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Alfred Micallef[a], Chris N. Deuchar[a] & Jeremy J. Colls[a]

[a] University of Nottingham, United Kingdom

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A System for Measuring Vertical Concentration Profiles of Gaseous Pollutants, Using Carbon Dioxide as a Case Study

Alfred Micallef
Chris N. Deuchar
Jeremy J. Colls

University of Nottingham, United Kingdom

An electronically-controlled sampling system, characterised by its organ pipe design, has been developed for sampling air sequentially, at different heights within the breathing zone. Data are automatically logged at the different receptor levels, for the determination of the average vertical concentration profile of gaseous pollutants. The system has been coupled to a carbon dioxide monitor and used in a brief study of the spatial and temporal variation of indoor carbon dioxide concentration. The system can easily be extended for different heights or modified for use with other types of gas monitor. The results of a trial run, which was carried out in a coffee room, are presented and applications of the Organ Pipe Sequential Sampling (OPSS) system are discussed.

concentration gradients spatial distribution multi-level sampling
human exposure indoor-outdoor air pollution

1. INTRODUCTION

Understanding how airborne pollutants are distributed in the vertical column over the first few metres from ground, in different human

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Correspondence and requests for reprints should be sent to Alfred Micallef, Physics Department, University of Malta, Msida MSD 06, Malta. Email: <alfred@phys.um.edu.mt>.

environments, is of major importance in improving the way that human exposure estimates are made. Current exposure models are based on relatively general assumptions about the distribution of contaminant concentrations in different environments (Committee on Advances..., 1991, p. 197). Hitherto, it has been assumed that the pollutant concentration is spatially uniform over some three-dimensional space, termed microenvironment, such as the volume of a workshop. An individual's exposure is then calculated as the product of the pollutant concentration and time spent in that microenvironment. The integrated human exposure would be the sum of all such products (Ott, 1981). This assumption of spatial uniformity can be erroneous for certain microenvironments, as shown by measurements of vertical concentration profiles of airborne particulate matter carried out in a small electronics workshop (c. 20 m^2) using the Kinetic Sequential Sampling (KSS) system (Micallef, Deuchar, & Colls, 1998). Furthermore, monitoring stations generally observe air quality levels that are different from those with which people come into contact in their daily lives (Monn, Carabias, Junker, Waeber, Karrer, & Wanner, 1997; Ott, 1980). This makes exposure estimates less accurate. Hence accurate knowledge of the spatial distribution of pollutants within the breathing zone and its temporal variation is very important when the concentration data is to be used in human exposure estimates. The paper describes in detail an automated sampling system for measuring vertical concentration profiles of gaseous pollutants. The system can also be used to measure concentration profiles at orientations other than vertical and hence it is possible to measure the spatial distribution of gaseous pollutants and its temporal variation after suitable modifications. The results of a trial run with the system, which was carried out in a coffee room, are presented and applications of the Organ Pipe Sequential Sampling (OPSS) system are discussed.

2. METHODOLOGY

There are three competing methodologies for obtaining vertical concentration profiles of an air pollutant: a vertical array of sensors, a single sensor that is moved sequentially to different vertical positions, and a vertical array of sample inlets that are switched sequentially to a single fixed sensor. The first method allows continuous measurements throughout the vertical profile, but presents problems of inter-calibration and,

in the case of high resolution monitors, cost. The second method has been used successfully for sampling environmental aerosol using a portable optical monitor (Micallef et al., 1998). This method cannot be used with high resolution (bench) gas monitors because they are cumbersome, require mains electrical supply in most cases, and manufacturers normally advise not to move the instrument during operation. The third method has been used to provide information on the percentages of outside air and recirculated air (Olcerst, 1994a) and to measure the effective ventilation and air exchange rates (Olcerst, 1994b, 1994c) in a ventilated compartment. The OPSS system employs the third method for measuring vertical concentration profiles of gaseous pollutants within the breathing zone.

2.1. Design and Operation of the OPSS System

2.1.1. Overview

The system is designed to enable sampling of a target gas at a maximum of six discrete heights between ground level and a few metres above ground. Pipes of a material non-reactive to the target gas, or inert material such as polytetrafluoroethylene (PTFE) or stainless steel, with their openings facing slightly downward to prevent rain entering (when used outdoors), proceed from each level to a central plinth where separate solenoid valves are fixed to control the airflow of each pipe into one or the other of two manifolds. One manifold is connected to the gas analyser, and the second is connected to an exhaust pump. The output of the latter is directed by a pipe which has its outlet at a sufficient distance (and downwind if used outdoors) to avoid influencing the measurement inputs. If the analyser employed does not contain its own sampling pump, then a second external pump will be required. The interconnections of the pumps, pipes, and solenoid valves are shown schematically in Figure 1.

The solenoid valves employed are the pulsed and latching, three-way type. They use power only momentarily to change state and are therefore suited to portable equipment for which battery life may be limited. The use of three-way valves enables the pipes to be continually aspirated; they are either connected to one manifold and routed to the analyser, or to the other for ventilation. Hence the analyser, and pipework, is constantly receiving "fresh" air and any reactions that

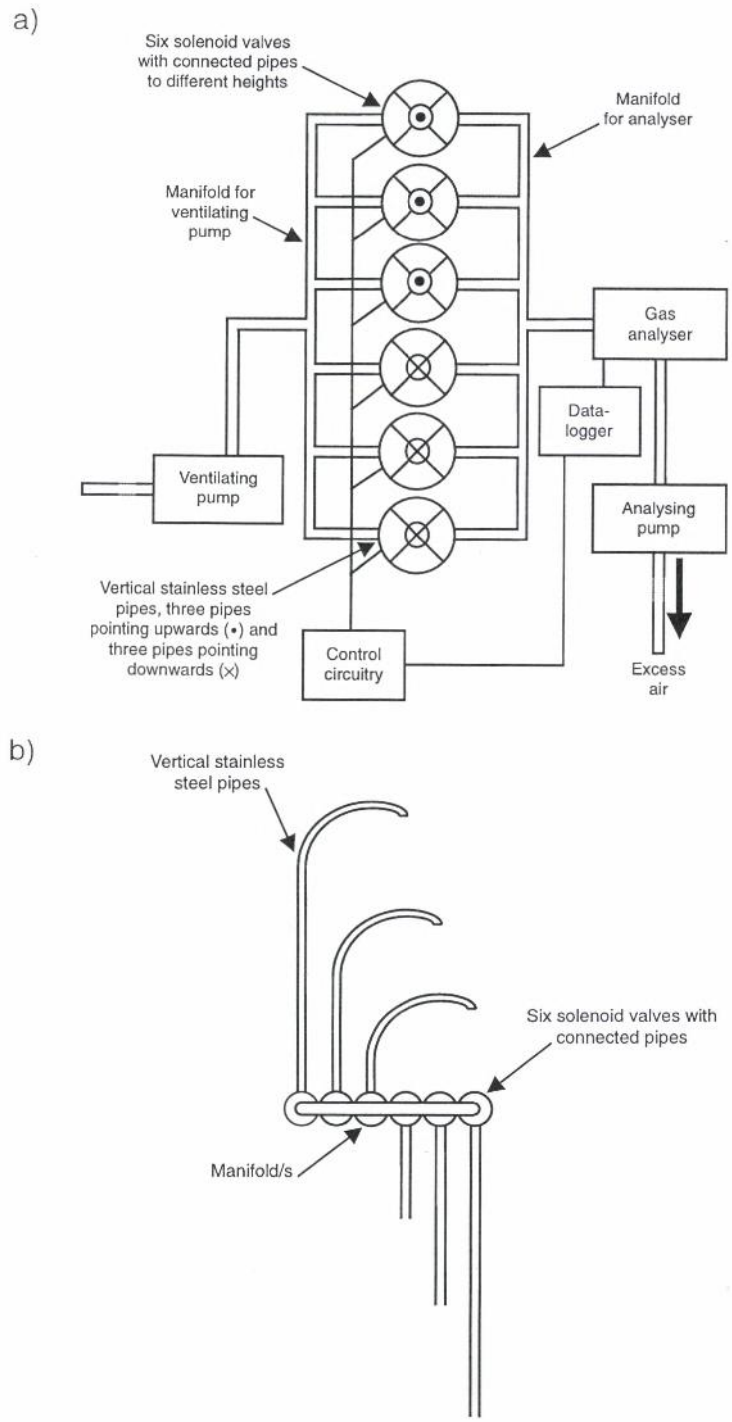

Figure 1. Schematic representation showing the general features of the Organ Pipe Sequential Sampling (OPSS) system: (a) plan of the entire system and (b) elevation of the pipework.

might take place in the pipework are limited to the time taken to travel through to the analyser. The system is therefore suitable for reactive gases (e.g., ozone) as well as relatively inert ones (e.g., carbon dioxide), provided that they are not incompatible with the materials of either the pipework or solenoid valves. If this feature turns out to be an unnecessary sophistication, such as for the case of carbon dioxide, then simple ON/OFF (i.e., two-way) solenoid valves can be employed.

2.1.2. System design and circuit requirements

The gas analyser in use is kept at a fixed height and the input to it is switched, at predetermined time intervals, to stainless steel pipes, which have their open ends at a range of heights above ground. The following description assumes that all six sampling points are used in measuring vertical concentration profiles, but in this work, five receptor heights (0.26, 0.95, 1.65, 2.35, and 2.81 m above ground) were employed, the other sampling point being used to measure ambient carbon dioxide concentration immediately outside the environment that was monitored. Monitoring commences at the lowest level and cycles through the other pipes, in order of ascent. On completion of monitoring at the upper level, sampling switches once again to the lowest level before repeating the ascent. Thus, not only is the time for monitoring at each level constant, but the time interval between successive monitoring at the same level is also identical. This is obviously an essential feature to enable comparison of successive data profiles.

The analyser monitors continuously and it is therefore imperative to be able to relate accumulated data to the appropriate measurement heights and, during the course of data collection, to be able to check that this is being done correctly. The analogue output voltage from the controller is logged alongside the gas measurement data, to enable correlation of gas concentration information with acquisition height. Although the time taken for switching between levels is negligible, it is a simple matter to disregard the last data set prior to each analogue output voltage change, should this be considered necessary.

The requirements for the solenoid valve control circuitry can therefore be seen to consist essentially of two categories—a timing and selection section for solenoid switching, and a counting and indicating section. These requirements are fulfilled by the circuitry shown in Figure 2(a) and the corresponding schematic diagram in Figure 2(b). The timing

operation is based around a ZN1034E precision timer (U1), and the counting, selection, and indicating sections based on standard C-MOS integrated circuits (U2-5)—along with associated transistors for power control of the solenoid valves.

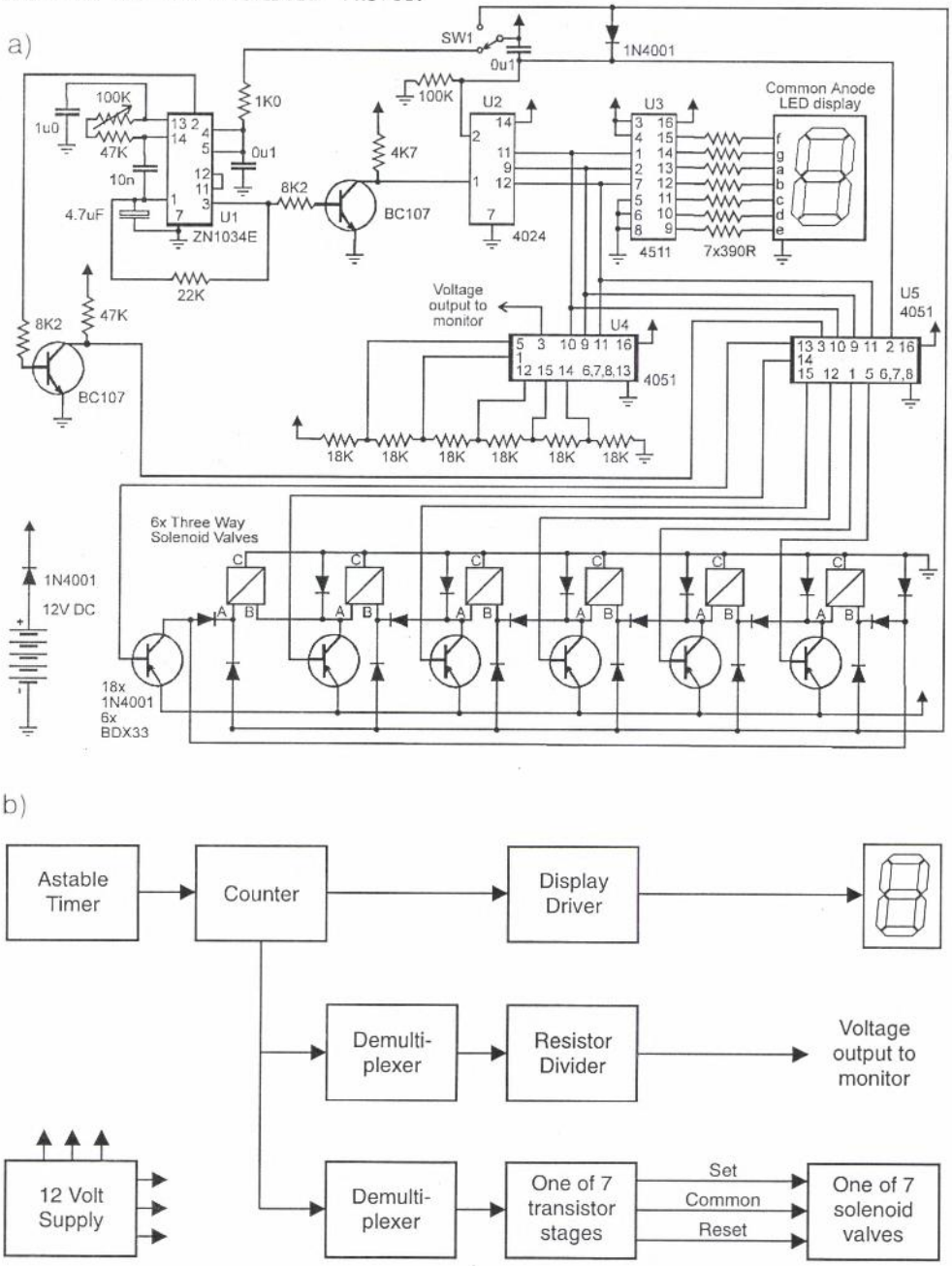

Figure 2. Control circuitry of the Organ Pipe Sequential Sampling (OPSS) system: (a) circuit diagram, (b) schematic diagram.

2.1.3. Circuit description

In Figure 2(a), the ZN1034E timer is a precision device, which contains its own oscillator circuitry and divider chain, and has proved robust and reliable in many different situations. The other integrated circuits are standard 4000 series C-MOS devices, chosen to allow the whole circuit and motor to operate from the same 12 volt car battery supply.

The timing period for the ZN1034E timer is determined by the combination of the 1 μF capacitor and the sum of the adjacent 100 k variable resistor and 47 k fixed resistor. In the circuit shown, the timing period is variable between approximately 2 and 7 min. The timer is operated in a stable mode and will repeatedly time for the programmed period. The timing period T (in seconds) is given by

$$T = 0.668 \times 4095 \times R \times C$$

where R is resistance in ohms and C is capacitance in farads.

The ZN1034E timer has two complementary outputs but these are not suitable for direct use in this case. The two transistors (Q1 and Q2) are utilised to send control pulses for driving the solenoid valves and to act as a voltage translator for the counter input, respectively. Associated capacitors serve to prevent multiple triggering of the counter. Six further transistors (Q3–8), and a number of diodes, which serve to protect and isolate them, are power devices to actually operate the solenoid valves.

As previously stated, it is necessary to be able to relate accumulated data to the appropriate instrument heights and also desirable to be able to check that this occurs. The three line digital output from the counter is therefore directed three ways. Firstly, it passes signals via a decoder-driver (U3) to a light-emitting diode (LED) display. Secondly, by means of a solid state multiplexing switch (U5), one of six power transistors is triggered in turn. Each power transistor turns ON one solenoid valve and simultaneously turns the previous one OFF. Thirdly, the digital bus controls a second solid state multiplexing switch (U4) and a resistor divider chain, to provide the voltage signal, which indicates the measurement height at any moment in time. Each output voltage therefore corresponds directly to a particular number on the LED display as well as to an individual height stage. For convenience in logic circuit design, the lowest level was designated "0" and the highest "5" with four intermediate stages. The resistor values in the divider chain were chosen

to give a maximum output of 10 volts to correspond with the chosen analyser's maximum permissible input. The voltage output in the presented circuit therefore varies by approximately 2 volts between adjacent stages.

2.1.4. Circuit operation

On power up, the reset switch (SW1) is operated and the timing cycle commences. Solenoid valve "1" will open and all others will be closed, the LED display will read "0," and a voltage of approximately 0 volts will be seen by the logging device. At the end of the first predetermined time period (2 min in the present case), a pulse from Q1 will pass via U5 to output transistor Q4 so that solenoid valve "1" will switch OFF and solenoid valve "2" will switch ON. As the second timing period starts, the counter will increment and the LED display will now therefore indicate "1" and a voltage of approximately 2 volts will be seen by the logger's analogue input.

At the end of the second time period, a second pulse from Q1 will pass via U5 to output transistor Q5 so that solenoid valve "2" will switch OFF and solenoid valve "3" will switch ON. As the third timing period starts, the counter will increment and the LED display will now therefore indicate "2" and a voltage of approximately 4 volts will be seen by the logger's analogue input. This cycle repeats through six complete operations until the sixth solenoid valve closes, "1" opens, and the whole sequence restarts.

2.2. Site Description

Measurements using the OPSS system were carried out in a small room (c. 16 m^2) with a height of 3.43 m (Figure 3), used as a meeting point during coffee break (starting at 11:00) by staff members of the Environmental Science Section. There is one door leading to the room, which was opened periodically during the time when it was occupied, and it has one large vertical sliding bay window, which was kept closed during the experiment. The room is naturally ventilated and smoking is prohibited.

A coffee room has been chosen for monitoring as such an environment is occupied only for a relatively short period of time (30–45 min); hence one can detect the effect of human activity (mechanically-generated

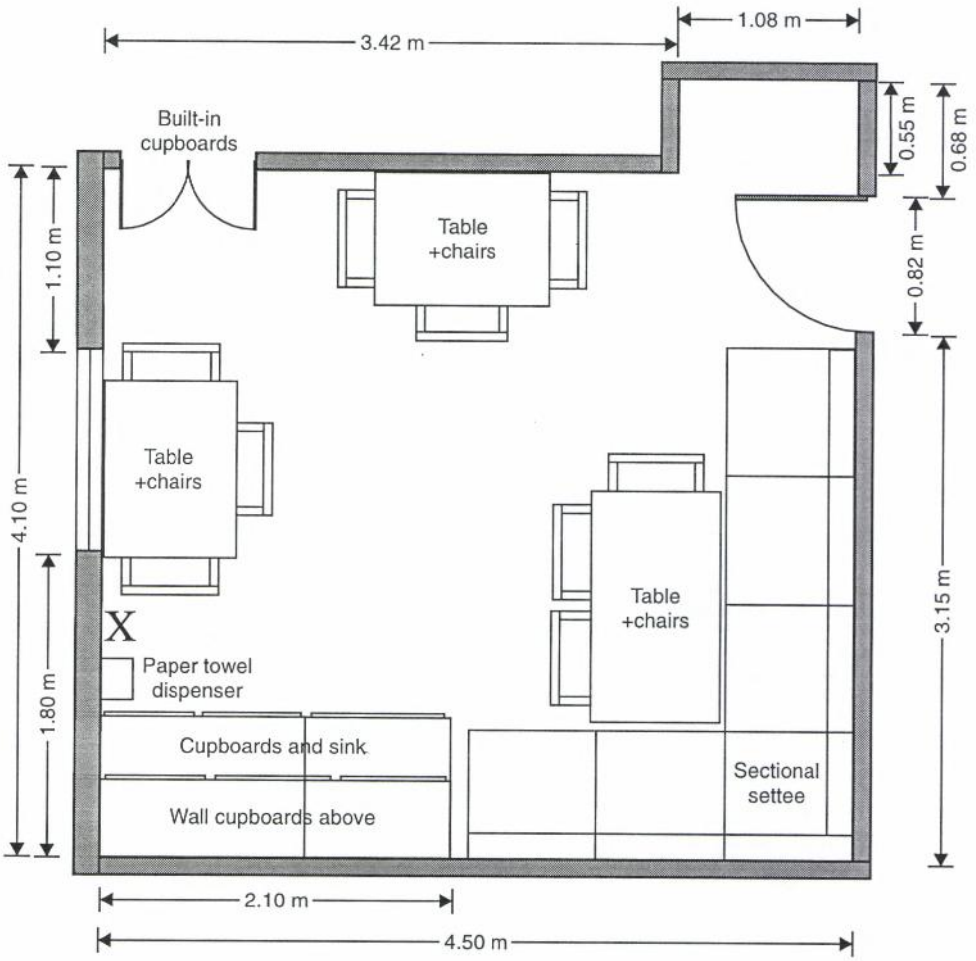

Figure 3. Plan of the coffee room where vertical concentration profiles of carbon dioxide were measured on 19 November 1997. The exact location of sampling is denoted with an X.

turbulence and breathing/exhalation) on vertical concentration profiles of carbon dioxide without having to carry out prolonged monitoring before, after, and during the event.

3. RESULTS AND DISCUSSION

Carbon dioxide has long been considered as an indicator of indoor air quality (Haghighat & Donnini, 1992; Haghighat & Donnini, 1993; Hung & Derossis, 1989; Oldaker, Taylor, & Parrish, 1995). Naturally-generated indoor carbon dioxide concentrations have been used to estimate venti-

lation rate in animal housing (Vantklooster & Heitlager, 1994), and in offices and laboratories (Jankovic, Ihle, & Vick, 1996). Hence carbon dioxide is important both as a natural tracer and as an indoor air quality indicator. For this reason, and because a carbon dioxide analyser

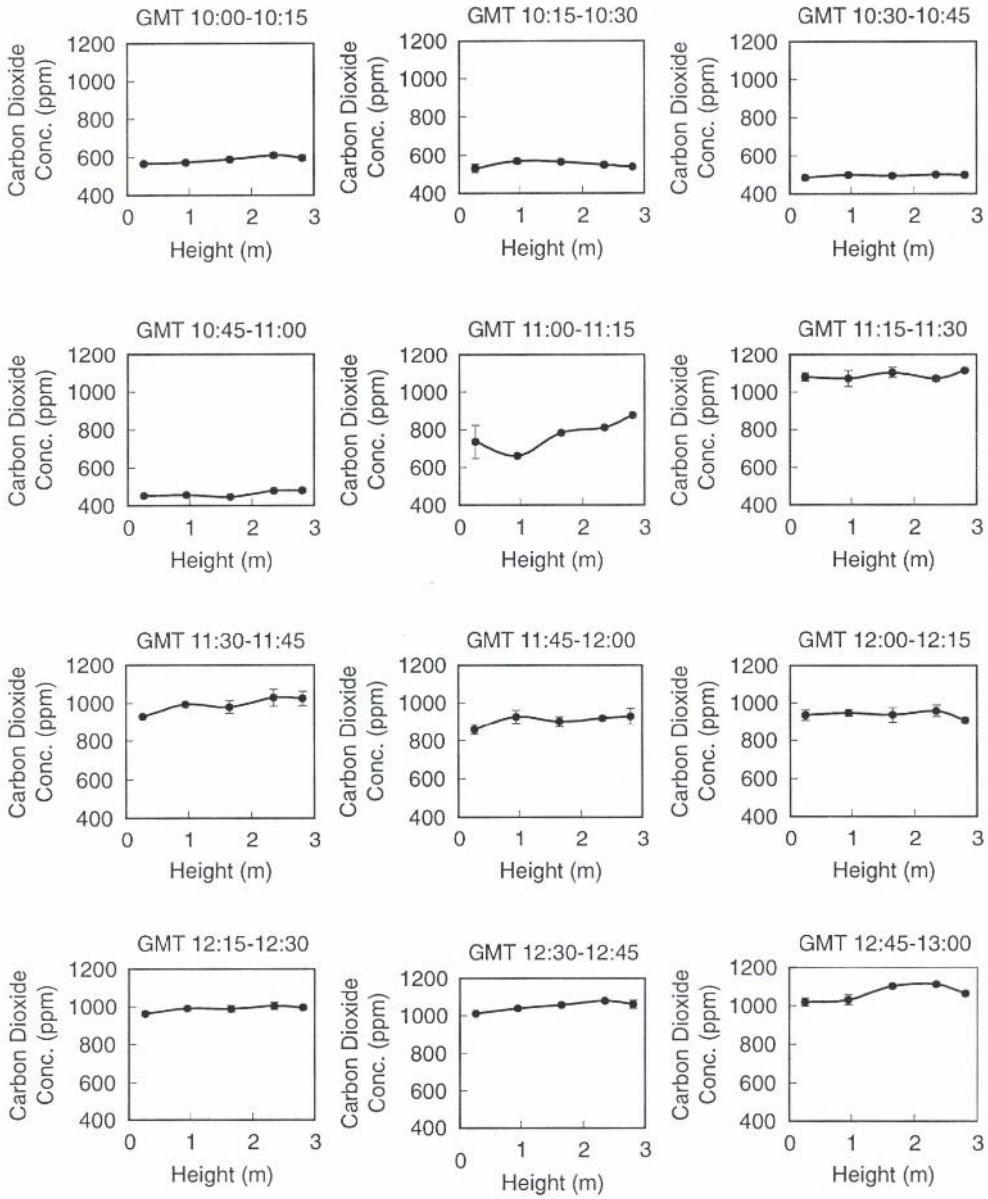

Figure 4. Sequence of vertical concentration profiles of carbon dioxide averaged over 15-min intervals, measured in the coffee room from 10:00 to 13:00 on 19 November 1997. The length of the error-bars is equal to one standard deviation of concentration at the given level. *Notes.* conc.—concentration.

(Model LCA-2, The Analytical Development Co. Ltd., Hoddesdon, UK) was readily available, the OPSS system was used to measure vertical concentration profiles of carbon dioxide. Monitoring was carried out on 19 November 1997, at the marked location on the plan for the coffee room (Figure 3), from 10:00 to 13:00. The concentration data were averaged over successive 15-min intervals, for each of the sampling points so that a sequence of 12 profiles was obtained (Figure 4). The level of increase in carbon dioxide concentration at all levels coincided, as expected, with an increase in human occupancy. From Figures 4 and 5, one can observe that concentration decreases between 10:00 and 11:00, coinciding with the operator leaving the room vacant, and then starts to increase again at 11:00 (start of coffee break). An interesting feature is that the maximum concentration gradient occurred during the first 15 min of coffee break (Figure 4, GMT 11:00–11:15). During this time, occupants were concentrated near the sampling location producing a build-up of carbon dioxide at the higher sampling levels, coinciding with the average breathing level for an adult. The large variation in concentration at the lowest level at the start of coffee break is thought

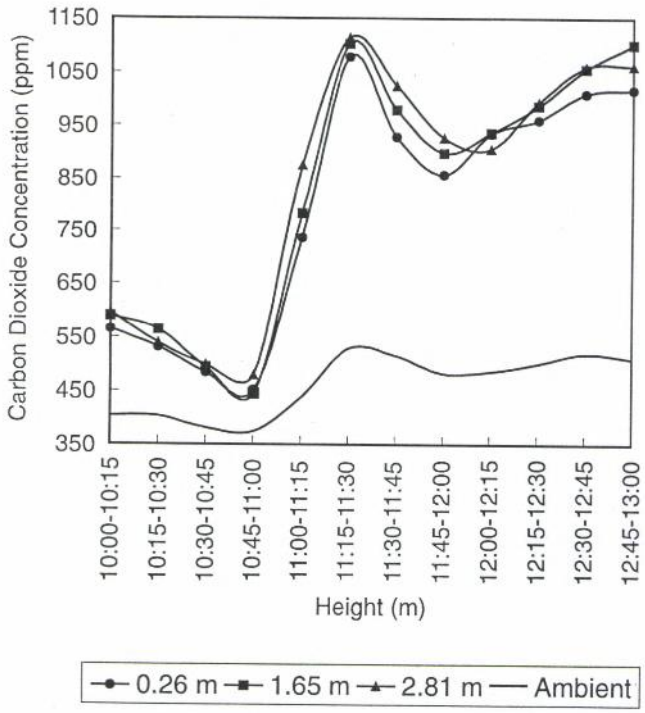

Figure 5. Time series of carbon dioxide concentration at three receptor heights (0.26, 1.65, and 2.81 m) in the coffee room and for ambient air immediately outside the room on 19 November 1997.

to be the result of mechanically-generated turbulence caused by movement of the occupants; otherwise, on average, the standard deviation of concentration was similar for all levels as can be observed from Figure 6.

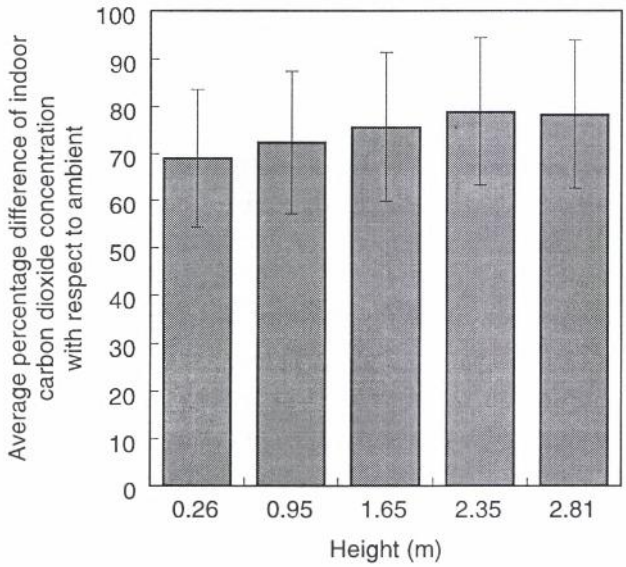

Figure 6. Daily average percentage difference of carbon dioxide concentration with respect to the average ambient concentration measured for the six receptor levels on 19 November 1997, in the coffee room. For each of the levels, the length of the error-bar is equal to one standard deviation of the percentage difference of the 15-min interval means of carbon dioxide concentration with respect to that measured at ambient.

Concentration started to decrease at all levels (Figures 4 and 5) after 11:30 when most of the occupants left the coffee room. Due to the relatively poor ventilation of the environment and because some of the personnel choose to have their lunch in the coffee room, the carbon dioxide concentration was well above 800 ppm at all times after 11:30, reaching a second peak during 12:45–13:00. Once more a build-up of carbon dioxide occurred at the higher sampling points due to occupants standing next to the paper towel dispenser situated very close to the OPSS system (see Figure 3).

Highest concentrations were shared between the two highest sampling levels (2.35 and 2.81 m) reflecting the thermal-buoyancy effect of exhaled air at the average breathing height, as can be seen from Figures 4–6. The ambient carbon dioxide concentration has traced the indoor concentration to some extent because ambient sampling was done immediately

outside the (closed) window that creates a source of ventilation and because the exhaust of the ventilating and analysing pumps was at close proximity to the pipe used for sampling ambient air. This is apparently in contradiction with the advice given previously that the ventilating duct should be as far away as possible from any of the sampling inlets, but the reason for doing so was to check on the magnitude of the interference effect.

The measured concentration gradients were not very large except on one occasion (Figure 4, GMT 11:00–11:15). One reason for this is the mobility of the occupants, which gives rise to mixing and is equivalent to having mobile "point" sources of carbon dioxide, and the different levels at which exhalation takes place (sitting and standing). It is thought that larger concentration gradients can be observed for fixed point emissions such as a burning flame (gas cookers and heaters).

4. CONCLUSION

The results of the brief monitoring exercise undertaken, using the OPSS system coupled with a carbon dioxide analyser, have shown that the system is useful in sequential logging of concentration data of gaseous pollutants whether for the study of spatio-temporal variations or indoor-outdoor comparison of concentration. Provided that the pipes, manifolds, and solenoid valves used do not react with the target gas, the system can be used to sample any gas commonly found in indoor and outdoor environments. This extends the usefulness of the system and allows for simultaneous measurement of vertical concentration profiles as well as more general spatial variability (by minor modification) of different gases.

Concentration data collected using the OPSS system can be used in estimating human exposure at different breathing levels and for studying the spatial and temporal variability of gaseous pollutants, and hence evaluation of air pollution models. Finally, it should be noted that tests with different airborne particle size ranges have shown that, due to the inevitable particle loss, which increases dramatically with an increase in particle size, mainly at the solenoid valves, the system cannot be used for sampling suspended particulate matter. In this case, the Kinetic Sequential Sampling (KSS) system (Micallef et al., 1998) should be used. KSS and OPSS systems form a comprehensive tool for studying the vertical distribution of airborne pollutants and should prove beneficial to researchers involved in occupational and environmental health research.

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