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Ventilation of small factory units

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Summary

Ventilation rates have been measured using tracer gas techniques in a number of modern factory units with no mechanical ventilation. Wind direction remained fairly constant throughout the tests on individual units, enabling the variation of ventilation rate with wind speed to be determined. In the second phase of the work, measurements were made on a single building under a wide range of weather conditions. Although no correlation with wind direction was apparent, it was shown that the ventilation rate varied not only with wind speed, but also with the difference between the internal and external temperatures, i.e. the "stack effect".

1. Introduction

Very little information is available on ventilation rates which are currently being achieved in modern factory units. A survey of the ventilation standards in small factory units on modern industrial estates carried out in 1985 by HSE, showed that in most cases there was no mechanical ventilation. Where mechanical ventilation was installed, it had in many cases been added by one of the occupants of the buildings. In 39% of the factories there was no ventilation at all, whilst in a further 29% there were either fixed ventilation openings or opening windows. Where mechanical ventilation was installed, the survey gave no assessment of its adequacy. In factories which are naturally ventilated, air change rates result from a combination of planned ventilation, e.g. through windows or roof vents, and infiltration through the fabric of the building, e.g. through gaps around doors and window frames, cracks in walls, gaps at the eaves, etc. It has been supposed that modern factory units are designed and constructed to have low air infiltration rates in order to reduce heating costs. Such units are, however, usually built on a speculative basis, down to a price; hence the lack of integral ventilation systems. In the past, uncontrolled infiltration of factory structures being between 0.5 and 2 air changes per hour [1], probably provided sufficient ventilation for buildings which do not house processes giving off fumes, etc., but the extent to which ventilation rates have been reduced to improve energy efficiency is not known with any degree of certainty. An investigation of air change rates was carried out in two phases. In the first

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phase, measurements were made in five factory units over periods ranging from one to three days. In all cases the units were single-storey buildings up to about seven years old on small industrial developments, and were unoccupied at the time when the measurements were made. In the second phase, measurements were made in a large occupied workshop on an exposed site over a period of several months, and hence under a variety of weather conditions.

2. Experimental methods

The method used to determine ventilation rates was the concentration decay technique. Dichlorodifluoromethane was used as a tracer gas in most of the tests, although SF_6, sulphur hexafluoride, was used in the later ones. The gas was injected into the outlet of a mixing fan for a period of two minutes. At the end of this time the fan was switched off and air was sampled sequentially at up to six points around the building at half minute intervals. Gas concentrations were evaluated using an infrared gas analyser and the results were stored on a PC for processing later. Wind speeds and directions were obtained from local meteorological data in Phase I and from an on-site weather station in Phase II. Indoor and outdoor measurements of temperature and humidity were also taken at approximately 1.5 m above ground level.

Two methods were used to analyse the concentration data: concentration decay rate and age analysis. The concentration decay rate is the more easily performed analysis. By integrating the continuity equation, the concentration, $C(t)$, at any time t can readily be shown to be

$$C(t)=C(0)\exp(-Qt/V),$$

where Q is the ventilating airflow rate, V is the volume of the room, and $C(0)$ is the concentration at time $t=0$. This assumes that the concentration of tracer gas in the incoming air is negligible and the tracer is well mixed (see Appendix A). If the air change rate, N ($=Q/V$), remains constant over the measuring period then the tracer gas concentration will decay exponentially. When the natural log of the concentration is plotted against time, a straight line, the negative gradient of which is equal to the air change rate, can be drawn through the points. However mixing will not be perfect and the concentration will not fall as quickly as the actual number of air changes would suggest. The air change rate found is an effective rate which will be smaller than the actual rate. This feature is sometimes taken into account by the use of a mixing factor [2]. In practice, the air entering any region of a room is a mixture of "fresh" air and air which has been "recirculated" and can be characterised by its "age" or "residence" time. The local mean age (T_i) of the air at any sample point (i) can be determined from the normalised first moment of the pulse response. That is

$$T_i = \frac{\int_0^\infty C_i(t)\, t\, \mathrm{d}t}{\int_0^\infty C_i(t)\, \mathrm{d}t}.$$

The local air change rate N_i at the point i is then given by $N_i = 1/T_i$. Note that because the integrations are carried out to infinity, an exponential tail has to be fitted to the experimental results.

In general these two methods of evaluation cannot be expected to give the same result. The log–linear concentration–time plot will underestimate the number of air changes per hour (ach), especially at low air change rates, whilst age analysis will show up areas where mixing is poor. However, if samples are taken at positions which might be considered typical of the general area, avoiding places such as closed rooms off the main measurement area, there should be a good correlation between the two sets of results. Figure 1 shows a plot of data from seventeen of the tests carried out in Phase I. At the low air change rates typical of unventilated factories, the air change rate based on age was overall approximately 1.4 times that from the decay method. Below 1 ach the

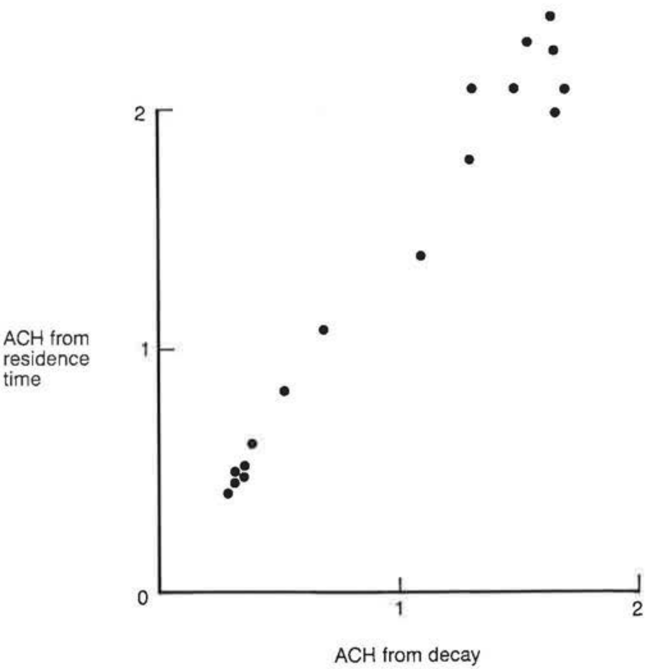

Fig. 1. Factory measurements.

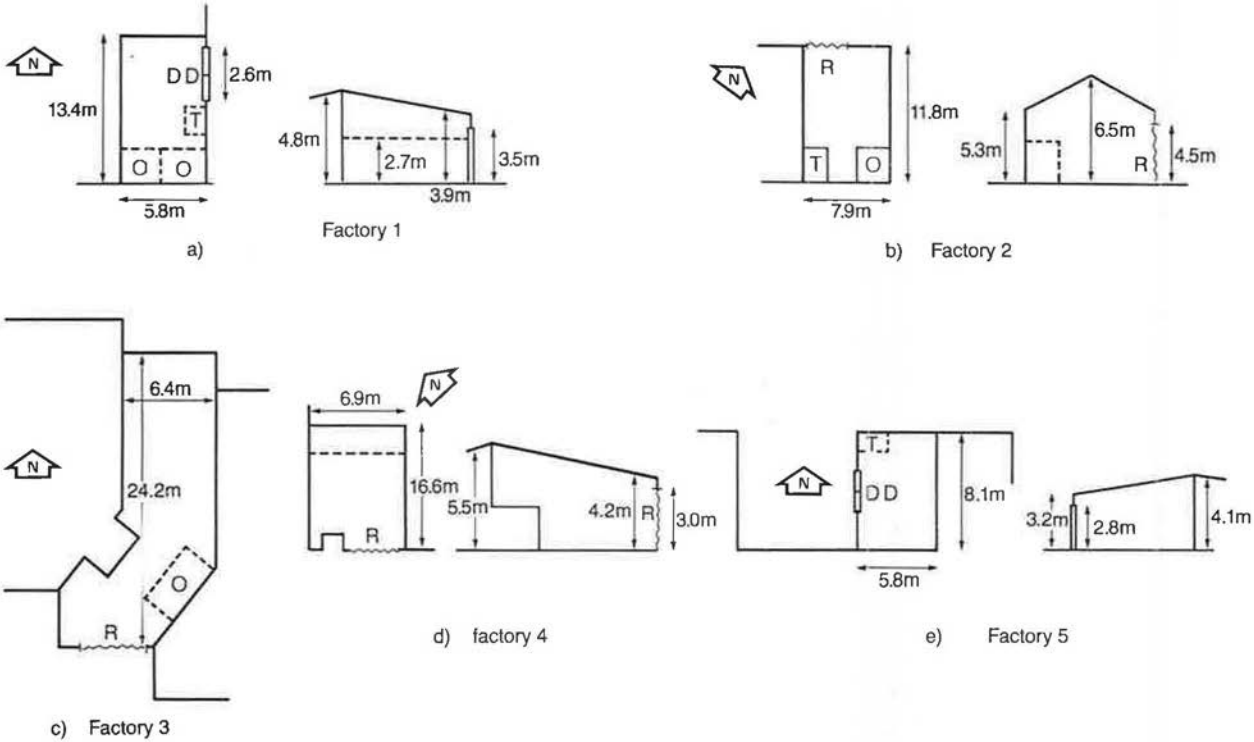

Fig. 2. O, office; T, toilet; R, roller door; DD, double doors.

factor was about 1.5; this was also found to be the case with the similarly low ach experienced in Phase II.

3. Phase I: description of units

All five units were parts of single storey blocks built since about 1982. The external walls were of either brick or brick with cladding on the upper parts. The interior walls were made of breeze or concrete blocks often with cladding on the upper half. The roofs were corrugated sheet lined internally. Factory 1 (Fig. 2a), on the corner of a block, had double doors which faced East. The end of the building was partitioned off into two offices and the total volume of the unit was approximately 330 m^3. Factory 2 was the end unit of a block and had roller doors which faced North-East (Fig. 2b). The volume of the building was about 510 m^3. Factory 3 (Fig. 2c) was the largest of the units having a volume of 700 m^3. All the windows were non-opening and the roller door on the South side of the building was well sealed at the floor although there was leakage from the sides and light could be seen entering at the top. It was a common feature of these units that the roller doors were very poorly sealed. Factory 4 had a roller door on the South-West side (Fig. 2d) and had a volume of 490 m^3. Factory 5 was on the same industrial estate as Factory 1 and also had double doors. It was the smallest unit (170 m^3) and was the only unit with a means of forced ventilation: a window mounted extractor fan. In the tests reported here the fan was not operated.

4. Phase I: results

Table 1 shows the results of seventeen tests carried out on the factory units. During the tests on any particular unit, the wind direction remained fairly constant. Figure 3 shows the variation of the air change rate with wind speed. Measurements on factory 3 were carried out during a particularly warm period and the difference between the internal and external temperatures did not exceed 1 °C. The variation in air change could therefore be attributed to the variation in wind speed. Although the difference between indoor and outdoor temperatures for the other four units varied from unit to unit, it was reasonably constant for individual ones and hence any "stack" effect would be constant for a particular unit. The results indicate an air change rate proportional to wind speed. Wind tunnel measurements by Tanaka and Lee [3] on a model atrium also showed the air change rate to be proportional to the wind speed.

Units 2, 3 and 4 all had roller shutter doors. Figure 3 shows that the air change rates in these factories were larger at any particular wind speed than was the case for a factory with double doors; this is consistent with the above observation on the fit of roller doors. For units 2 and 4 the orientations of the doors relative to the wind direction were very similar and Fig. 3 shows the air

Table 1

Data from factories

Factory No. and symbol	Air changes (h)		Temperature (°C)		Wind	
	Age	Decay	Inside	Outside	Speed (m/s)	Direction
1	0.88	0.54	11.0	8.0	4.6	NNE
●	0.95	0.69	16.0	11.0	5.1	NE
	0.55	0.38	11.8	7.8	3.1	NE
	0.65	0.38	16.4	11.0	3.6	NE
	0.49	0.35	13.0	8.6	3.6	NW
	0.55	0.38	17.6	12.6	3.1	NW
2	2.27	1.67	12.1	10.3	7.2	NNE
+	2.05	1.30	14.5	11.1	6.2	NNE
3	2.0	1.67	23.2	22.6	4.1	N
■	2.1	1.49	24.6	25.2	3.6	N
	2.1	1.70	24.7	25.0	4.1	N
	1.4	1.11	23.8	22.8	2.6	NE
	1.8	1.44	23.8	22.8	3.1	NNE
4	2.4	1.62	14.8	15.1	7.7	WSW
○	2.3	1.54	17.8	18.8	7.2	WSW
5	0.42	0.35	18.5	21.5	2.6	WSW
×	0.49	0.29	22.0	20.0	3.1	SSW

change rates to be comparable. The roller door of factory 3 faced due South and, during the particularly warm weather at the time of the tests, strong convection currents were induced by the hot inner surface of the door. This feature may at least partially account for the relative high change rates found. Factories 1 and 5, which were on the same estate, had double doors which had the same orientation with respect to the wind and, although the doors on unit 5 were shielded from the wind by the neighbouring building, the air change rates were similar.

5. Phase II.

In the second phase of the study measurements were made in a heated, occupied workshop in an isolated building on an exposed site near Buxton, approximately 370 m above sea level. The main body of the workshop occupied almost half of the building and had a volume and floor area of about 4275 m^3 and 570 m^2 respectively (see Fig. 4). It was adjoined by a large welding shop (2385 m^3) and had a large well-fitting roller door in the NW wall. The building was partially shielded towards the South-East by a bank but was otherwise well away from other obstructions. The location was chosen because of the

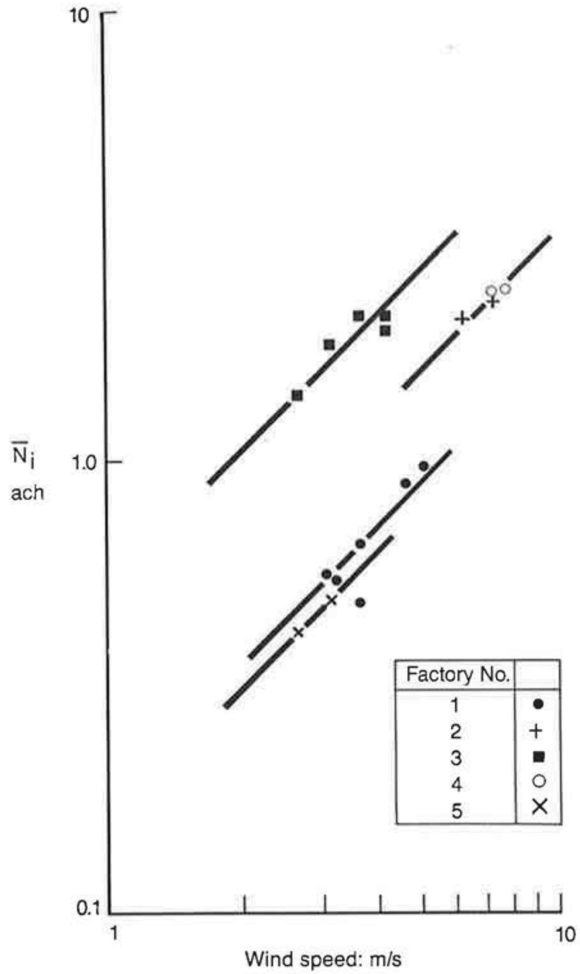

Fig. 3. Variation of air change rate with wind speed.

variability of weather conditions, especially wind speed and direction. Initially measurements were made at six points around the building but later tests used a single sample drawn from two points via a T-piece. All samples were taken at a height of 1.5 m. The air change rates were calculated from the gradient of the concentration decays.

6. Phase II: results

Air change rates changed from 0.53 to 2.08 ach. Approximately equal values could however be obtained for widely different wind speeds and temperature differences. For example:

(1a) 0.53 ach at 2.0 m/s and 3.5 °C,
(1b) 0.54 ach at 7.0 m/s and 12.0 °C,
(2a) 2.04 ach at 4.0 m/s and 3.5 °C,
(2b) 2.08 ach at 11.0 m/s and 14.5 °C.

Measurements carried out in Phase I had shown that the air change rate induced by the wind could be taken as being proportional to the wind speed. For any given building it would also be reasonable to assume that the air change rate will be a function of the wind direction. In the first phase this had remained reasonably constant from building to building; however when ach is plotted against wind speed for the second phase results, there is no obviously discernible correlation. Figure 5 shows results from the first 24 tests (out of a total of 48) plotted in this way. A third factor affecting the air change rate is the difference between the internal and external temperatures. This phenomenon is commonly known as the stack effect. As the air density is approximately proportional to the inverse of its absolute temperature, the air change could be taken to be proportional to the square root of the temperature difference. The rates of air infiltration due to wind and stack driven pressure differences were calculated independently and combined in various ways, e.g. by summing in quadrature. Of these, a relationship of the form

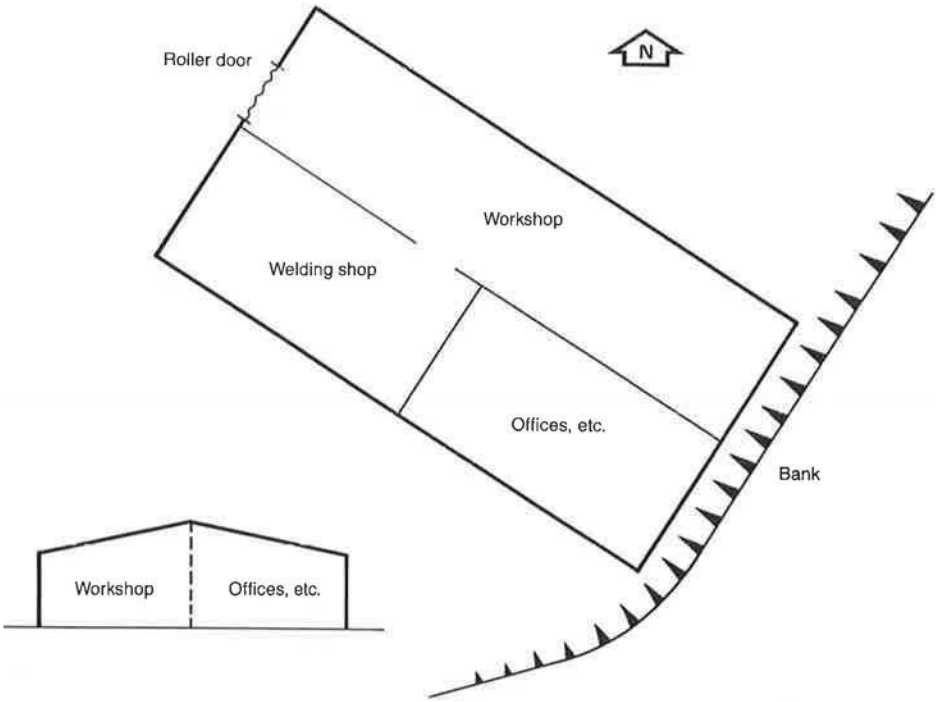

Fig. 4. Buxton workshop.

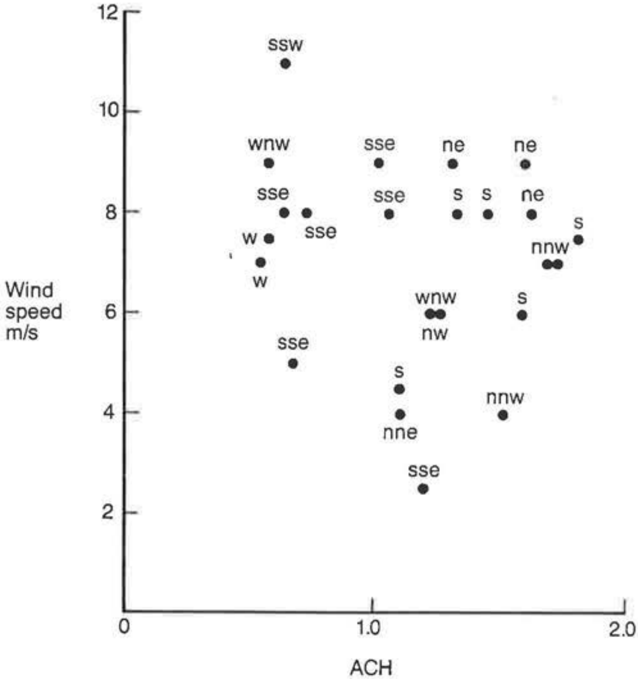

Fig. 5. Variation of ach, in the Buxton workshop, with wind speed and direction.

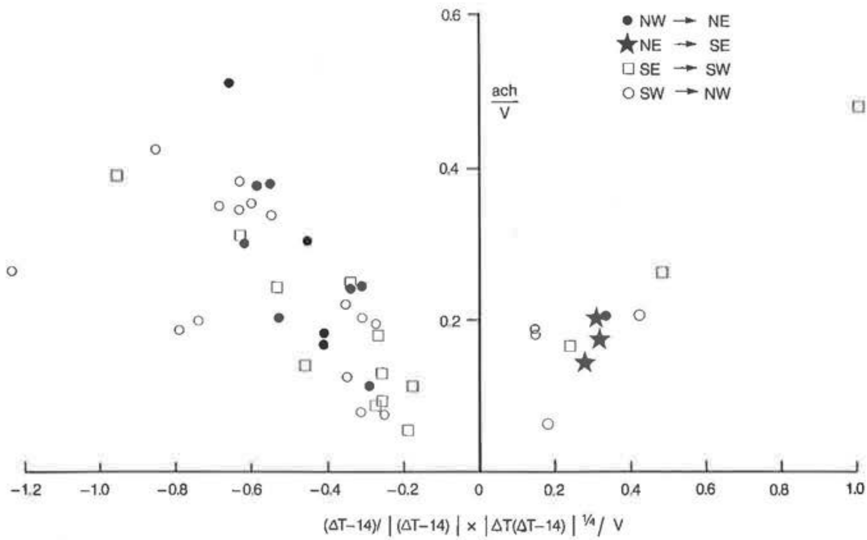

Fig. 6. Air change rates in the Buxton workshop.

$$\text{ach} = C_1 V + C_2 (\Delta T)^{1/2},$$

where ach is the air infiltration rate (air changes/h), V the wind speed (m/s), ΔT the internal and external temperature difference (°C) and C_1, C_2 are coefficients, gave the best correlation. This form of relationship was used by Jones and Powell [4] to evaluate data obtained on a factory where the wind direction was almost without exception from the South or South-West. Good correlation was found between infiltration rates and wind speeds. The correlation is not particularly good for the results of Phase II plotted in this way, and the effect of wind direction is not apparent (see Fig. 5). A better correlation is found when the results are replotted (see Fig. 6) as:

$$\frac{\text{ach}}{V} \quad \text{against} \quad \frac{[\,|\Delta T(\Delta T - 14)|\,]^{1/4}}{V} \frac{\Delta T - 14}{|\Delta T - 14|}.$$

7. Discussion

There is a tendency for small modern factory units to be built without an integral mechanical ventilation system, reliance being placed upon natural ventilation for a fresh air supply. Natural ventilation results from static pressure differences across the fabric of the building created by a combination of wind speed and temperature difference between the interior and exterior of the building (usually known as the "stack" effect). Natural ventilation is thus subject to the vagaries of the weather. It is therefore difficult to control or even predict natural ventilation rates which have been observed to vary by a factor of five with changing conditions [5]. In the factories tested in Phase I, the internal/external temperature differences were small and the stack effect would also have been small; the ventilation could therefore be mainly attributed to the pressure differences caused by the wind. The air change rate was approximately proportional to the wind speed. This would not necessarily be the case in a mechanically ventilated building where the effects of mechanical and natural ventilation may not be cumulative.

HSE Guidance Note EH 22 [1] suggests as the minimum ventilation volume flow rate for factories the greater of either 5 l/s per person or 0.8 l/s m^2 of floor area. Table 2 gives rates which would be required in the five factory units based on floor area. (Note that, on the basis of floor area, the required air change rate is inversely proportional to the height of the building).

Comparison of these values with the measured values given in Table 1 shows that, for factory units 2, 3 and 4, the measured air change rates easily exceed the minimum recommended values. These three units were each fitted with a roller shutter door. In comparison with other doors, they formed a major air leakage path in the factories to the extent that they may be the source of a significant proportion of the heat losses. Although the wind speeds were high

Table 2

Minimum required ach based on 0.8 l/s m^2

Factory No.	Minimum ach
1	0.67
2	0.52
3	0.64
4	0.67
5	0.80

during the measurements on units 2 and 4, Fig. 3 suggests that the ventilation would have been adequate for wind speeds down to about 2 m/s. In the case of factory 1, a wind speed in excess of 3.7 m/s should induce the minimum required air change rate whilst for factory 5 a speed of 5 m/s may be required. One consequence of "building down to a price" is that the factory units are not particularly well sealed and infiltration through the fabric of the building may provide sufficient fresh air to meet current minimum standards. However, although it may achieve relatively high ventilation rates, infiltration should not be regarded as a suitable method of ventilating factories because of its inherent unpredictability and dependence on weather conditions.

BS5925:1980 [6] deals with the natural ventilation of buildings for human occupation. The basis for the choice between natural and mechanical ventilation is given, the design of mechanical ventilation being dealt with in BS5720:1979 [7]. The mechanisms governing natural ventilation, i.e. pressure differences generated by wind and temperature differences, are outlined and discussed. It is supposed that a reasonable approximation to the ventilation rate can be made by calculating the rates which would be expected for the wind (flow rate proportional to the wind speed) and the temperature difference (flow rate proportional to the square root of the temperature difference) separately and by taking the larger to apply in the combined case. This is clearly not a very satisfactory approach. One should differentiate between infiltration through gaps in the building fabric and planned natural ventilation through windows, roof vents, etc., when considering the calculation of air flow rates into buildings. As far as planned ventilation is concerned, the areas, positions and flow characteristics of the openings may be known. These factors are necessary to carry out flow rate calculations. For openings (including cracks in the fabric of the building, gaps in window frames etc.) where this information is not available, the equivalent areas would have to be determined experimentally.

The measurements by Jones and Powell [4] were made on a lightweight industrial unit constructed about 1986. Wind speeds during the experimental period, averaged over intervals of 30 min, were in the range 0 to 7 m/s, the

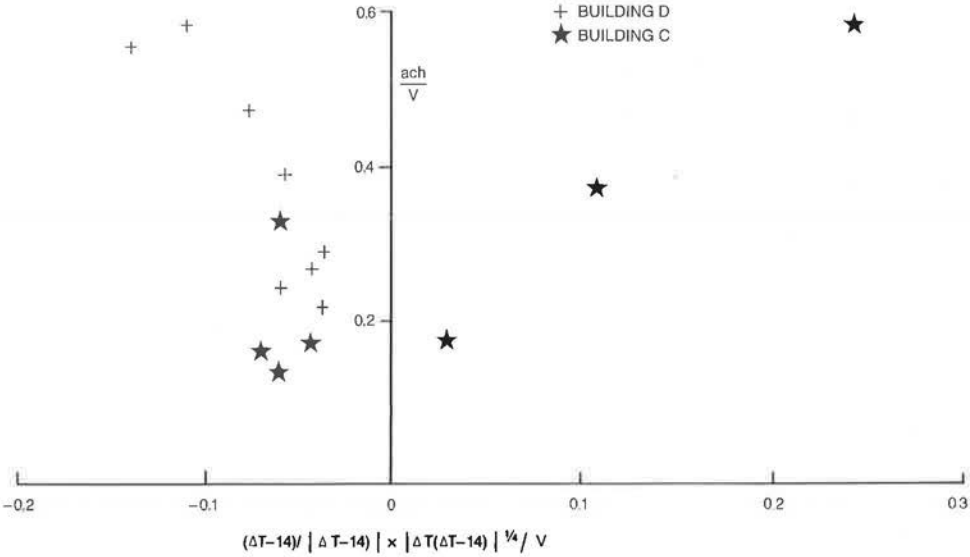

Fig. 7. BRE results.

direction of the wind being predominantly South or South-West. External temperatures were recorded in the range 11 to 21 °C. On average the air infiltration was measured to be 0.4 ach. The production space floor area and volume were 466 m^2 and 3050 m^3 respectively and, on the basis of 0.8 l/s m^2, the air change rate was about 10% lower than the minimum requirement. Measurements made in Phase II showed a dependence of air change rates on both wind speed and the difference between internal and external temperatures. The minimum air change rate measured during this phase corresponds to a minimum volume flow rate of over 1.1 l/s m^2 of floor space i.e. well above minimum requirements. A minimum air change rate for a given wind speed was found for a temperature difference of about 14 °C. The occurrence of an air change rate minimum (see Fig. 6) can be explained by the opposing contributions caused by wind speed and temperature difference, as illustrated in BS5925 although the combined effect cannot be expected to be as suggested there. Measurements of Potter, Jones and Duxbury [8] on a factory unit (building C) and a building, (D), housing a wind tunnel at the Building Research Station are shown plotted in the same way in Fig. 7. In each case the mean measured air change rate for all the tests (1.5 and 3.2 l/s m^2 respectively) was high, and for building C, was considered to be typical of modern industrial estate factory units.

Appendix A

When measuring air change rates it is usual to specify the initial condition that the tracer gas is uniformly mixed throughout the space. The time history of the concentration is then recorded with the ventilation system operating normally. The decay rate, and hence the local age, will vary from point to point throughout the space. If the decay at a point P_1 is greater than that at P_2 the local age of the air at P_1 will be less than that at P_2. After any time t_1, the concentration at P_2 will be greater than that at P_1, that is the concentration will no longer be uniform throughout the space. However the calculated value of the local age does not depend on the initial value of the concentration, and therefore the "zero" for the time could be moved to t_1 and yet leave the local ages unchanged. It therefore follows that the condition of uniform mixing of the tracer gas is not necessary. It is usually found, even in a room with a uniformly mixed tracer, that the concentration decay takes some time before it settles down into a log–linear state. The initial non-linear portion of the plot can be taken as the time required for concentration equilibrium, rather than uniformity, to be reached.

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