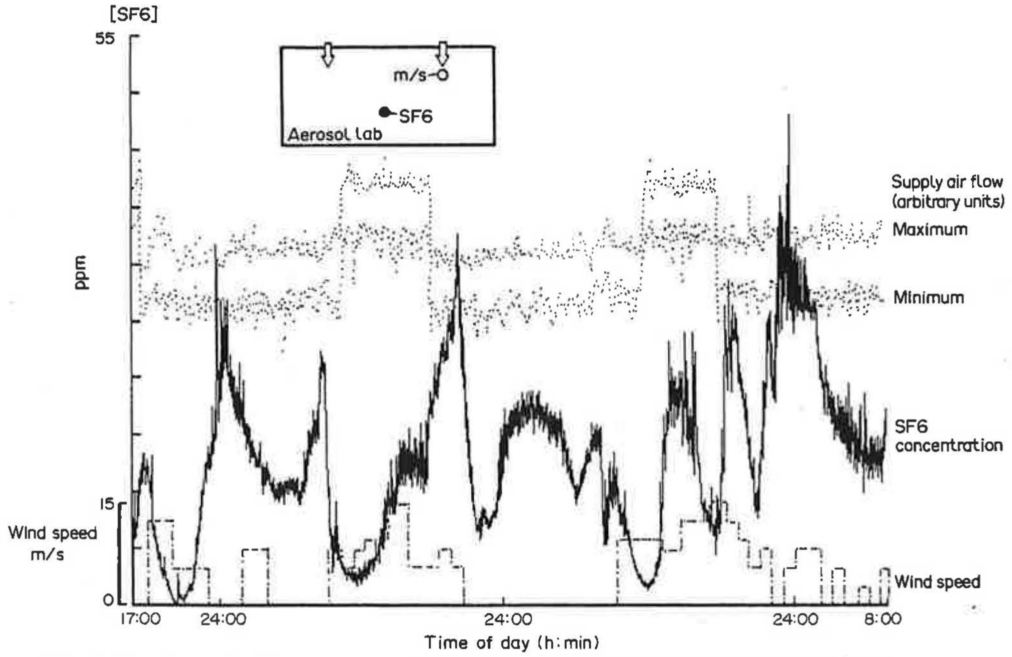

Fig. 6. Experiment 2. SF_6 concentration, supply air velocity, and local wind speed for $2\frac{1}{2}$ days.

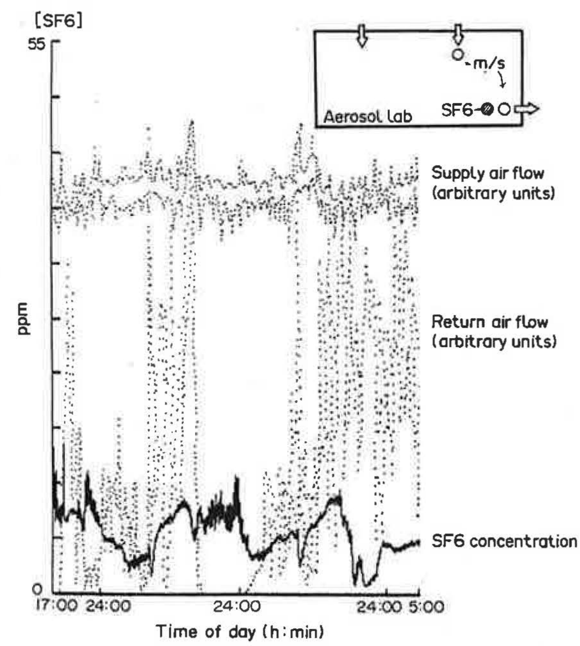

Fig. 7. Experiment 3. SF_6 concentration, supply airflow and flow at low-wall, return air equalizer duct for $2\frac{1}{2}$ days.

driving the observed exfiltration, but it was not the fan designated to this section.

A second positive peak, at about 49 h, is probably the double of the 24 h observation.

Figure 10 shows the power spectra for the four records over the frequency range 0–1.67×10^{-4} Hz, corresponding to a period of 100 min. This represents a portion of the entire spectrum which extends to the Nyquist frequency of 8.33×10^{-4} Hz. The first three peaks for the power spectrum of Experiment 1 represent the relative power contributed by fluctuations at about 25, 13, and 6 h. Since the concentration record is not truly periodic, the spectrum is spread over all frequencies in the range and not concentrated just at these frequencies. Most of the power occurs at the 25 h peak; at periods greater than 100 min there is no significant contribution.

The autocorrelation function for Experiment 2 is calculated over a lag period of 30 h, showing two positive peaks at 19 and 24 h. The power spectrum shows this major peak at 24 h and two smaller ones at 10 and 6 h.

The autocorrelation for Experiment 3 is calculated for lags up to 25 h and gives one peak at about 18 h. The corresponding spectrum shows most of the power to be at 18 and 8 h.

The autocorrelation and spectrum of Experiment 4 from the test room B differ markedly from the above results from test room A. Both curves have only a single peak, that at 19 h. This period also corresponds to the interval between zero crossings in the autocorrelation.

Velocity cross-correlations

The results of the cross-correlation calculations at zero lag suggest that the length scale of the airflows in the test cell room is less than 1.5 m. Cross-correlation coefficients were approximately zero for separation distances of 1.5 m and greater (Fig. 11). Correlations at 0.1 m separation were moderately strong, but still less than unity. The data represent the range of average values among the different measuring levels, from 0.4 to 2.6 m from floor level. The range in mean velocities was 0.07–0.16 m s^{-1}; the range in standard deviations was 0.02–0.06 m s^{-1}.

Probability distribution functions

Figure 12 compares the probability distribution functions for the four experiments; there is no indication of the hypothesized lognormal distribution of concentrations.

The absence of a skewed distribution at higher concentrations is evidence that a certain minimum amount of mixing and dilution usually occurred, limiting the

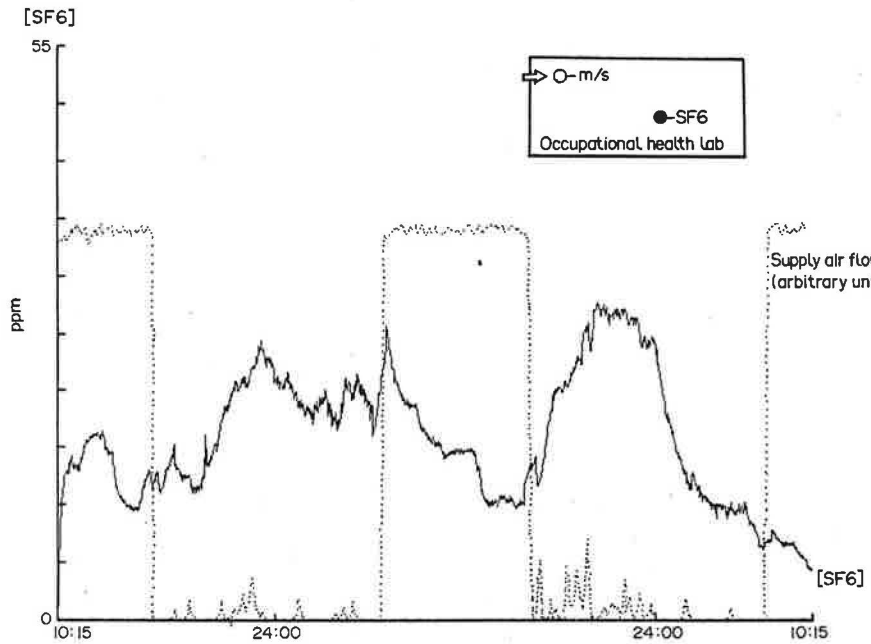

Fig. 8. Experiment 4. SF_6 concentration and supply airflow for 2 days.

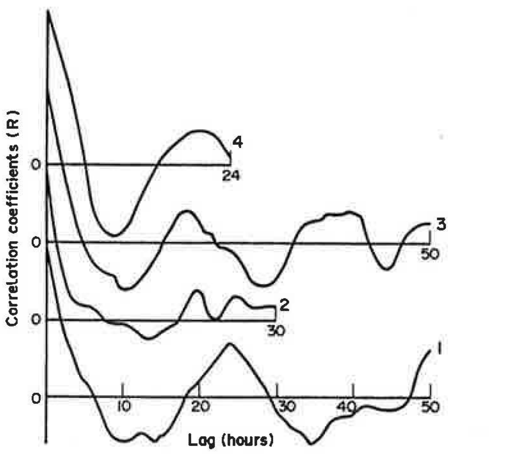

Fig. 9. Autocorrelation function for SF_6 records in Experiments 1–4 for lags up to 50 h. Original data was resampled at 10 min intervals.

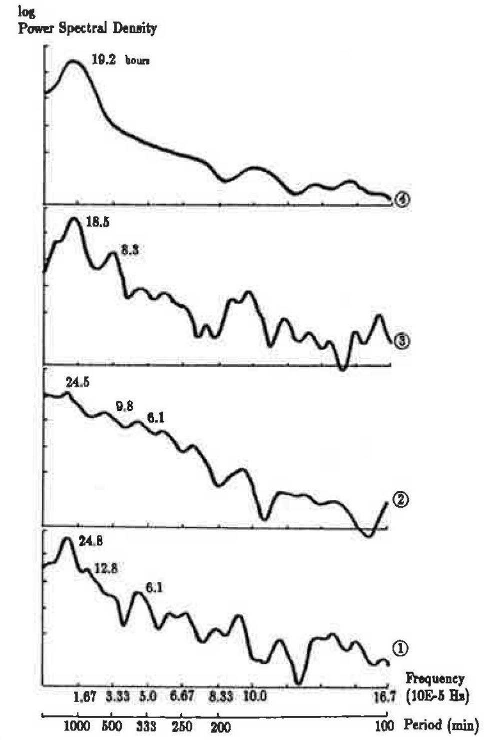

Fig. 10. Smoothed power spectra of SF_6 records of Experiments 1–4. Power spectral density is plotted in arbitrary power units on a logarithmic scale.

number of readings at maximum concentration. The SF_6 concentration in the supply duct was measured to be about the same as the maximum levels observed in the room, indicating that there are times of no significant infiltration flows when the tracer gas does achieve a short-term equilibrium. However at other times, with minimum concentrations in the room as low as 1/5 of this, it may be concluded that natural flows can reach four times the rate of the forced ventilation.

It must be remembered however that source concentrations were in the range of only 25 ppm; with the very large contaminant concentrations such as occur in industrial ventilation situations, then a lognormal distribution may be more likely.

DISCUSSION

The results as summarized in Table 1 suggest that most of the power in the ventilation fluctuations occurs at the low frequencies corresponding to time scales of 6–24 h. This is certainly longer than what the local age of the air would be expected to be at the measuring point since only 2–3 h were required to reach a short-term maximum concentration after tracer gas was initially injected. Also, the mean age of fully-mixed air on leaving the room, as calculated from the nominal time constant, would have been only 0.9 h.

Rather than representing large, slow, room-size eddies

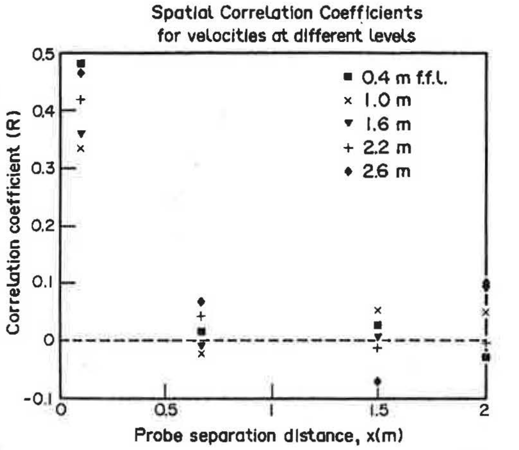

Fig. 11. Spatial correlations of airflow velocities at different levels in test cell, calculated at zero lag between signals.

Table 1. Summary of peaks and peak-to-peak periods in autocorrelations, and major peaks in spectrum. Record length, *N*, and SF_6 measurement position (floor, mid-height or celing) are noted. A = Test room. B = Test room B

Expt. no.	Position	Autocorrelation *N* (h)	Peak (h)	Period (h)	Spectrum Peak (h)
1	A ceiling	123	24	23	24.8
					12.8
					6.1
2	A mid-hit	63	19		24.5
			23.5		9.8
					6.1
3	A floor	120	17	17	18.5
			39		8.3
4	B mid-hit	48	19.2	19.2	19.2

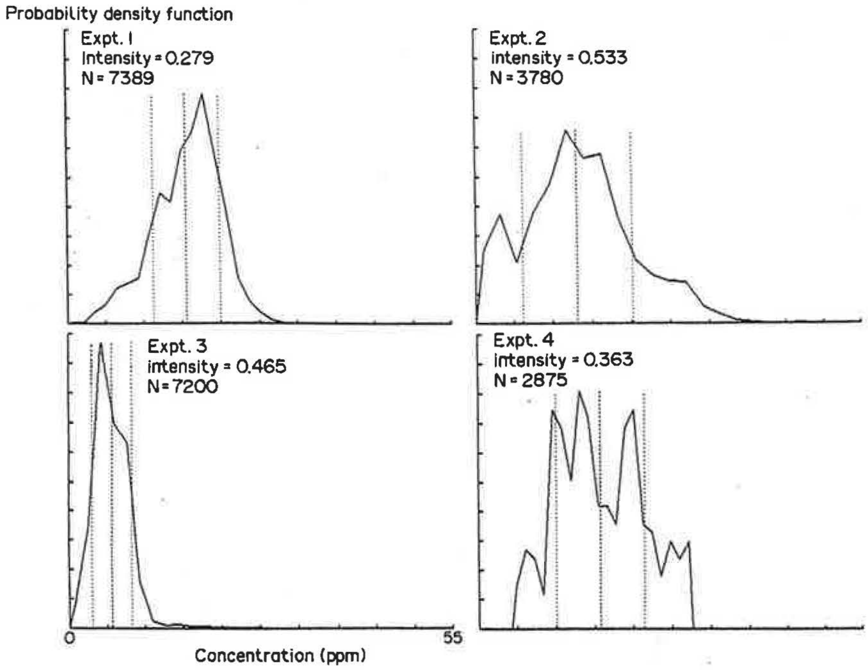

Fig. 12. Probability distribution functions of SF_6 records from Experiments 1–4.

having periods of several hours to a day, these long time-scale fluctuations were more likely to have been the result of activities in the room and building as a whole. It was not the object of this project to determine the exact causes of these fluctuations, but rather to provide statistical tools and illustrative data of realistic room behavior. Indeed, it is proposed that it is not feasible to attempt to evaluate all the determining factors, so great is their number and short-term variability.

Exfiltration flows sometimes showed more periodicity than did the HVAC system, but was a no more realiable predictor of SF_6 concentration than the HVAC signal. The poor correlation between tracer gas concentration and measured flows might be explained in part by the damping caused by the large volume of air in the room relative to the mechanical ventilation rates, i.e. the high value of the nominal time constant. Dilution effects at concentration probe by the measured flows could be expected to be slow and irregular.

Because of the long-term fluctuations, an estimate of the average conditions in the room would have to be based on several days' samples. Samples would have to be at least one time scale apart, i.e. separated by about 1 day where that was the major spectral frequency. This implies that concentration averages based on monitoring over even a few days has considerable uncertainty if such unsteady flow exists. Predictions of short-term concentrations would have even greater uncertainty since the small variations in concentration are superimposed on the large.

In order to determine with confidence just the mean of these records, monitoring would have to continue much longer. The maximum duration of 5 days in these tests was not long enough to allow all the time and length scales present to interact. This was demonstrated by the distribution functions, which were more closely normal than lognormal and had more than a single peak. Most environmental flows display a single peak and lognormal distributions in the long term. The absence of this distribution or of an approximation of it indicates that the measurement duration was insufficient to show the full development of the flow.

Table 1 compares the periods predicted by the autocorrelation function and the power spectrum for each record. The peaks of the autocorrelation function correspond reasonably well to the major spectral peaks, but with much less information about possible cycles with shorter periods. The exception is the record of Experiment 1 which did not display as much oscillation as the autocorrelation function.

A comparison of the three results from test room A suggests that whatever the causes of the apparent periodicity in ventilation, their effects are least disturbed at the floor and ceiling in these tests.

Airflow conditions in test room B were less affected than in room A by occupants' activities, influences from connecting rooms or the effects of a high ceiling. The results from this room produced the simplest autocorrelation function and spectrum, with a single low-frequency peak corresponding to a period of 19 h. This room also had a distinct HVAC set-back cycle.

Spatial correlation

The spatial-correlation coefficients from the mid-line plane did not indicate the existence of any room-sized eddies. Such large flow structures would have been expected to produce significant correlation coefficients at the large separation distances. However airflows at all five measurement levels did show significant correlation at the minimum separation distance, demonstrating that the procedure was functional. One may conclude that these flows had length scales in the order of less than 0.7 m.

At this minimum separation distance, the correlation coefficient was less than unity. Even at distances as small as 10 cm in airflows of supposedly large structure, it is possible that there still exist smaller perturbations that interfere with the perfect correlation of the two velocity signals.

Correlation was reported here only for zero lag time; plotting correlation coefficient vs lag might show greater positive correlations at a lag time greater than zero and help to identify a significant velocity scale in the process, since both a distance and a time scale would then be known.

CONCLUSIONS

1. Frequency-domain analysis provides a way of dealing with the randomness that characterises ventilation flows, identifying trends that are particular to a room or mechanical system and minimizing the effects of signal noise. A large data record of several days and several thousand data points can be reduced to one power spectrum, representing a unique, quantitative description of that particular flow.

2. The tested ventilation flows are unsteady in both the short and the long term. In this investigation, the flows were unsteady over time scales as long as days.

3. Most of the power in the fluctuations in the supply air of the rooms was at low frequencies, of the order of several hours to a day in length. There was relatively little power in higher frequencies.

4. The probability distribution function can indicate if all scales of flow have been adequately measured. Five days was too short a measuring duration to develop a definitive distribution curve for the ventilation flows in these experiments.

5. There was poor correlation between the tracer gas concentration record and various airflow records. Information about HVAC flows, a single exfiltration flow or prevailing wind speed may alone not be sufficient to predict the effect on the distribution of ventilation air or on the dilution of a contaminant in a room within a large building.

6. Data acquisition systems based on a PC microcomputer have the capability to acquire and process the information necessary to describe useful statistics of complex ventilation flows.

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