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An Experimental Determination of Ventilation Rate in Occupied Rooms Using Atmospheric Carbon Dioxide Concentration

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Ventilation rate determination by measuring the amount that the atmospheric carbon dioxide concentration in an occupied space is raised above the outside ambient level has been tested in a mechanically ventilated part of Exeter University Library. The rate obtained is compared with that expected from the fan rating. It is shown that besides the ventilation rate, the occupants' average carbon dioxide production rate could in principle have been estimated from the data.

INTRODUCTION

VENTILATION loss probably accounts for approximately 20% of the heating load in existing housing stock [1]. In a well insulated building the proportion can easily exceed 80%. Proper control of ventilation is obviously an important factor in energy conservation in buildings. However, it remains the most difficult quantity to measure in a heat balance determination. An alternative to tracer gas techniques would be to monitor ventilation by measuring the amount by which the occupants of a room or building raise the concentration of CO_2 in the internal air above the level in the air outside. In principle, this would allow continuous or quasi-continuous monitoring of ventilation during occupation. The main difficulties in this approach are accurate estimation of the mean rate of production of CO_2; there is some variation between individuals and individual production rates vary greatly with activity, and unless the air flowing into the room is unequivocally fresh, estimation of its initial CO_2 concentration. This problem arises because division of a building into rooms means that the internal air as a whole is unlikely to be well mixed. There seems to be few published accounts of the use of metabolic CO_2 to estimate ventilation, although Hunt [2] took subsidiary CO_2 spot measurements in his study of ventilation using SF_6 as a tracer in a large office building.

DISCUSSION AND RESULTS

The carbon dioxide method has been tested in part of Exeter University Library. Two large rooms (stack rooms) are ventilated by a ducted fan-driven system. The supply and extract fan ratings are such that the stacks are kept at positive pressure with respect to the rest of the building, so there should be little infiltration of internal air into the stacks. During the test period, one day, there was no mixing of extract and fresh air, thus, the second difficulty was removed, i.e. all incoming air was fresh and therefore of known CO_2 concentration. This was measured at Exeter to be 340 ppm. The stack rooms are of equal volume and the system is balanced with similar quantities of air being extracted per unit time from each room. Since the few windows in the stacks are sealed the ventilation rate is determined by the supply fan rating which was known and used to make an independent assessment of the ventilation rate.

The rate of change with time of carbon dioxide concentration r' in room air is given by

$$\frac{dr'}{dt} = \frac{Q(t)}{V} + \frac{P}{V}(r - r') \tag{1}$$

where $Q(t)$ is the total CO_2 production rate, V the room volume, P the ventilation rate and r the proportion of CO_2 in the supply air. Continuous measurements of r' were made using an IR gas analyser to test the air in the extract duct. $Q(t)$ was assessed by counting the number of people in the stacks at frequent intervals throughout the day (see Table 1) and

Table 1. Numbers of people in stacks

Average time of count (decimal hours)	Number	Average time of count (decimal hours)	Number
8.83	5	14.91	103
9.23	30	15.32	100
9.46	45	15.83	92
9.83	36	16.18	94
10.17	53	16.48	80
10.46	73	16.87	59
10.79	72		
11.13	76		
11.66	95		
11.89	87		
12.20	78		
12.53	69		
12.90	42		
13.21	44		
13.97	71		
14.22	94		
14.52	104		

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multiplying the number by a mean individual CO_2 production rate estimated from data on the energy cost of various activities given by Astrand and Rodahl [3] to be $350 \pm 50\,cm^3\,person^{-1}\,min^{-1}$. The volume of the stacks was calculated from plans of the library to be $4770\,m^3$. The estimated volume occupied by books was subtracted from this to give a net volume of $3800\,m^3$. The position and size of the bookcases was taken from the plans and they were assumed 80% full.

Assuming P to be constant, the solution of (1) is

$$r'(t) = \exp\left(\frac{-Pt}{V}\right) \int_{to}^{t} \frac{Q(t')}{V} \exp\left(\frac{Pt'}{V}\right) dt' + r + (a-r)\exp\left(\frac{P}{V}(to-t)\right) \qquad (2)$$

where $r'(to) = a$.

Thus, the run of $r'(t)$ may be calculated from $Q(t)$. A computer programme written to do this was used iteratively to find for any assumed mean individual CO_2 production rate the value of P to within 0.1 air change (ac) per hour giving the best (i.e. least squares) fit between calculated values of r' and those observed at nineteen equally spaced times during the test period. With $350\,cm^3\,person^{-1}\,min^{-1}$ as the production rate, the value of P obtained gave 4.0 air changes per hour with an error of ± 0.6 ac/h corresponding to the uncertainty in production rate. The observed and calculated variations of r' are shown in Fig. 1. Other CO_2 production rates were tested, finding for each one the value of P giving the best fit between observed and calculated $r'(t)$. In Fig. 2 the summed least squares difference corresponding to these best fit cases is plotted against the assumed mean CO_2 production rate per person. The curve has a minimum at about $280\,cm^3\,person^{-1}\,min^{-1}$ which, since the best fit of all would correspond in principle to the true mean individual CO_2 production rate suggests that $350\,cm^2$ $person^{-1}$ min^{-1} might be a high estimate. However, the observed variation of $r'(t)$ shown in Fig. 1 displays some structure not adequately represented in the calculated variation based on occupation data. These discrepancies, probably signifying fluctuations in the number of occupants not recorded by the periodic counting, must influence the position of the minimum as Fig. 2 and therefore it seems reasonable to prefer the independent physiological estimate of production rate. Nevertheless, the existence of the minimum on Fig. 2 implies that a two dimensional iterative least squares fit in the variables ventilation rate and mean individual production rate should allow *both* to be estimated from data of this type, although a very detailed occupation record may be needed for an accurate production rate estimate.

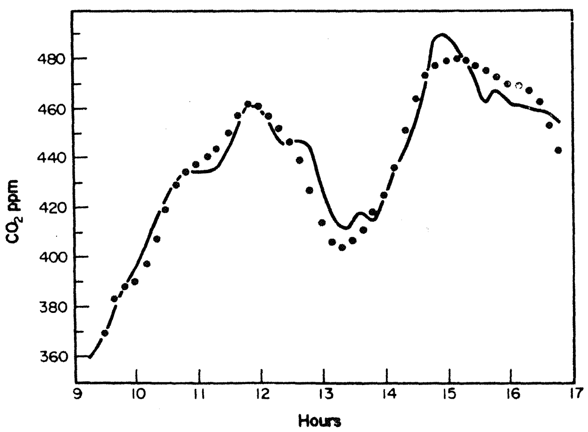

Fig. 1. Observed variation with time of the carbon dioxide concentration in the stack air (solid line) compared with the variation calculated on the basis of an average CO_2 production rate of $350\,cm^{-3}\,person^{-1}\,min^{-1}$ and a ventilation rate of 4.0 ac/h (dots).

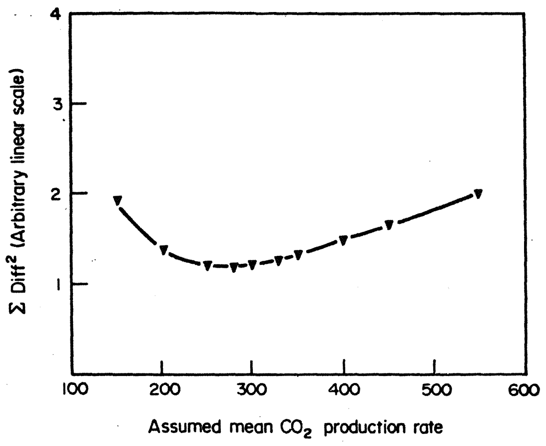

Fig. 2. Summed least squares difference between observed and calculated $r'(t)$ corresponding to the best fit ventilation rate as a function of assumed average individual CO_2 production rate in $cm^{-3}\,person^{-1}\,min^{-1}$.

The ventilation rate calculated from the fan rating was 4.2 a/h, agreeing very well with the CO_2 method estimation and showing clearly that the CO_2 method can provide a fair determination of ventilation rate so long as the system being investigated is properly understood. Clearly, the method is applicable to cases where the incoming air is known to be fresh. If this does not hold, but the air coming into a room is from one predominant internal source, e.g. a corridor, the method can still be used provided the CO_2 concentrations in both the room and the incoming air are recorded. This could be accomplished by switching the gas analyser between two probes; a second instrument need not be involved. If r is found to be a function of time the solution of (1) becomes

$$r'(t) = \exp\left(\frac{-Pt}{V}\right) \int_{to}^{t} \frac{1}{V}(Q(t') + Pr(t'))\exp\left(\frac{Pt'}{V}\right) dt' + a\exp\left(\frac{P}{V}(to-t)\right). \qquad (3)$$

The difficulty in extending this idea to several internal sources is that of determining their relative importance.

Direct sampling at one point of air in a naturally ventilated room will give reliable results only if the CO_2 is well mixed with the rest of the air in the room. Although practical investigation is needed, it is thought that in a room of normal proportions, the air would not support large gradients of CO_2 concentration horizontally and that it is unlikely that significant variation in concentration would result from gravitational or thermal effects. In situations where relatively large numbers of people are contributing to the CO_2 level (e.g. classrooms, open plan offices, libraries) their spatial distribution will facilitate mixing. However, large populations are not necessary to define the mean CO_2 production rate sufficiently accurately. For a specific activity, it will usually be possible to predict an individual's CO_2 production to within 10% (Denison, private communication). The error assumed for the library experiment, approx. 14% in production rate, is so large because of uncertainties in the relative numbers of men and women present and because different activities (sitting, standing, walking) were occurring simultaneously. More detailed observations would have reduced the uncertainty and therefore decreased the error band on the ventilation rate estimation.

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