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Field Evaluation of CO_2 Detector Tubes for Measuring Outdoor Air Supply Rate in the Indoor Environment

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Abstract

Indoor carbon dioxide (CO_2) concentration can be used to estimate the degree of air recirculation and outdoor air supply rate. Three types of CO_2 detector tubes were evaluated by using Fourier Transform Infra-Red (FTIR) Spectroscopy as a reference method. Two types of detector tubes (Draeger CH 30801 and Kitagawa 126 B) showed a good correlation with the reference method ($r = 0.98$), the 95% confidence interval of the slope being 0.89-1.06 and 0.80-0.95, respectively in linear regression analysis. The third type (Gastec 2LL) showed lower correlation ($r = 0.91$) and a wider 95% confidence interval (0.52-0.80) of the slope. At CO_2 concentrations in the range 800-1000 5 l/l (ppm), control values suggested for the indoor environment, the Draeger and the Gastec tubes underestimated the CO_2 concentration, while the Kitagawa tube showed a correct value. The difference in reading between observers was similar for all three brands of detector tubes (5-7%), expressed as relative standard error. No significant influence of the air humidity or temperature on the readings could be demonstrated. It is concluded that some brands of CO_2 detector tubes can be used to measure indoor carbon dioxide concentration with sufficient precision and accuracy. Since the relative error is relatively large at lower CO_2 concentrations, the use of such tubes for the determination of air recirculation in ventilation systems should be avoided. As a crude estimate of the outdoor air supply rate, however, CO_2 detector tubes may be used. In order to minimize the error in reading, the type of detector tube and the need for recalibration should be considered. When using CO_2 measurements as an estimate of outdoor air supply rate, the influence of age and workload on the individual's emission of CO_2, and the time needed to reach equilibrium, should also be taken into consideration.

KEY WORDS:
Carbon dioxide, Detector tube, Fourier Transform Infrared spectrophotometry, Indoor air quality, Outdoor air supply, Physical workload, Sick building syndrome, Ventilation rate.

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Introduction

The rate of outdoor air supply is used as the criterion of most ventilation standards (ASHRAE, 1989; Sundell, 1982; Yaglou et al., 1936). Since humans emit carbon dioxide (CO_2), there is a relation between CO_2 concentrations in indoor air and outdoor air supply. As early as 1858 it was shown that CO_2 could be used as an indicator of human emissions (body odour), and at levels above 1000 5 l/l (ppm), non-adapted visitors found the air quality unacceptable (Pettenkofer, 1858). Today, similar ventilation standards are used, and 800 5 l/l has been suggested as a control limit for carbon dioxide (Berglund et al., 1984). Direct reading detector tubes have been suggested by an expert group of the World Health Organization, as a part of the first step in the practical investigation of sick buildings (Akimenko et al., 1986). Such detector tubes have also been used in published investigations on indoor air quality (Hung and Derossis, 1989) and on the sick building syndrome (Norbäck et al., 1990). Besides a limited evaluation of three types of CO_2 detector tube at low concentration (Ancker et al., 1989), no field evaluations of CO_2 detector tubes are available in the literature.

This study was performed in order to evaluate various types of detector tube for the measurement of CO_2 concentration in the indoor environment, and to evaluate their usefulness for the determination of the rate at which outdoor air is supplied.

Material and Methods

Three subjects (sedentary adults) stayed in a small room (16 m^3 volume) at normal air pressure (760

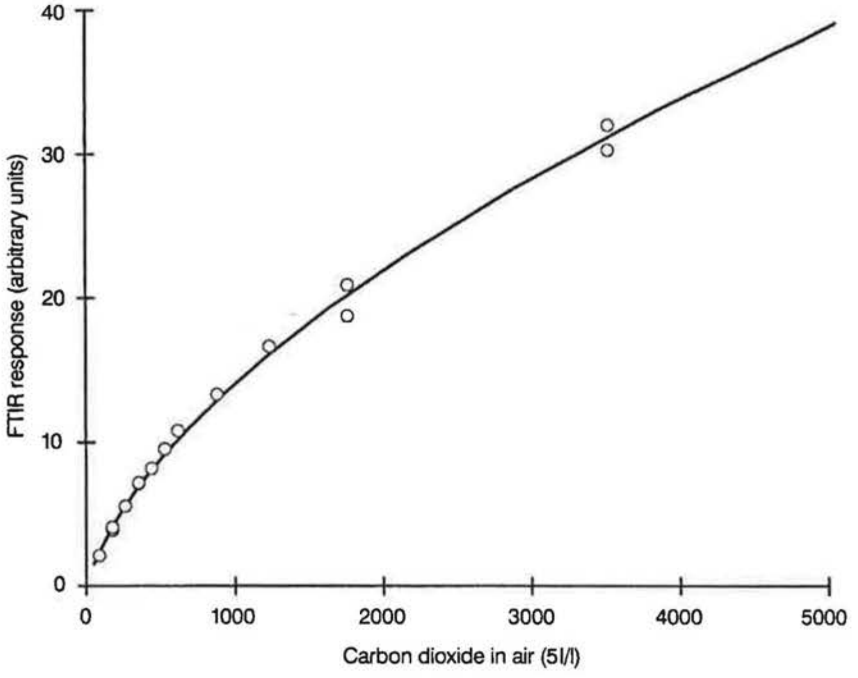

Fig 1 CO_2 calibration curve for the FTIR instrument, used as reference method. The curve was calibrated in the range 90 – 20 000 5l/l.

mm Hg). Carbon dioxide levels in the range 400-2200 5 l/l were generated by varying the outdoor air supply rate. The CO_2 concentration was measured continuously by a Fourier-transform infrared spectrophotometer (FTIR) (Michelson 110-D11, Bomem) equipped with MCT-detector, a 20 metre gas-cell (MIRAN, Foxboro) and a personal computer. Carbon dioxide was measured at the wave numbers 719 and 740 cm^{-1}, after subtracting the baseline signal measured at 850-900 cm^{-1}. These wave numbers were selected in order to ensure that water vapour or other gases did not affect the measurements. The FTIR-instrument was calibrated by adding various mixtures of carbon dioxide and nitrogen in the gas cell. The FTIR instrument could be used to measure the CO_2 concentration over a wide concentration range (90-20 000 5 l/l), and a four degree polynomial was used to yield the best fit of the calibration curve (Figure 1). The method error of the reference method, expressed as coefficient of variation, was 1.6% (N = 30) at 200 5 l/l and 0.4% (N = 30) at 10 000 5 l/l CO_2.

Three different types of CO_2 detector tube from three different manufacturers were evaluated: Draeger CH 30801 (0.01%/a), Kitagawa No. 126B (0.01-0.7% CO_2), and Gastec No. 2LL (300-5000 ppm CO_2). Three different batches of each type of detector tube, purchased at different times over a one-year period, were tested. Parallel measurements (8 tubes/batch) were made with all three types of detector tube, and the results were compared with the average CO_2 concentration measured by FTIR during the actual time period. In order to eliminate a possible reader's bias, three persons, independently of each other, read off the tubes at each measurement. The number of pump strokes followed the recommendations of the manufacturers. Ten pump strokes were drawn through the Draeger detector tube and one pump stroke was drawn through the Gastec detector tube. For the Kitagawa tube, three pump strokes were drawn at CO_2 concentrations below 1000 5 l/l, and one pump stroke was drawn at higher concentrations. The actual volume per pump stroke was measured for each detector tube pump, and the readings were adjusted proportionally if the pump stroke differed from the nominal volume. In addition, room temperature and air humidity were measured by means of an Assman psychrometer during each test.

The standard error (SE) of variation between the three observers was calculated from the formula:

$$SE = (((\Sigma a^2-(\Sigma a)^2/n)+ (\Sigma b^2-(\Sigma b)^2/n)+(\Sigma c^2- (\Sigma c)^2/n))/6(n-1))^{0.5} \quad (1)$$

where a = difference in reading between observer 1 and observer 2

b = difference in reading between observer 2 and observer 3

c = difference in reading between observer 1 and observer 3

n = number of triplicate readings

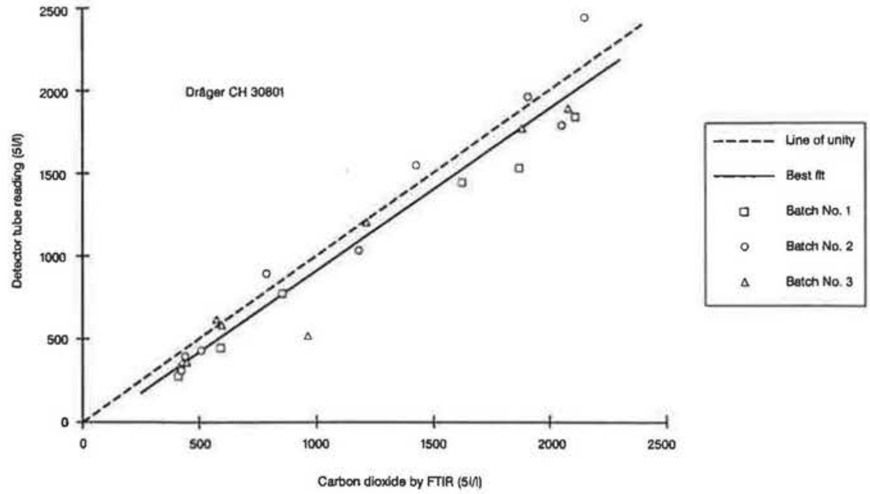

Fig 2 The readings of the Dräger detector tube (CH 30801) as a function of the CO_2 concentration measured by FTIR-spectrophotometry.

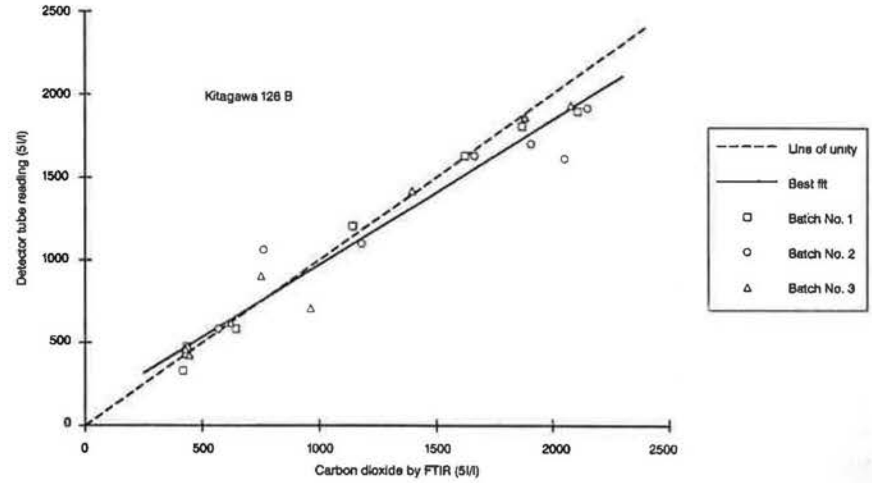

Fig 3 The readings of the Kitagawa detector tube (126 B) as a function of the CO_2 concentration measured by FTIR-spectrophotometry.

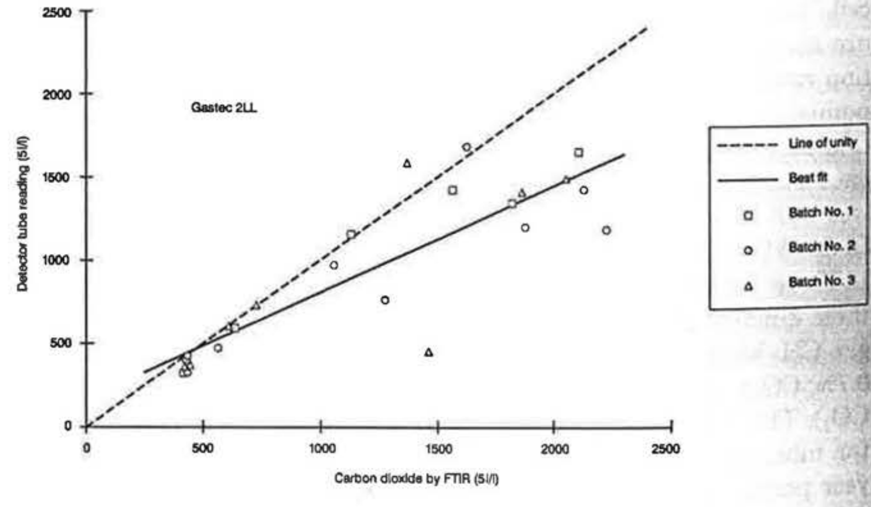

Fig 4 The readings of the Gastec detector tube (2LL) as a function of the CO_2 concentration measured by FTIR-spectrophotometry.

Table 1 The reading of CO_2 detector tubes as a function of CO_2 concentration measured by Fourier Transform Infrared Spectrophotometry in the range 400-2200 5l/l.

Type of detector tube	N	Slope of regression	95% CI of slope	Intercept (5l/l)	R
Dräger CH30801	24	0.97	0.89-1.06	-47	0.98
Kitagawa 126 B	24	0.87	0.80-0.95	+109	0.98
Gastec 2LL	24	0.66	0.52-0.80	+170	0.91

N = Number of measurements
R = Correlation coefficient
CI = 95% confidence interval for the slope of regression

Table 2. Variability between readers and batches in the readings of three types of CO_2 detector tubes

Type of detector tube	N	Variability between readers (RSE%)	Source of variance reader	batch
Dräger CH 30801	72	6.8	NS	$p<0.001$
Kitagawa 126 B	72	5.2	NS	NS
Gastec 2LL	72	4.6	NS	$p<0.05$

N = Number of observations
RSE% = Relative standard error
NS = Nonsignificant p-value (>0.05) calculated by two-factor analysis of variance. The residuals of the detector readings were used as dependent variable.

The average readings of the three observers were compared with the reference method by means of linear regression analysis. The possible effects of room temperature and air humidity were estimated by multiple linear regression analysis. Variations between batches and between observers were evaluated by two-factor variance analysis (ANOVA). In the variance analysis, the difference between the individual reading and the expected result, calculated from the regression analysis, was used as dependent variable.

Assuming rapid mixing and uniform distribution of CO_2 in the available space of the room, and equilibrium, the outdoor air supply rate (A, l/s) was calculated from the indoor CO_2 concentration by the formula:

$$A = P/(C_{eq}-C_o)*10^6/3600 \quad (2)$$

where P denotes the emission rate of CO_2 in l/h from persons present in the room. C_{eq} and C_o denote the air CO_2 levels in 5l/l in room air at equilibrium and outdoor air, respectively. When the CO_2 production rate is given per person, the air supply rate is also obtained per person.

To construct the curves in Figure 5, the following CO_2 production rates were used; 12 l/h for active preschool children (Friis-Hansen et al., 1985), 18 l/h for sedentary office work, 36 l/h for walking, light industrial work or domestic work, and 90 l/h for athletics or other types of heavy physical exercise. These rates were computed from energy expenditure data given in the Geigy Scientific Tables (Lentner, 1981). In Figure 5, the concentration of CO_2 in outdoor air was assumed to be 340 5l/l (Keeling et al.,1984).

One critical point in assessing the air supply rate from CO_2 measurements is whether the equilibrium condition applies or not. Given the previous assumptions, the change in the indoor air CO_2 concentration (C) when people enter a room may be described as a function of time as:

$$C = C_o + (C_{eq}-C_o) * (1-e^{-(3.6*A/V)*t}) \quad (3)$$

where V denotes the volume of the room in m^3, and t denotes time after entrance to the room in hours. From Equation 2 it follows that the time needed to reach a certain percentage of the new equilibrium level of CO_2 after people have entered the room is a linear function of the air supply rate and the volume. Thus, the time needed to reach 90% of the new equilibrium (i.e. to meet the condition $C-C_o = 0.9*(C_{eq}-C_o)$) is:

$$t90\%(h) = \ln(10)*V/(3.6*A) = 0.64*V/A \quad (4)$$

For example, in a classroom intended for 30 per-

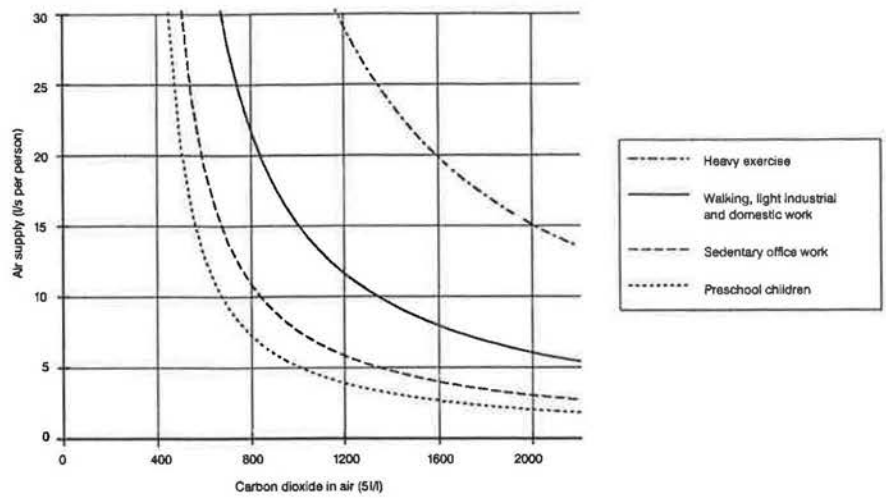

Fig 5 The relationships between outdoor air supply rate and indoor CO_2 concentration, at equilibrium, for different CO_2 emission conditions.

sons, with the dimensions 10, 15, and 3 metres ($V = 450$ m³) and an air supply rate of 8 l/s/person($A = 240$ l/s), the time needed will be:

$$t90\% = 0.64*450/240 = 1.2 \text{ h}$$

Result

The actual volumes of the pump strokes used in our calculations differed slightly from the nominal values for the Draeger, the Kitagawa as well as the Gastec pumps (-3%, -6% and +3% difference respectively). The correlation with the reference method was high ($r = 0.98$), both for the Draeger and for the Kitagawa detector tubes. The Gastec tube, however, had a substantially lower correlation coefficient ($r = 0.91$) (Table 1 and Figures 2-4). The Draeger tube appeared to have the smallest bias, as the intercept of the regression line was close to zero and the slope was not significantly different from unity. The other two brands had larger intercepts and the slopes of their regression lines were significantly less than unity ($P < 0.05$). As can be calculated from the equations in Table 1, the Draeger tube underestimated the CO_2 concentration by about 60-100 5l/l in the actual range (400-2200 5l/l). The Kitagawa tube, however, overestimated the concentrations below 850 5l/l, and underestimated them at higher CO_2 concentrations. The relative standard error between readers was similar for all three types of tube (5-7%), and there was no significant difference in readings between different observers. For two of the detector tubes, however, significant batch-to-batch variations were demonstrated (Table 2); they were most pronounced for the Draeger tubes, where a difference in sensitivity in the order of 50-100 5l/l CO_2 was observed for different batches. No significant influence of variations of air humidity (30-45% RH) or room temperature (20.0-24.5 °C) could be demonstrated for any detector tube.

A conversion diagram, which enables the calculation of outdoor air supply rate from CO_2 measurements at different ages and workload was constructed (Figure 5). Calculations made by Equation 4 indicate that at outdoor air supply rates below current ventilation standards (< 7 l/s/person) and at large room volumes (> 20 m³ per person), the time needed to reach a new equilibrium concentration may be several hours.

Discussion

During the last decade, there has been growing concern regarding the use of indoor air carbon dioxide as an indicator of indoor air quality (Akimenko et al., 1986; Hung and Derossis, 1989), outdoor air supply rate (Berglund et al., 1984) and degree of return air (Göthe et al., 1988). Detector tubes are an inexpensive and convenient means of measuring the concentration of airborne compounds, and are frequently used by safety engineers. The lack of published field evaluations, however, leads to a lack of confidence among users concerning the accuracy of their measurements.

We could demonstrate that both Draeger and Kitagawa CO_2 detector tubes showed a good agreement with the more sophisticated FTIR reference method. Furthermore, no influence of air humidity or temperature could be demonstrated. In order to achieve high accuracy, however, the actual pump stroke volume should be checked regularly. According to the manufacturers, the Gastec and the Draeger detector tubes are based on the same detection principle, namely a specific reaction between CO_2 and hydrazine, which discolours a redox indicator (crystal violet). The Kitagawa detector tube is based on the more unspecific reaction between CO_2 and sodium hydroxide, which leads to a colour change of a pH sensitive indicator absorbed on alumina. No interference except from ammonia at concentrations above 1000 5 l/l, and from hydrogen cyanide at concentrations above 120 5 l/l are reported by the manufacturers. Such concentrations are unlikely to occur in a non-industrial indoor environment.

It has been demonstrated earlier that the use of CO_2 detector tubes for measuring air recirculation could lead to large errors at CO_2 concentrations in the range 400-600 5 l/l (Ancker et al., 1989). This finding is in agreement with our results, since the relative errors of the detector tubes are relatively large at lower concentrations. Ancker et. al. found that both the Draeger and the Kitagawa tubes showed 50-100 5 l/l lower CO_2 values than the reference method (Infrared spectroscopy). Their finding agrees with our present results concerning the Draeger but not the Kitagawa tube. On the contrary, we found that the Kitagawa detector tube overestimated the concentration at low concentrations.

However, if detector tubes are used to estimate the outdoor air supply or to investigate whether the control values of CO_2 are exceeded, they may have sufficient accuracy and precision. A personal CO_2 emission of 18 l/h has been assumed in the literature (Berglund et al., 1984). This value corresponds well with the measured CO_2 emission rate from sedentary adults (Wang, 1985). Many suspected sick buildings, however, are primary schools or day care centres (Widström and Norbäck, 1988) where a lower CO_2 emission rate (e.g. 12 l/h) should be assumed, since otherwise the outdoor air supply rate would be overestimated. On the other hand, if CO_2 measurements are performed in indoor environments where physical activity takes place, higher CO_2 emission rates should by assumed, otherwise the outdoor air supply rate would be underestimated. Another potential source of bias is the absence of equilibrium due to fluctuations in the number of people in the buildings. In order to check that conditions are close to equilibrium, repeated measurements of CO_2, or observations of the subjects' migration in the building should be made. Empirical results from Persily and Dols indicate that measuring CO_2 decay rates after the occupants leave the building can provide reliable estimates of building air exchange rates. The use of instantaneous CO_2 concentrations to determine air exchange rates may, however, lead to significant errors since equilibrium conditions rarely exist in office buildings and many other building types (Persily and Dols, 1990).

In conclusion, CO_2 measurements by detector tubes may be used as an indirect means of estimating the personal outdoor air supply rate. In such applications, the age of the subjects as well as the physical workload should be taken into consideration. In addition, one should ensure that the measurements are performed in conditions close to equilibrium. If the actual CO_2 emission rate is difficult to estimate, or if equilibrium conditions do not prevail, there may be sources of error greater than the measurement error of the detector tubes, particularly if the ventilation is low or if the level of physical activity is high. On the other hand, if the CO_2 concentration itself (e.g. 800 5 l/l) is accepted as a control value, these problems do not arise, and detector tube readings should be precise enough to determine whether the value is exceeded. In order to achieve the best precision, an appropriate type of detector tube should be selected and the actual pump stroke volume should be checked regularly. To achieve the best accuracy, the tubes may be recalibrated by applying a similar method as the one described in this paper.

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