Atmospheric Environment Vol. 27A, No. 11, pp. 1743–1753, 1993.
Printed in Great Britain.

0004–6981/93 $6.00+0.00

RELATIONSHIPS BETWEEN INDOOR AND OUTDOOR AIR QUALITY IN FOUR NATURALLY VENTILATED OFFICES IN THE UNITED KINGDOM

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(*First received* 8 *March* 1992 *and in final form* 22 *December* 1992)

Abstract— Three offices in central London and one at a rural location were characterized with respect to air quality. All four offices were naturally ventilated. The characterization was supplemented by using a mobile laboratory to monitor the outdoor air quality. Results indicate that indoor pollutant concentrations may be up to 80% of the concentration outdoors but can greatly exceed outdoor concentrations. Additionally, it has been shown that indoor pollutants usually follow outdoor pollutant trends at lower levels, with only a small time delay due to mixing and dilution factors. The interaction between indoor and outdoor air is discussed with respect to ventilation characteristics and pollutant sources. A comparison between actual and modelled carbon dioxide levels may provide a useful indicator of ventilation.

Key word index: Indoor air quality, outdoor air quality, CO_2, CO, oxides of nitrogen, temperature, relative humidity, ventilation.

INTRODUCTION

Research over the past 10–20 years has shown that air quality inside homes, offices and other buildings may be as poor or indeed poorer than that outdoors (Budiansky, 1980; Repace, 1982; Suess, 1988). However, much remains unknown about the relationship between the indoor and outdoor air quality. Indoor pollutant sources, their pathways, lifetimes, fates and sinks, and the impact of criteria such as building design and location are still poorly understood.

Outdoor air quality has been of concern for several decades, and many countries have implemented regulations to control ambient air pollution. The U.S.A.'s Clean Air Act (1971) is probably the most widely cited. It is enacted in the National Ambient Air Quality Standards set and enforced by the Environmental Protection Agency (1972). The standards are designed to protect the public from outdoor air pollutants. Much work has been carried out to establish the composition of both badly polluted and non-polluted outdoor environments. The sources, transport, lifetime, fate and sinks of commonly occurring outdoor air pollutants have been extensively studied. Whilst these are of importance to human health, in the developed world the composition of the indoor air may be of as much or greater concern because the majority of people spend most of their time, some 75–90%, inside buildings (Lebowitz *et al.*, 1985). The most vulnerable groups of society, the old, the sick and the very young, often spend 100% of their time indoors. Therefore, an appraisal of indoor air quality is most important to the understanding of the impact of air pollution on human health.

The composition of the atmosphere in terms of gross constituents (oxygen and nitrogen) is basically the same indoors and outdoors; however, pollutant concentrations (e.g. carbon monoxide, oxides of nitrogen, ozone) will alter with time and space. The nature and quantities of contaminants indoors may differ considerably from those outdoors. A less reactive gas such as carbon monoxide readily penetrates the indoor environment and gross trends may be related to traffic flow outdoors; however, indoor sources such as unvented gas appliances may cause indoor levels to greatly exceed those outdoors.

Indoor pollution levels will be determined by a number of factors: (i) the air exchange rate between the indoor and outdoor environment; (ii) the outdoor air quality; (iii) any indoor sources of pollutants; (iv) the removal of pollutants from the room by methods other than ventilation, e.g. adsorption of pollutants to surfaces. Attempts to characterize the indoor air of various non-industrial buildings have shown a diverse number of contaminants from a variety of sources. Combustion products, including polyaromatic hydrocarbons, may have a significant impact on health due to a known carcinogenity. Solvents evaporated from cleaning materials, paints, adhesives as well as other volatile organic compounds (VOCs), are employed in most buildings and are a cause for concern. Building materials may also be a source of pollution, for example formaldehyde may be emitted from particleboard or urea-formaldehyde foam insulation.

In the U.K. there is a general paucity of information concerning the quality of indoor air and, although considerable time has previously been devoted to examining the effects of environmental tobacco smoke in the office environment, little attention has been paid to other contaminants. Internationally, a large number of indoor air quality surveys have concentrated either on individual contaminants such as radon or asbestos (White *et al.*, 1989; Wilbourn *et al.*, 1988; Rood, 1988); have measured only one or two parameters (Kirk *et al.*, 1988; Miksch *et al.*, 1982; Johansson, 1978; Repace and Lowrey, 1980); or have measured a combination of parameters but over a very limited time scale (e.g. 1 h) (Mouilleseaux *et al.*, 1989; Collett and Ross, 1990).

The survey reported here was designed to characterize the air quality of a number of typical office environments with no perceived air quality problems. Four offices were monitored during the months of February and March 1990. To determine the relationship between outdoor and indoor air quality both environments were monitored concurrently for a range of contaminants and physical parameters.

METHODOLOGY

Locations

These were selected to provide differing examples of typical office environments and to permit meaningful comparisons. Amongst the variables included for study were urban and rural locations, height above ground, activity level and the presence of smoking occupants. A detailed characterization of the selected offices is included in Table 1.

Sampling procedure

For the purpose of this study those contaminants considered most characteristic of indoor air quality in an office environment were selected. These were, carbon dioxide, carbon monoxide, nitrogen oxides (NO_x, NO, and NO_2), temperature and relative humidity. Observational data concerning the size and layout of the rooms, furnishings, ventilation conditions, occupancy levels and activities, and outdoor weather conditions were also recorded. Instrumentation for the measurement of these contaminants and air quality parameters was rack mounted and situated as near to the centre of each office as possible.

Air flow patterns in each office were checked at the onset of the monitoring period, using a Draeger Air Flow Tester (Draeger Ltd, Hemel Hempstead, U.K.), to ensure that there were no unexpected air movements, such as draughts, in close proximity to the sampling equipment. A quantitative assessment of air volume flows in, around and out of each building was beyond the scope of this study. Other measurements, such as carbon dioxide levels, were used to assess ventilation.

Instrumentation

To collect continuous outdoor air data a mobile air monitoring laboratory was located as close to each of the offices as possible. The instruments and methods used to measure the outdoor quality parameters are shown in Table 2; the operation of the mobile laboratory has been described previously (Clark *et al.*, 1984). The instruments and methods used to measure the indoor parameters are also included in Table 2.

Calibration and quality control

The instruments were calibrated once a week. This calibration involved a zero and a single span point. Linearity of the instruments had previously been checked in an intercomparison with Warren Spring Laboratories (Stevenage, U.K.).

Frequency of measurements

Temperature, relative humidity, CO_2, CO and NO_x were recorded at 5 min intervals throughout each sampling period. This interval was used wherever practical. Hourly arithmetic means were calculated from the 5 min interval data for weekly graphical presentation and statistical analysis. Suitability of this method of data collection for outdoor air has previously been demonstrated (Clark *et al.*, 1984 and 1988).

Table 1. Site locations and summary descriptions

	Office 1	Office 2	Office 3	Office 4
Location	Office in South Kensington, London (urban)	Office in South Kensington, London (urban)	Office in South Kensington, London (urban)	Office at Silwood Park, Ascot (rural)
Sampling dates	11/2–17/2/90	18/2–24/2/90	4/3–10/3/90	11/3–17/3/90
Building description	Concrete, five stories	Concrete, five stories	Concrete, five stories	Brick, four stories
Floor level	5th	5th	Ground	1st
Room size (m^3)	26	109	22	82
Floor area (m^2)	11	46	11	29
Floor covering	Carpet tiles	Carpet tiles	Carpet tiles	Deep pile carpet
Wall covering	Paint	Paint	Panelling	Panelling
Ceiling covering	Paint	Paint	False ceiling tiles	Paint
Number of windows	6	6	1	7
Number of doors	1 (+1 not in use)	2 (+2 not in use)	1	2
Ventilation	Natural	Natural	Natural	Natural
Number of occupants	2	6	1	1
Activity level	Low	High	Moderate	Low
Smoking	No	Yes	No	No
Plants	Yes	No	No	Yes

Table 2. Instruments and methods used to measure indoor and outdoor parameters

Parameter	Instrument	Method	Manufacturer
Indoor			
Carbon dioxide	Horiba (model PIR-2000)	Non-dispersive infra-red	Horiba Ltd, Northampton, U.K.
Carbon monoxide	Dasibi (model 3006)	Non-dispersive infra-red (NDIR)	Quantitech Ltd, Hemel Hempstead, U.K.
Oxides of nitrogen ($NO_x = NO + NO_2$)	Horiba Model APNA-350E	Chemiluminescent detector	Horiba Ltd
Temperature and relative humidity	Vaisala VH-L humidity probe		Grant Instruments (Cambridge) Ltd, Cambridge, U.K.
Outdoor			
Temperature and relative humidity	Hygrotest model 55	Sheltered probe mounted externally, close to the sample duct	Testoterm Ltd, Emmsworth, Hampshire, U.K.
Carbon monoxide	Beckman 6800 Air Quality Chromatograph (AQC)		Rosemount, Bognor Regis, U.K.
Oxides of nitrogen	Model 14D/E NO_x detector	Chemiluminescent detector	Thermo Electron, Warrington, U.K.

Table 3. Summary of temperature and relative humidity data from our offices, with the concurrent outdoor data, recorded during February and March 1990

	Office 1	Outdoors	Office 2	Outdoors	Office 3	Outdoors*	Office 4	Outdoors†
Temp. (°C)								
Max.	24.8	13.0	24.6	18.0	28.1	15.8	29.9	21.8
Min.	17.2	3.6	17.3	7.1	21.4	7.1	20.3	−2.5
50%ile	22.6	6.2	22.0	11.8	26.1	10.5	23.0	—
Mean	21.9	3.6	21.6	11.6	26.0	10.35	23.3	8.2
SD	1.6	4	1.7	2.1	1.0	1.83	1.5	—
RH(%)								
Max.	63	97	50	95	34	88	40	—
Min.	30	42	33	40	17	36	27	—
50%ile	36	72	42	77	27	69	36	—
Mean	36	42	42	75	27	67	35	—
SD	3	42	4	12	4.0	10	2	—

*Data obtained from hourly averages supplied by the Meteorological Office, London.
†Data from permanent weather station located at Silwood Park (— information unavailable).

RESULTS

Temperature and relative humidity

The four offices were naturally ventilated. The occupants had the option of opening or closing windows at their discretion. A summary of temperature data from the four offices with the concurrent outdoor data is shown in Table 3. Outdoor diurnal temperature fluctuations are reflected in the indoor data. The relatively small temperature range in the offices is probably due to the fact that they were continuously heated, nighttime temperatures in the offices being in the order of 19–21° C, aided by the heat retention properties of the office buildings. The weather during the survey was generally mild and sunny, this resulted in windows being opened and room temperatures being lowered. Maximum temperatures were reached during the mid-afternoon whilst minimum temperatures occurred between 2.00 and 4.00 a.m. Data from office 3 show the lowering of daytime, indoor temperatures (Table 3) by the opening of the main entrance and office doors. An electric fan was also used to increase air circulation. Outdoor relative humidity exhibited strong diurnal fluctuations, falling during the day as temperatures rose. Minimum relative humidities corresponding to maximum temperatures were generally recorded in the afternoon. This pattern was reflected in the indoor data which can be seen in Table 3. The most significant impact on indoor relative humidity occurred in office 1, a maximum value of 62.9% was recorded when a kettle was left boiling for 5 min.

Carbon dioxide

Previous work has shown outdoor, background levels of carbon dioxide (CO_2) to generally vary about a mean of 400 ppm, the variation being a result of diurnal fluctuations and the influence of local combustion sources (Yocum, 1982). A pollution event may, however, result in greatly elevated outdoor levels of CO_2 (Field *et al.*, 1992). This must be taken into consideration if a steady-state concentration of CO_2 is being assumed for ventilation assessment. Indoor concentrations of CO_2 at night and over the weekend were comparable to those outdoors. Daily trends showed levels rising during the morning, dropping at lunch time and rising again in the afternoon. The indoor CO_2 levels followed this pattern with night-time concentrations falling to about 400 ppm. Office 1 exhibited typical levels (Fig. 1a), but daytime concentrations reached a high of 1928 ppm on Tuesday afternoon at 4.00 p.m. with four people in the room and no doors or windows open. The daily concentrations of CO_2 exceeded 1000 ppm in every office at some time during working hours, but fell towards evening reaching the background value by midnight. A summary of recorded data for CO_2 is included in Table 4.

A simple model using recorded and predicted CO_2 levels was applied to each office to give an indication of their ventilation efficiency and to help interpret observational data. The estimated CO_2 concentration for a given time period was calculated from the occupant CO_2 production, making the assumption that an average individual at light work produces 0.30 $\ell\,\mathrm{min}^{-1}$ CO_2 (ASHRAE, 1989). This is expressed in equation (1):

$$c = \frac{p \times t \times o}{v} \tag{1}$$

where c = concentration of CO_2 (ppm) in the room; p

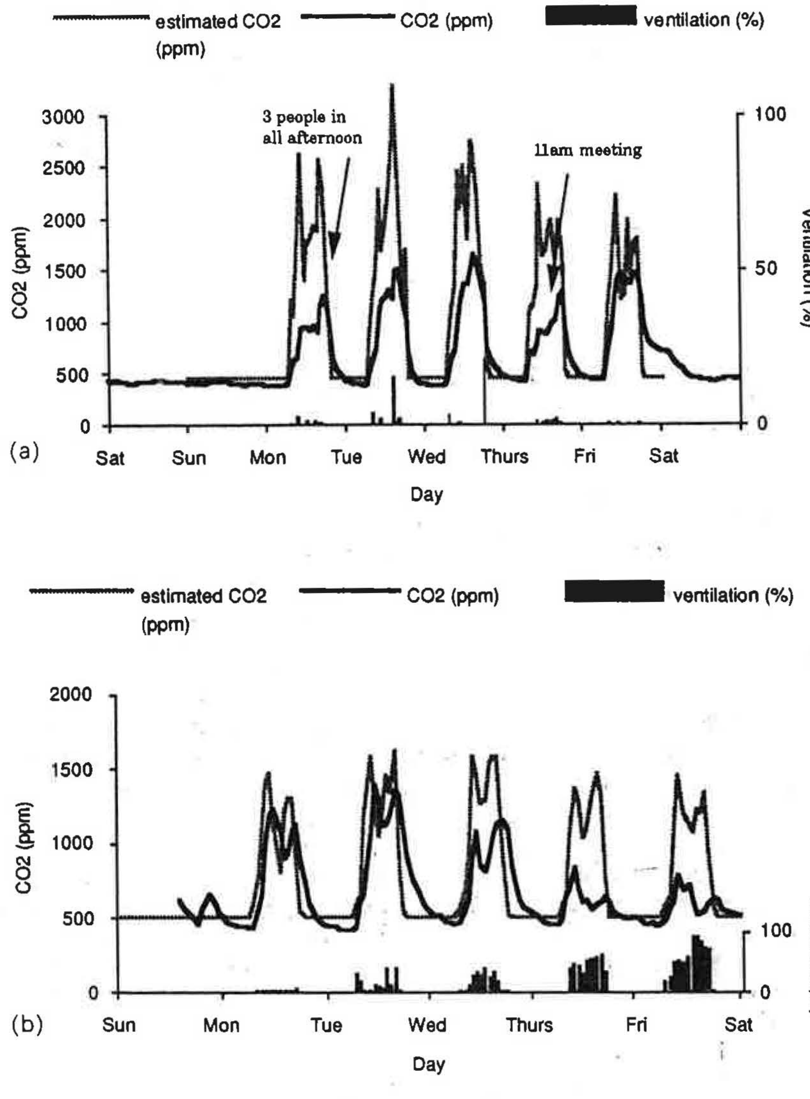

Fig. 1. (a) and (b).

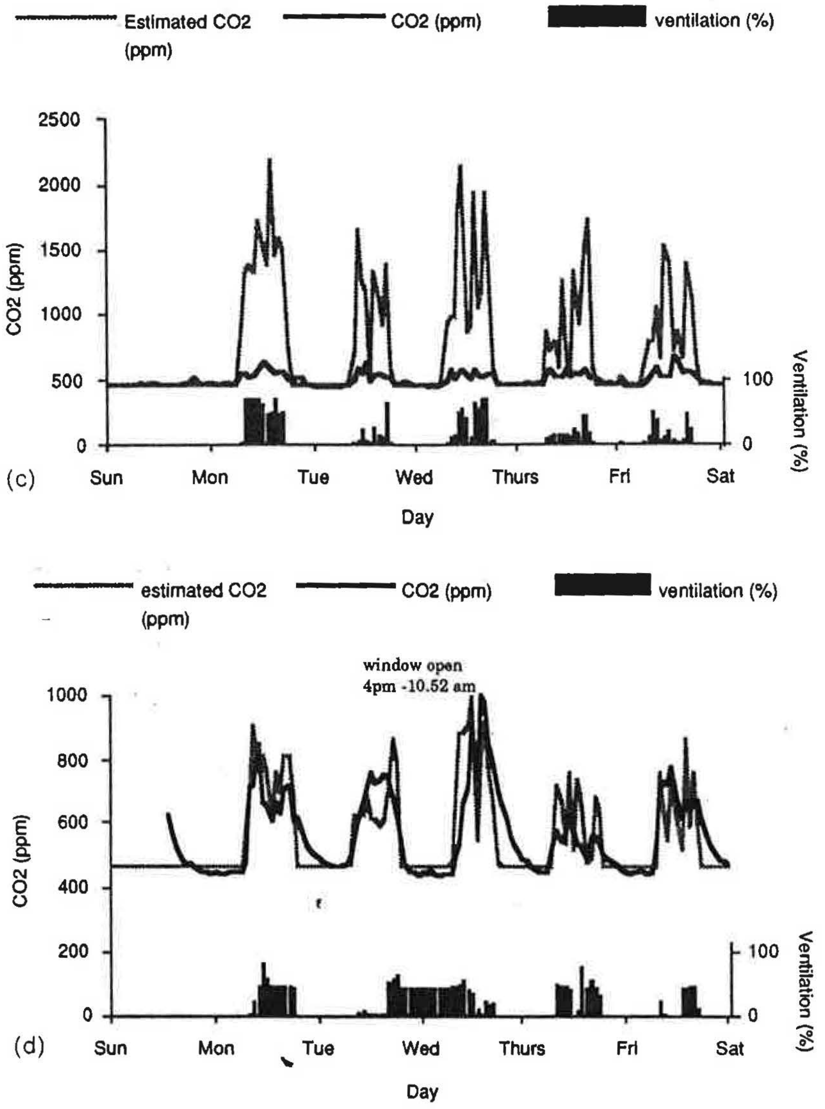

Fig. 1. Estimated and actual CO_2 concentrations and ventilation in (a) office 1, (b) office 2, (c) office 3, and (d) office 4.

Table 4. Summary of carbon dioxide (ppm) data from four offices recorded during February and March 1990

	Office 1	Office 2	Office 3	Office 4
Max.	1928	1465	1003	1799
Min.	334	411	411	411
50%ile	797	540	463	488
Mean	644	627	481	546
SD	345	240	56	127

= production of CO_2 per person in ml min^{-1}; t = time in minutes; o = average occupancy over the time period; v = the volume of the room (m^{-3}). This was then added to the mean background concentration measured at night. It was found that by resetting the CO_2 concentration to background at the end of each time period, removal processes were accounted for and so were not included in the equation. Figures 1a–1d demonstrate the observed and estimated CO_2 for the offices using a time period of 1 h [$t = 60$ in equation (1)].

This simple model can be used to examine unexpected changes in ventilation in a room and to give some comparison between rooms. It can be seen from Figs. 1b and 1d that there were several days in offices 2 and 4 when predicted CO_2 concentrations follow recorded CO_2 concentrations quite closely. During these times the air exchange of 1 h ($t = 60$) is fairly accurate. Behaviour relating to changing ventilation characteristics may explain many of the differences between observed and calculated concentrations. The ventilation percentages shown in Figs 1a–d have been estimated from the percentage area of the room open to external air influence. Cumulative effects of having both windows and doors open were accounted for in the assessment. A maximum of 100% was assumed when all doors and windows were open for the 1 h time period. A downward scale to minimum ventilation when the room was closed (0%) was estimated for each office (air exchange via window frames, door frames etc., being relatively constant, was ignored in this calculation). The percentage of ventilation for the hour was calculated from observational notes relating to the duration that doors and/or windows were open for within the period. This, combined with the CO_2 comparison, illustrates the value of the model and shows how reduced ventilation may lead to a build up of indoor pollutants. The effect of changing ventilation characteristics in a room can be seen on Thursday and Friday in office 2 (Fig. 1b) when windows were opened to provide better temperature control.

A drastic departure can be seen between observed and estimated CO_2 concentrations in office 3. This is explained by the room being excessively warm and being cooled by the occupant leaving the door open and using an axial fan. The very high ventilation rate in this office makes use of the 1 h resetting time ($t=60$ equation in (1)] difficult to justify as the difference between observed and estimated was so large that a meaningful comparison is not possible. To accommodate the need to vary the resetting time (which is a crude measure of the air exchange rate in the room) equation (1) can be modified to equation (2):

$$ch = \frac{\sum_{i=1}^{j}(C_1,,,C_j)}{60/t} \qquad (2)$$

where ch = hourly concentration; j is the number of time segments in an hour (i.e. $j=60/t$). This allows for any resetting time to be incorporated. In fact, ch can be obtained by calculating c from equation (1) and dividing by $60/t$ because this study examines hourly averages. Figure 2 illustrates the application of this to office 3. The estimated CO_2 concentration was modified by changing the value of $60/t$ to obtain the optimum match. The value of $60/t$ gives an indication of the air exchange rate of the office. For office 3, $60/t=10$. In offices 1, 2 and 4, equation (2) could be used to quantify variations in ventilation between days over the sampling period.

This technique, employing optimum match, was verified using data recorded in an air-conditioned office. The room had an expected air exchange rate of 2 a ch^{-1} which could be directly entered into equation (2) (i.e. $60/t=2$). In this case, by comparing the estimated and the actual CO_2 concentrations an idea of the efficiency and adequacy of the office ventilation could be gauged. There was a very close match between the estimated and observed concentrations when $60/t=2$ which indicated that equation (2) gave a good indication of ventilation rate in a room.

Although very general, the value of this model for showing changes that occur in ventilation is apparent. It allows cases of poor ventilation to be identified and so mitigated. Problems associated with the use of CO_2 as an indicator of ventilation have been widely discussed (Warren, 1982; Indoor Air Quality Update, 1989). A particular problem is that in a dynamic environment, such as an occupied office, CO_2 levels will rarely reach a steady-state concentration.

Carbon monoxide

Carbon monoxide (CO) data exhibited marked diurnal variation both indoors and outdoors. The outdoor levels were generally higher (Table 5) but both indoor and outdoor data followed similar trends, reaching peak concentrations during mornings and afternoons (Fig. 3). Peak levels correspond to periods of peak traffic flow, the major anthropogenic source of CO in the urban environment being motor vehicle exhaust. For this reason, CO levels in the rural area where traffic was less were generally lower and exhibited

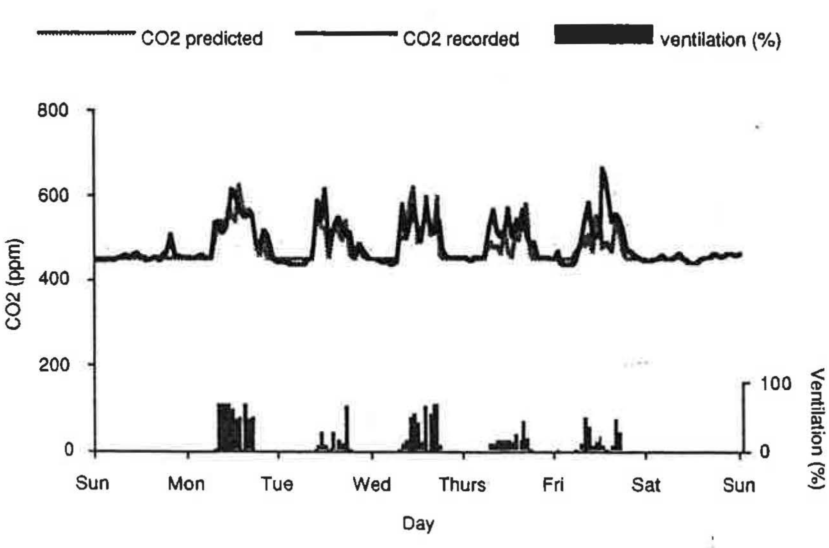

Fig. 2. Estimated ($60/t=10$) and actual CO_2 concentrations and ventilation in office 3.

done, the mean is reduced to 1.8 ppm and the standard deviation to 0.38 ppm, showing less variance than the original data set (Table 5).

On Monday and Tuesday morning, during the monitoring of office 1, indoor levels exceeded outdoor levels suggesting a very local or indoor source of CO. Elevated levels were not reflected in the indoor NO_x data from office 1; however, there was a higher NO/NO_2 ratio which is also indicative of a local or indoor combustion source. From the CO_2 model it can be seen that on days when the indoor/outdoor air exchange was minimal, the indoor CO concentration exceeded outdoor levels. This also suggests an indoor source. Unvented gas cooking appliances in the kitchens two floors below were identified as the probable cause of these anomalies. There was further evidence of this as the maximum indoor levels occur up to the lunch-time period. This shows the value of being able to compare reported contaminant concentrations with a simultaneous ventilation measurement in the same space.

Mean concentration of CO did not exceed 2 ppm indoors or outdoors for any of the monitoring periods. However, mean indoor levels were higher or the same as mean outdoor levels for offices 1 and 2 due to the presence of an indoor combustion source.

Oxides of nitrogen

Concentrations of the oxides of nitrogen (NO_x) follow similar weekly trends to those of CO. This suggests a relationship with vehicle emissions, which is corroborated by indoor levels being lower but generally following similar patterns to the levels outdoors.

Between offices maximum indoor nitrogen dioxide (NO_2) levels varied from 25 ppb in the rural office (office 5) to 57 ppb in the urban offices. However, they exhibited a much less marked diurnal pattern than total NO_x or nitrogen oxide (NO). Outdoor levels of NO_x, NO_2 and NO all exceeded indoor levels indicating that the major source was outdoors; however, the ratio of NO to NO_2 was different indoors compared to outdoors (Table 6). In offices 1 and 2, which had the same orientation and were only approximately 25 m apart, the NO_x distributions showed the same trends. NO levels were similar to or exceeded NO_2 levels suggesting a local NO_x source. The most probable source being exhaust fumes from the kitchens below. Offices 3 and 4 showed NO_2 exceeding NO as would be expected.

The indoor and outdoor NO_x levels in office 2 are depicted in Fig. 4. A time delay of up to 2–3 h is evident between peak outdoor and indoor NO_x concentrations, although the trends are very similar. This can be seen on Monday morning, Tuesday morning, Wednesday evening and Thursday morning. It suggests that the air infiltration rate from outside was reduced and therefore the response to outdoor variations was slow at these times. NO_x were able to build up indoors over a greater time period with no enhanced ventilation to remove them rapidly. Further corroboration of this is shown in Fig. 1, by observational data of closed windows and doors. External factors such as wind direction and wind speed, and the orientation of the office would also have had an influence. Levels of NO_x and CO in office 3 exhibited very little time lag between the outdoor and indoor peaks although indoor concentrations were an order of magnitude smaller. Office 3 was located on the ground floor whilst offices 1 and 2 were on the 5th floor. This vertical parameter will also have affected the indoor/outdoor relationship and response rate.

DISCUSSION

Any building is enveloped by an outdoor atmosphere that varies in quality both temporally and spatially. Indoor air quality will respond to changes in outdoor air quality but the rate of response and final indoor pollutant concentrations will depend on factors such as the permeability of the structure and the stability of the pollutant. Where the indoor/outdoor air exchange rate is high, outdoor air quality becomes of major significance. This can be seen by comparing results where air exchange patterns differ due to the opening of doors and windows. Indoor air quality in naturally ventilated offices is linked particularly closely with outdoor air quality. However, all buildings will have some indoor/outdoor air interfaces as even forced ventilation systems derive their air from an outdoor inlet.

The survey corroborates work by Anderson (1972), demonstrating that the concentration of a pollutant in a room is dependent on three principle factors: supply to the room, generation in the room and removal from the room. Mixing patterns within the room due to concentration gradients and air flow patterns will become important. Adequate ventilation is required to prevent high concentrations of such indoor air contaminants. Of the gaseous pollutants measured during this survey carbon dioxide was predominantly generated by people indoors whilst carbon monoxide and the oxides of nitrogen were predominantly from outdoor sources.

A comparison of pollutant concentrations recorded in these offices with current guidelines (Table 7) shows levels to be, on the whole, below the recommended limits.

Occupant comfort is important in any working environment if maximum productivity is to be attained. Recommended comfort requirements can be found in the International Standard, ISO 7730-1984 (1984). However, any comparison between temperatures recorded in other office surveys must take into account the country's climate and comfort preferences of the indigenous population.

The constantly high nighttime temperatures in office 3, particularly evident from this winter survey data, were a result of the small office being located above the building's boiler room. This office was

particularly low relative humidities (mean 27%) which along with the high temperatures could help explain the perception of poor air quality in this office. Relative humidity comfort ranges will also vary for different countries, but levels are also of importance regarding infection and mould incidence (Sykes, 1989).

The importance of ventilation is clearly evident with its affects on personal comfort and pollutant concentrations and is a controlling factor in the outdoor/indoor relationship. Several standards have been set for ventilation and fresh air supply rates to offices (CIBSE, 1988; British Standard 5720, 1979). In the U.S.A., the ASHRAE Standard 62-89 sets a minimum of $8\,\ell\,s^{-1}$ per person in areas such as open corridors and a minimum of $10\,\ell\,s^{-1}$ per person in office areas, whether or not moderate smoking occurs (ASHRAE, 1989). CIBSE, however, recommends much higher values when there is smoking. ASHRAE's widely accepted standard has been developed to maintain CO_2 levels below a maximum of 1000 ppm throughout a building as a whole. Occupant-generated CO_2 levels have been proposed as an indicator of ventilation rate (Turiel and Rudy, 1980) and a recent study (Turner and Binnie, 1990) suggests that overall a CO_2 level of 800 ppm, which equates to approximately $10\,\ell\,s^{-1}$ of fresh air per person should be regarded as a satisfactory and realistic working limit.

Carbon dioxide is not normally considered as being a pollutant. However, there is concern over levels building up in sealed buildings, and concentrations of 1000–2000 ppm are frequently associated with sick building syndrome (Hall and Lavite, 1988). CO_2 levels indoors are believed by many ventilation engineers to be one of the most important parameters for setting ventilation standards in energy efficient buildings (Södergren, 1982) as levels appear to be an indicator of the ability of the air exchange rate to provide required fresh air rates in the absence of smoking.

Carbon dioxide concentrations can be related to the number of occupants in a room, the air exchange rate (ventilation), the degree of in-room air mixing and the concentration gradient between indoor and outdoor CO_2 levels. Moschandreas *et al.* (1981) have correlated CO_2 concentration with occupancy, indoor activity patterns and air infiltration rates. Existing guideline values for CO_2 include an industrial 8 h exposure limit of 5000 ppm (Health and Safety Executive, 1989) and a maximum short term permissible level of 21,600 ppm (WHO, 1987). Neither of these are really applicable to the office or domestic environment.

Outdoor levels of CO and NO_x have been largely attributed to traffic levels (Department of the Environment, 1988; Berglund *et al.*, 1982). In the offices, diurnal variations of these contaminants have been found to coincide generally with traffic flow patterns. Indoor and outdoor levels at the rural location (office 4) were generally much lower. This can be corroborated by earlier studies carried out by Clark *et al.* (1988) who found mean CO concentration of 1.76 ppm at the urban site and 0.48 ppm at the rural site in 1983. The urban office mean values range from 1.3 to 1.7 ppm while the rural mean was 0.8 ppm. The rural mean was elevated by the anonymously high readings recorded on Monday evening as noted in the results. By deleting this data from Monday evening a mean of 0.7 is attained which compares well with the findings of Clark *et al.* (1988). Comparable data were also recorded in Stockholm (Berglund *et al.*, 1982). Peak CO concentrations of 17 ppm were recorded at street level at 7.00 a.m. and 4.00 p.m. that corresponded to indoor peaks of 2.5 ppm at 8.00 a.m. and 5.00 p.m. The WHO propose guidelines concerning CO to aim at preventing carboxyhaemoglobin exceeding 2.5–3% in non-smoking populations (WHO, 1987).

The WHO time-weighted average exposure limits for CO, NO_x and NO_2 (WHO, 1987) were not exceeded in any of the offices for the duration of the survey periods. General levels of indoor pollutants encountered in the office have been reported. However, with the vast variation in indoor and outdoor parameters, any general characterization may be proven to be an over simplification of the indoor environment and caution must be exercised when assessing possible pollutant levels and patterns.

Weather conditions, particularly wind direction and speed, as well as the proximity of the source to the monitoring equipment will have affected the results and factors may lead to inexplicable results. The indoor/outdoor air quality relationship can be seen to be a complex function of several factors including outdoor air quality, meteorology, permeability of structures, indoor generation of pollutants, pollution depletion mechanisms and ventilation (Yocum, 1982).

CONCLUSIONS

The relationship between indoor and outdoor air is dependent, to a large extent, on the rate of exchange between these two environments. The outdoor air quality is of major significance when the outdoor/indoor air exchange rate is high. Pollution levels inside a room will be determined by ventilation rates, patterns of air mixing and concentration gradients as well as by source location and contaminant characteristics. Pollutants from indoor sources may build up if ventilation is inadequate for the room size and interior design.

Meteorological conditions affect the indoor/outdoor air quality relationship by altering the air exchange rate. Natural air exchange mechanisms such as this have been impaired by sealing building to conserve energy. Without providing adequate ventilation by controlled means, this has been a major factor in the recognition of indoor air quality as a problem of general concern. Other factors include the increased use of synthetic compounds in building materials and furnishings with unknown health consequences.

With such factors in mind, future building design should consider the location of any development, its orientation with regards to local wind direction and meteorological conditions, position of outdoor air intake sources for ventilation purposes, as well as the choice of building materials.

Of the offices studied, three were considered by the occupants to be satisfactory and one, office 3, was not. The latter was clearly shown to have inadequate ventilation and temperature/humidity control.

Acknowledgements—Two authors, J. L. Phillips and R. A. Field, gratefully acknowledge SERC for their research funding.

REFERENCES

American Society of Heating, Refrigerating and Air-Conditioning Engineers (1989) Standard 62-1989. Ventilation for Acceptable Air Quality.

Anderson I. (1972). Relationships between outdoor and indoor air pollution. *Atmospheric Environment* **6**, 275–278.

Berglund B., Johansson I. and Lindvall T. (1982) The influence of ventilation on indoor/outdoor air contaminants in an office building. *Envir. Int.* **8**, 395–399.

British Standard (1979) BS 5720. Code of practice for mechanical ventilation and air conditioning in buildings. BSI, Milton Keynes.

Budiansky S. (1980) Indoor air pollution. *Envir. Sci. Technol.* **14**, 1023–1027.

Chartered Institute of Building Services Engineers (1988) Guide Section B2. Ventilation and air conditioning requirements. London, U.K.

Clark A. I., McIntyre A. E., Lester J. N. and Perry R. (1984) Air quality impact assessment. *Envir. Monit. Assess.* **4**, 205–232.

Clark A. I., McIntyre A. E., Reynolds G. L., Kirk R. W., Lester J. N. and Perry R. (1988) Statistical analysis of gaseous air pollutant concentrations at urban, rural and motorway locations. *Envir. Technol. Lett.* **9**, 1303–1312.

Collett C. W. and Ross J. A. (1990) Indoor air quality in two south american office buildings. In *Indoor Air Quality and Ventilation* (edited by Lunau F. and Reynolds G. L.), pp. 269–278. Selper Ltd, London, U.K.

Department of the Environment (1988) Digest of environmental protection and water statistics. Her Majesty's Stationary Office, Holborn, London, U.K.

Environmental Protection Agency (1972) Indoor–outdoor carbon monoxide pollution study. General Electric Company final report EPA-RA-73-020, Office of Research and Monitoring U.S.

Field R. A., Phillips J. L., Goldstone M. E., Lester J. N. and Perry R. (1992) Indoor/outdoor interactions during an air pollution event in central London. *Envir. Technol.* **13**, 391–408.

Hall S. K. and Lavite S. A. (1988) Indoor air quality of commercial buildings. *Pollut. Engng* **6**, 54–59.

Health and Safety Executive (1989) Guidance Note EH 40/89. Her Majesty's Stationary Office, Holborn, London, U.K.

Indoor Air Quality Update (Nov. 1989) Tools and techniques — measuring ventilation rates, pp. 6–12. Cutter Information Corp., Arlington, MA, U.S.A.

International Standard (1984) ISO 7730-1984. Moderate thermal environments—determination of the PMV and PPD indicies and specifications of the conditions for thermal comfort.

Johansson I. (1978) Determination of organic compounds in indoor air with potential reference to air quality. *Atmospheric Environment* **12**, 1371–1377.

Kirk P. W. W., Hunter M., Baek S. O., Lester J. N. and Perry R. (1988) Environmental tobacco smoke in indoor air. In *Indoor and Ambient Air Quality* (edited by Kirk P. W. and Perry R.), pp. 99–103. Selper Ltd, London, U.K.

Lebowitz M. D., Holberg C. J., Boyer B. and Hayes C. (1985) Respiratory symptoms and peak flow associated with indoor and outdoor air pollutants in the south west. *J. Air Pollut. Control Ass.* **35**, 1154–1158.

Miksch R. R., Hollowell C. D. and Schmidt H. E. (1982) Trace organic chemical contaminants in office spaces. *Envir. Int.* **8**, 129–137.

Moschandreas D. J., Zabransky J. and Pelton (1981) Comparison of indoor and outdoor air quality. Electrical Power Research Institute Report EA-1733, Research Project 1309, Palo Alto, CA, U.S.A.

Mouilleseaux A., Squinazi F. and Festy B. (1989) A few studies of air conditioned environments. In *Present and Future of Indoor Air Quality* (edited by Bieva C. J., Courtois Y. and Govaerts M.), pp. 309–315. Excerpta Medicia, Amsterdam, The Netherlands.

Repace J. L. (1982) Indoor air pollution. *Envir. Int.* **8**, 21–36.

Repace J. L. and Lowrey A. H. (1980) Indoor air pollution, tobacco smoke and public health. *Science* **208**, 464–472.

Rood A. P. (1988) Environmental asbestos. In *Indoor and Ambient Air Quality* (edited by Kirk P. W. and Perry R.), pp. 389–393. Selper Ltd, London, U.K.

Södergren D. (1982) A CO_2-controlled ventilation system. *Envir. Int.* **8**, 483–486.

Suess J. S. (1988) Comparative evaluation of indoor and ambient air quality—healthy guidelines. *Envir. Technol. Lett.* **9**, 461–470.

Sykes J. M. (1989) Sick building syndrome. *Building Serv. Engng Res. Technol.* **10**, 1–11.

Turiel S. and Rudy J. (1980) Occupant generated CO_2 as an indicator of ventilation rate. Report LBL 10496, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, U.S.A.

Turner S. and Binnie P. W. H. (1990) An indoor air quality survey of twenty six (26) Swiss office buildings. *Envir. Technol.* **11**, 303–314.

Warren B. F. (1982) Energy saving in buildings by control of ventilation as a function of indoor carbon dioxide concentration. *Building Serv. Engng Res. Technol.* **3**, 4–12.

White S. B., Bergsten J. W., Alexander B. V. and Rosica-Battista M. (1989) Multi-state surveys of indoor radon-222. *Health Phys.* **57**, 891–896.

Wilbourn J. D., Suess M. J. and Tuerck R. (1988) IAQ: Radon-report on WHO Working Group. (WHO Reg. Off. Europe, Copenhagen 2100, Denmark). *J. Envir. Radioact.* **8**, 73–91.

World Health Organization (1987) Air Quality Guidelines for Europe. WHO Regional Publications, European series: No. 23, Geneva, Switzerland.

Yocum J. E. (1982) Indoor–outdoor air quality relationships. A critical review. *J. Air Pollut. Control Ass.* **32**, 500–520.