THE MEASUREMENT OF VENTILATION AND AIR MOVEMENT IN FACTORY BUILDINGS

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1. Introduction

The majority of factory buildings may be considered as large single-cell structures. In order to measure the air infiltration characteristics of such buildings, it has been found necessary to consider air movement patterns within them. The simultaneous consideration of both air infiltration and internal air movement has the added advantage that the dispersal of air-borne contaminants within the factory can also be studied. Using multi-zone air movement theory, in which one zone represents the outside air, air exchange between the inside and the outside and between internal zones may be measured and evaluated.

The equations governing flows in the multi-zone model are well known (1,2). Application of these equations to multi-zone tracer decay measurements (3) has shown how it is possible to:

1. determine the best initial distribution of the tracer gas, i.e. the most advantageous seeding strategy,

2. avoid inaccurate results due to ill conditioning or linear dependence,

3. maximise the information that can be obtained from a set of measured data.

An automated tracer gas monitoring system has been designed and built. The system is being used to measure air infiltration and air movement in a range of large single cell buildings, most of which are factories. The objective is to gain experience of the operation of the equipment, to refine data analysis techniques, and to provide a data bank as a basis for further developments of the theory.

2. Instrumentation

An automated six channel tracer decay system, using sulphur hexafluoride as the tracer gas, has been specially designed and constructed (4). The design is based on the experience of a pilot study (5), and a review of similar work in large single cell buildings (e.g. 6). The principal features of the system are:

1. Tracer gas concentration is measured by six independent gas chromatographs, one per channel. This allows fast sampling on each channel, so that rapid changes in tracer gas concentration may be followed.

2. Each chromatograph uses a pulse modulated electron capture detector. This gives a combination of high sensitivity and a wide linear operating range, so that large changes of tracer gas concentration can be measured without loss of accuracy.

3. The chromatograph parameters have been optimised for sulphur hexafluoride, thereby minimising interference due to other electrophilic compounds which may be present in industrial atmospheres.

To avoid cross contamination, the tracer injection system is separate from the measuring system. It consists of a gas cylinder, flow meter, and nozzle, the nozzle being attached to a small fan to provide mixing of the tracer at the point of injection.

3. Theory and Data Analysis

Accepted methods of measuring infiltration rates by tracer gas methods require that the air is uniformly mixed. Whilst this is easily achieved in small buildings, in large single cell buildings it is rarely possible. Also, the position of openings such as industrial doors, and the existence of internal air movement patterns, create variations in the effective infiltration rate throughout the building. Artificial stirring would destroy these variations.

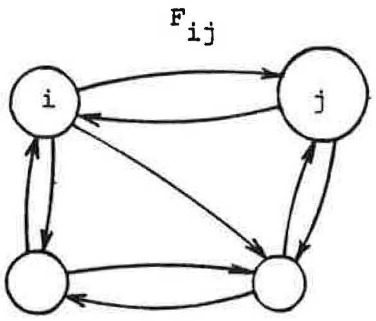
An alternative approach is to divide the space into a number of hypothetical zones and, assuming the air in each zone is fully mixed, sample the concentration in each zone. This enables multizone theory to be used, from which may be derived the inter-zone flow rates. Summing the individual flows into each zone from the outside gives the infiltration rate for the whole building. Figure 1 illustrates the essentials of the multizone model, and defines the essential terms.

Initially, each zone contains a known concentration of tracer gas, and there is no injection of tracer gas after time zero. A volumetric balance on tracer gas gives

$$V_j \dot{c}_j(t) = \sum_{\substack{i=o \\ i \neq j}}^{n} F_{ij} c_i(t) - c_j(t) S_j \qquad 1.$$

where n is the number of zones within the building, and S_j is the summation of the flows into or out of zone j. Conservation of total flow into any zone gives

$$S_j = \sum_{\substack{i=o \\ i \neq j}}^{n} F_{ij} = \sum_{\substack{i=o \\ i \neq j}} F_{ji} \qquad 2.$$



F_{ij} = flow from i to j

V_i = volume of i

c_i = tracer concentration in i

Figure 1. The multizone model

This is a system of first order equations with the general solution

$$\underline{c}(t) = \sum_{k=o}^{n} a_k \underline{x}_k e^{\lambda_k t} \qquad 3.$$

where the n + 1 values of λ_k and $\underline{x}_k$ are the eigenvalues and eigenvectors of

$$\lambda V \underline{x} = F \underline{x} \qquad 4.$$

The coefficients a_k are determined by the initial tracer gas distribution.

In a system of n zones, each connecting with the outside, there are $n^2 + n$ flows, F_{ij}. The necessary $n^2 + n$ equations to find the F_{ij} may be formed from n of the conservation equations 2, and measurement of the concentrations $c_1(t)$, ... $c_n(t)$ and their derivatives $\dot{c}_1(t)$, ... $\dot{c}_n(t)$ at n different points in time, since at each point in time equation 1 yields n tracer equations. Assuming $c_i(t)$ and $\dot{c}_i(t)$ can be measured, and providing the data set is error free, there is no difficulty in solving for the F_{ij}, provided the following dangers are avoided:

1. Irrespective of initial conditions, zonal concentrations tend to relative magnitudes equivalent to the components of the dominant eigenvector of equation 4. If more than one set of

$c_i(t)$ and $c_i(t)$ are taken as this condition is approached, an ill conditioned set of equations yielding an inaccurate solution will result. Therefore adequate time must be available for n significantly different sets of measurements to be made before this condition is approached. It can be shown (3) that this is best achieved by seeding only that zone which will have the lowest equilibrium concentration. This is the seeding strategy which is normally used.

2. Care must be taken when seeding buildings with symmetric zone layout and symmetry in the flow patterns, because, if the ratio of the concentrations in two zones remains constant with time, linear dependence in the equations will occur. In practice, this type of linear dependence is usually masked by experimental scatter, and is therefore observed as ill-conditioning (3), which again leads to an inaccurate solution.

Real experimental data is subject to scatter from a variety of sources, and since the solution technique relies on measurement of gradient as well as magnitude, the resulting errors in the F_{ij} may be substantial . The effects of errors are reduced by the following analysis procedure:

1. The data for each channel is smoothed using a standard fourth difference technique (7). This is preferred to the time-wise integration method used by Penman and Rashid (8).

2. Because of building geometry, not all F_{ij} exist, and so the number of unknowns is reduced by setting non-existent F_{ij} to zero.

3. Using the smoothed data, a constrained least squares technique is used to obtain the non-zero F_{ij} from equations 1 and 2. Constraints are necessary to avoid the appearance of negative values of F_{ij} in the solution. Penman and Rashid (8) used the constraint $F_{ij} \geqslant 0$. Additional upper and lower bounds may be obtained for some of the F_{ij} by examining the tracer concentrations at the start of the process (4); these additional constraints are also used here.

In addition to the multizone analysis, the readings from all six channels are combined to give a volume weighted average, which is fitted to a simple exponential decay curve. The decay constant is expressed as an infiltration rate for the whole building.

For both methods of analysis, each data set is split into six blocks (first third, second third, last third, first two-thirds, last two-thirds, whole set) and results computed for each block. For the multizone solution, the F_{ij} should be approximately the same whichever block is used. Large differences, therefore, indicate poor consistency in the data or possibly ill-conditioning in the solution. For the volume weighted average solution, the decay constant taken from the first third of the data will over estimate the infiltration rate, whereas that taken from the final third will underestimate it (3). Thus, the infiltration rate may be found within limits.

4. Results

Measurements have been carried out in five buildings, ranging in internal volume from 4220 m^3 to 31300 m^3. A similar pattern of results has been obtained in all these buildings. Some of the results for one of them (9) have been selected to illustrate the main points. This is a vehicle maintenance depot, a simple rectangular building approximately 81m x 48m x 8m high, as shown in figure 2.

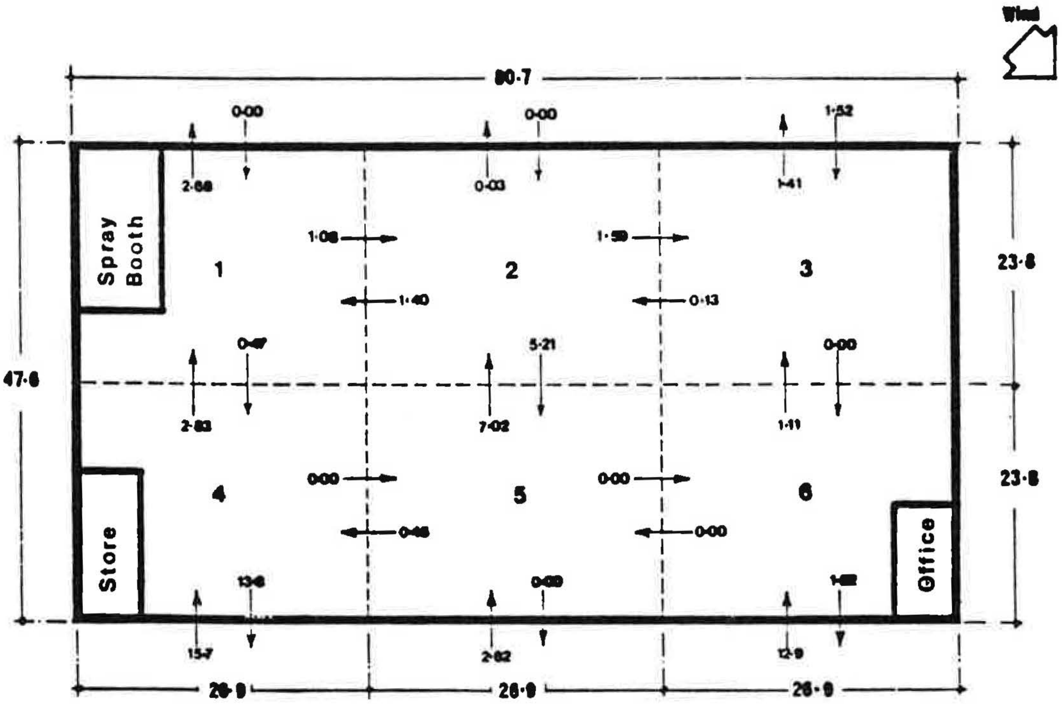


Figure 2. Vehicle maintenance depot, showing interzone flow rates in $m\ s^{-1}$.

Apart from the office, store and spray booth, the interior is obstructed only by vehicles and their repair equipment. For measurement purposes, the building was imagined to be divided into zones of approximately equal volume, with sampling points placed at the plan centre of each zone and at a height of about 5.7m (to allow clearance for vehicles). The building is naturally ventilated, but over each vehicle repair bay there is an extract nozzle for clipping to the exhaust pipe of the vehicles to remove engine fumes. Table 1 shows the whole building infiltration rate computed from 9 measured data sets by the methods described in Section 3. The infiltration rates obtained from the averaged data behave in the manner expected, with few exceptions. That is, the highest rate is obtained from the first third of the data set, and the lowest from the last third. Where this occurs, i.e. in the majority of the measurements, it is therefore reasonable to take the value from the whole data set as the best estimate, and the other two values as limits. Thus, for example, the result for run number 4 may be expressed as:

$$\text{Infiltration rate} = 3.17 \begin{array}{l} + 1.12 \\ - 0.21 \end{array} \text{ air changes per hours.}$$

Table 1. Measured infiltration rate, Duddeston vehicle maintenance depot.

Run No.	Infiltration rate in air changes per hour											
	From interzone flows						From averaged data					
	a	b	c	d	e	f	a	b	c	d	e	f
1	3.65	4.05	6.08	2.01	4.65	2.20	3.54	2.54	2.83	2.77	2.74	2.81
2	0.53	1.00	2.12	2.26	1.66	0.91	3.14	2.47	2.46	2.60	2.46	2.51
3	1.75	1.38	0.81	0.46	1.78	0.80	6.42	4.29	3.65	4.79	3.86	4.09
4	1.40	4.04	4.33	2.98	4.94	3.76	4.29	3.26	2.96	3.50	3.06	3.17
5	6.55	2.89	5.14	2.33	4.94	4.36	9.29	6.07	4.91	6.81	5.28	5.63
6	0.88	1.97	1.27	0.61	2.31	1.17	1.97	2.59	2.83	2.46	2.76	2.69
7	0.54	2.16	3.71	0.99	2.15	0.75	4.47	3.85	3.36	4.00	3.52	3.61
8	0.96	2.85	1.14	0.54	1.05	1.20	2.92	2.52	2.56	2.61	2.55	2.58
9	6.05	3.07	4.33	3.42	5.75	4.19	3.44	2.73	2.81	2.94	2.78	2.87

Key: columns a to f give results for blocks of data as follows:

a	first third	d	first two thirds
b	second third	e	last two thirds
c	last third	f	whole data set

The infiltration rates obtained from the multizone analysis of flow rates are sometimes consistent with expectation. Runs 1, 4 and 5 show a measure of consistency between results from different portions of the data set, and the result in column f for the whole data set is reasonably close to the corresponding value from the averaged data. In these cases, the individual interzone flows are probably a good indication of air movement patterns within the building. The flows shown in figure 2 were obtained from run 4. However, some of the runs show marked inconsistencies. For run 7 for example the infiltration rate computed from interzone flows varies between 0.54 and 3.71 air changes per hour, depending on which portion of the data set is analysed. In such cases there is little agreement with the infiltration rate obtained from the averaged data. Also, where there is inconsistency in the overall infiltration rate, it is found that the individual interzone flows computed from different portions of the data set also show lack of consistency.

5. Discussion and Conclusions

The fact that the results for some data sets are not only plausible but exhibit an internal consistency gives grounds for some degree of optimism. It suggests that dividing a large building into only six hypothetical zones is sometimes sufficient to give a reasonable description of the air infiltration and air movement patterns. However, the lack of consistency in many of the results has lead to several possible avenues of improvement. Experimentally, the next stage of the measurement program will examine the effect of multiplexing the channels in order to increase the number of zones and sample points. Also, the effect of sampling the air over a greater part of each zone will be investigated (currently each sample head draws air over a 2m radius). Both these measures, however, will increase the level of disruption to the building occupants. Theoretically, the effect of time lags on the decay curves will be examined. For a two zone model, Waters (10) has shown that time lags in the flow between zones produces an oscillation in the decay curves. Similar oscillations have been observed in many of the measured results, where it appears as a high frequency ripple. Figure 3 is part of the measured tracer concentrations for run 7. The ripple, which is clearly visible, cannot be explained, on the basis of normal multizone theory.

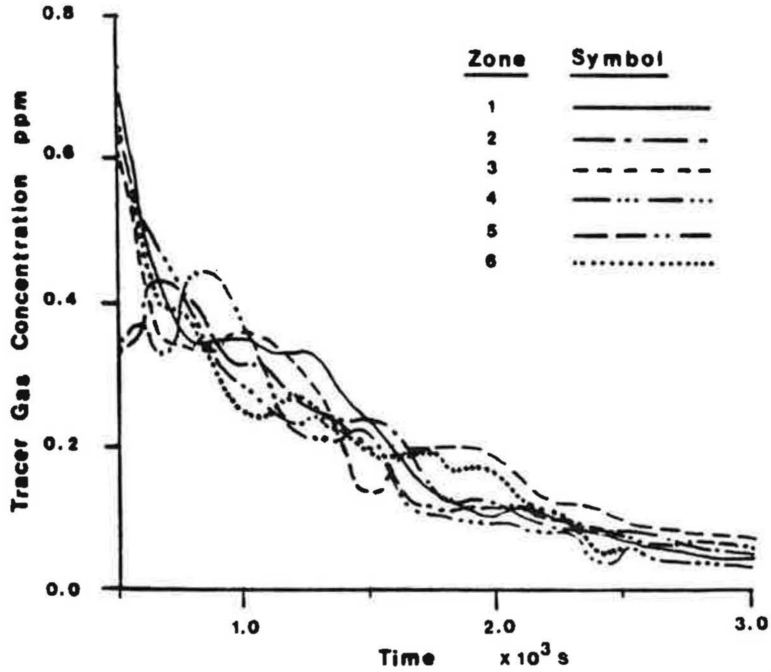


Figure 3. Tracer gas decay curve showing ripple effect.

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