The effect of outdoor pollution and ventilation on Indoor Air Quality

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ABSTRACT

The importance of reducing the ingress of outdoor pollution into the indoor environment is becoming increasingly important as concerns rise regarding the acute and chronic health effects of air pollution. In general, people in developed countries spend typically 90% or more of their time indoors, with the most susceptible individuals, such as the elderly and those with pre-existing medical conditions, spending almost all of their time indoors. It is therefore vital that optimum ventilation with good quality air is provided and that the ingress of urban pollution into buildings, where occupant exposure is likely to be the highest, is minimised. This will result in good indoor air quality (IAQ) for occupant respiration, health, comfort, wellbeing and productivity.

However, while the benefits of healthier buildings are recognised, and some studies have been carried out over the years on the concentrations of outdoor pollutants found indoors, there is still a general lack of understanding of how outdoor pollutant sources ingress into buildings, their interaction with ventilation/infiltration processes and indoor generated pollutants, and the resulting effect on IAQ. BRE has carried out a number of studies over the years investigating these issues in some types of buildings. The present paper gives a summary of some of these studies.

KEYWORDS

Indoor air quality, outdoor pollution, ventilation, health, wellbeing

1 INTRODUCTION

With increasing urbanisation, the United Nations estimates (UN, 2014) that by 2050 approximately 65% of the developing world and 85% of the developed world will live in urban areas. The concentration of human activities into urban areas has thus resulted in their containing the majority of buildings and being the areas with the highest concentrations of polluting discharges. For example, in the UK there are regular news reports of how in many areas, in particular in London, air quality standards for common pollutants (such as nitrogen dioxide and fine particles) are breached (BBC, 2017).

Such high concentrations of pollutants have a direct impact on buildings, their indoor environments and occupant exposure through infiltration and ventilation processes. Exposure to pollutants can affect health in a number of ways, ranging from premature deaths caused by heart and lung disease to worsening of asthmatic conditions and irritation of the skin.

In addition to contaminants from outdoor sources being entrained into a building, pollutants are also generated internally. Those of most concern are water vapour, carbon dioxide, odour, volatile organic compounds and formaldehyde from, for example, building materials, furnishings, and cleaning and personal care products; these need to be ventilated out of buildings. It is important therefore that effective ventilation of buildings in urban areas, whether by natural or mechanical means, is considered carefully in order to minimise the combined effects of contaminants from indoor and outdoor sources.

At present, despite ongoing work in this area (For example, by Allen et al., 2016) and Taylor et al. (2014)), there is still little information on how outdoor pollutants affect the indoor environment, especially in urban areas. There is limited understanding of interactions between indoor air quality, outdoor air pollution levels and ventilation requirements.

BRE has carried out a number of studies over the years investigating the ingress of outdoor pollutants into buildings, infiltration and ventilation, IAQ and various factors that affect these (Kukadia and Palmer, 1998; Kukadia et al., 1999; Kukadia et al., 2000, Kukadia et al., 2011). Each new study has built on the previous one. The present paper gives a summary of the most comprehensive building monitoring study (BRE Study A) carried out by BRE so far, in order to gain a greater understanding of the effect that outdoor pollution and ventilation has on IAQ. Only selected results from this study are shown and these are also compared with previous BRE studies (Studies B and C).

2 BUILDING MONITORING STUDIES

The most comprehensive BRE Study (A) by Kukadia et al. (2011) involved extensive environmental monitoring in a large urban office/workshop building over 12 months in central London. The aim was to gain a better understanding of the impact of outdoor pollution on IAQ over all the seasons in a year.

The 1930's building (Figures 1(a) and 1(b)) was essentially naturally ventilated via openable windows and purpose-provided ventilators. It consisted of a four-storey office block at the front (west side) of the building, with a two-storey section containing offices and workshop areas. The fabric of the office building consisted of a reinforced concrete frame, with reinforced concrete floor slabs and roof slab and masonry cladding. This type of construction generally results in very few air leakage paths in the actual fabric of the building itself.

(a) West side

(b) North side

Figure 1. Pictures of the building monitored in central London (from Kukadia et al., 2011).

Table 1 summarises the parameters monitored, which included airborne gaseous and particle pollutants (indoors and outdoors), some occupant behaviour (window and door opening), ventilation and airtightness and local meteorological data. During this time, the building was occupied with normal heating during the winter months and unheated during the summer.

Table 1: Environmental parameters monitored in a London office building (from Kukadia et al., 2011).

Characteristic measured	**Parameter measured**	**Location**	**Monitoring frequency**
Unreactive gas	Carbon monoxide (CO) and nitric oxide (NO)*	Ten pairs of indoor/outdoor sampling locations. All building façades, two floors (1 and 3).	2-minute averages, twice per hour at each sampling location.
Reactive gas	Nitrogen dioxide (NO_2)	Ten pairs of indoor/outdoor sampling locations. All building façades, two floors (1 and 3).	2-minute averages, twice per hour at each sampling location.
Particle mass fraction	PM_{10}	Outdoors – building roof. Indoors – on Floor 1.	2-minute averages, twenty times per hour.
Particle size distribution	Particle numbers within 13 size bands (0.3, 0.4, 0.5, 0.65, 0.8, 1, 1.6, 2, 3, 4, 5, 7.5, 10 μm).	Outdoors – building roof. Indoors – on Floor 1.	5-minute averages, twelve times per hour.
Temperature	Air temperature (ºC)	Outdoors – building roof. Indoors – all sampling locations.	5-minute averages, twelve times per hour.
Relative humidity	Relative humidity (%)	Outdoors – roof. Indoors – one location on each floor.	5-minute averages, twelve times per hour.
Ventilation – general	Ventilation rate in each monitored area.	Indoors – all locations where air pollutants monitored.	2-week averages
Ventilation – inter-zonal	Air movement between zones	Indoors – all locations where air pollutants monitored.	2-week averages
Meteorological data	Wind speed and direction	Building roof.	Measurements taken every 30 seconds.
Door and window opening	Door and window opening	Some doors & windows (16 in total) on both Floors 1 and 3.	5-minute averages, twelve times per hour. 2-week periods.
Building airtightness (1)	Overall air leakage rate	Whole building.	Single measurement
Building airtightness (2)	Air leakage rates through window areas, internal and external doors	At a number of locations on Floors 1 and 3.	Single measurements

*NO is relatively unreactive in the indoor environment when little ozone is present.

Figure 2 gives floor plans of the monitored building showing indoor-outdoor pairs of sampling locations in red for (a) Floor 1 and b) Floor 3 (from Kukadia et al., 2011).

Concentrations of nitric oxide (NO), nitrogen dioxide (NO_2) and carbon monoxide (CO) were measured at a number of sites both externally and internally in matched pairs, on two floors (Floors 1 and 3) of the building using multi-point samplers operating sequentially around the building. This also gave the vertical and lateral variations of pollutant concentrations. PM_{10}

particle mass fraction and particle size distributions were measured at one internal site and one external site only.

In addition, a number of building characteristics and environmental parameters were monitored including: ventilation rates; inter-zonal airflows; building air-tightness; air-leakage of components; local wind speeds and directions; relative humidity; temperature and human activity.

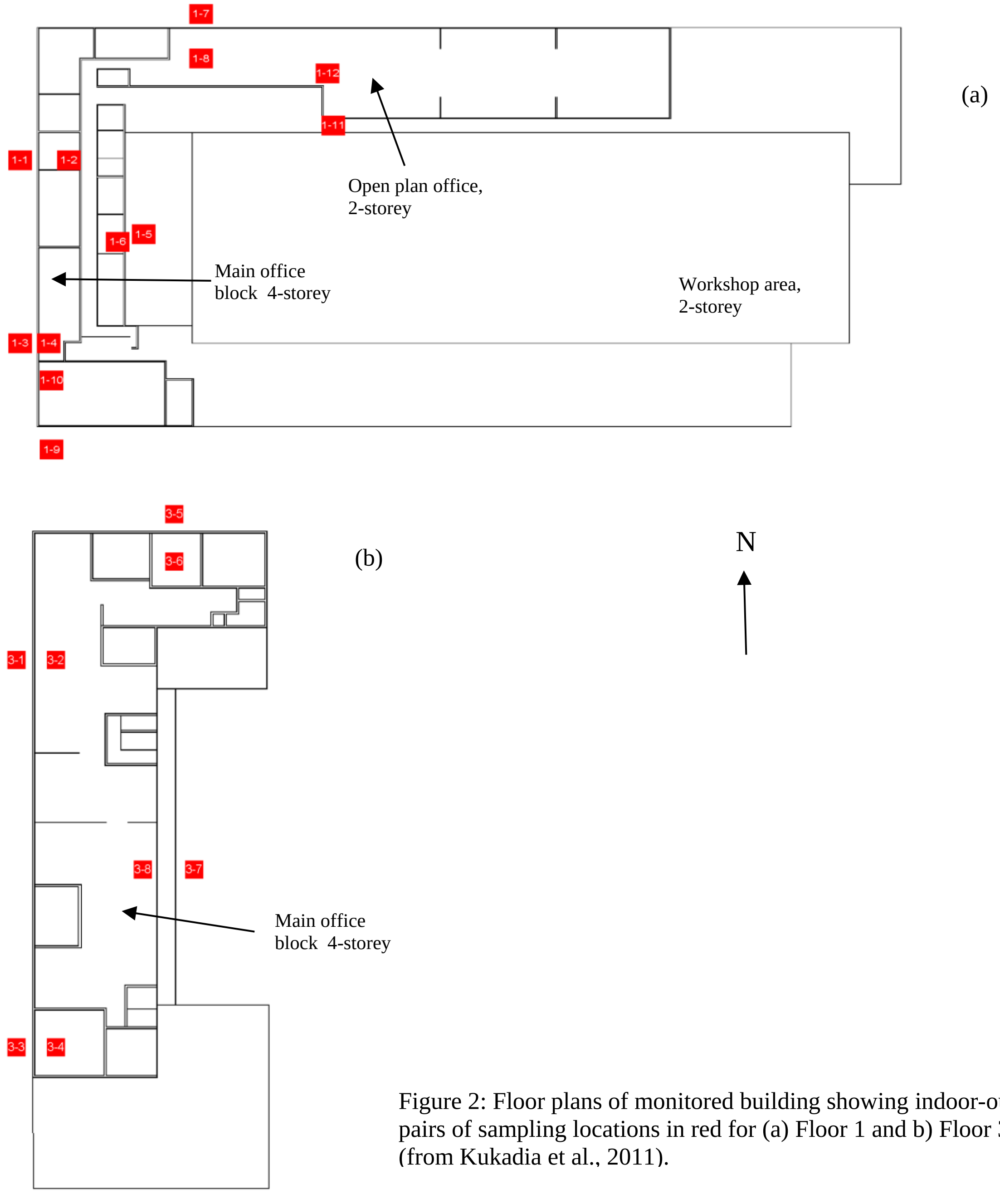

Figure 2: Floor plans of monitored building showing indoor-outdoor pairs of sampling locations in red for (a) Floor 1 and b) Floor 3 (from Kukadia et al., 2011).

3 RESULTS

Figure 3 from BRE Study A (taken from Kukadia et al., 2011), shows that pollutant concentrations measured outdoors fluctuated rapidly and were generally higher than those measured indoors, although the latter followed the outdoor pollutant trends with some damping and a time-lag. Rapid decreases in outdoor concentrations often resulted in indoor concentrations that were higher than those outdoors due to this time-lag. For indoor concentrations, the high peaks in the external concentrations were attenuated by the building fabric and the transient peak concentrations measured externally reduced. This indicates the ability of the building to reduce short-term exposure to peaks in external pollutant levels.

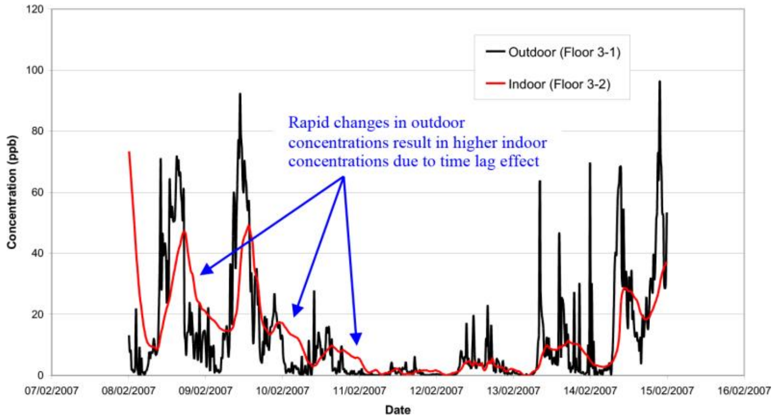

Figure 3: Indoor and outdoor NO concentrations (from Kukadia et al., 2011).

For most of the time, due to the distance of the building from major pollutant sources, the different sides of the building recorded near-uniform pollutant concentrations.

However, during one weekend, the parking area immediately outside of the west façade of the building (shown in Figure 1(a)) was used as a location for lorries, vans and a mobile electricity generator. This resulted in pollutants from the diesel-engine exhausts being emitted very close to the building (typically within ~5 m). Exhaust emissions from diesel engines contain a large proportion of NO and, as a result, during this time high concentrations were measured at the west façade. As these emissions were very close to the building, compared with normal traffic sources, it was also possible during this time to see differences in the measured concentrations at the different façades of the monitored building.

Figure 4 shows the concentrations of NO measured at the key pairs of outdoor and indoor sampling locations at the building. It also contains the wind direction data for this period (shown as both 30-second and 1-hour averages).

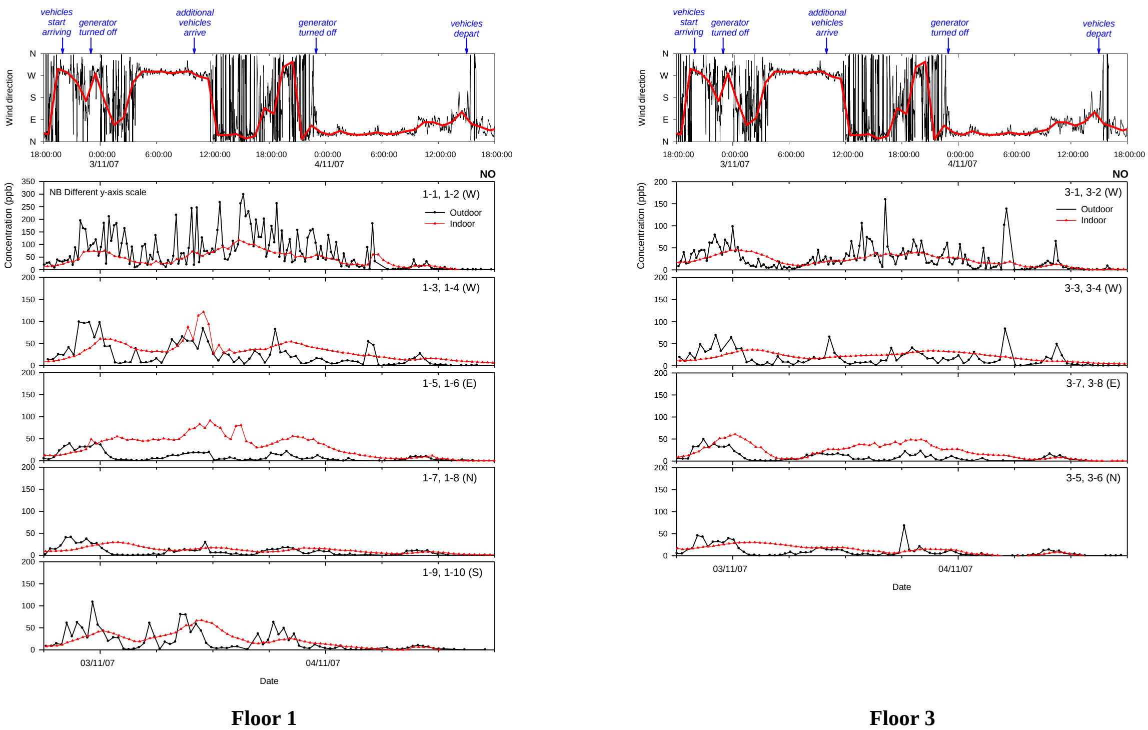

Figure 4: Wind direction and variation in NO concentrations on building facades (short-range local source).

The following characteristics can be seen for outdoor NO concentrations (black lines) and indoor NO concentrations (red lines).

- **West side, Floor 1 (Sampling locations 1-1, 1-2):** These were the nearest sampling locations to the vehicles located in the parking area during this period. Relatively high outdoor concentrations of NO that fluctuated significantly with time were monitored (note: increased y-axis scale for 1-1, 1-2). Indoor NO concentrations followed those outdoors quite closely.

- **West side, Floor 3 (Sampling locations 3-1, 3-2):** These were near to the source location, but higher up the building. Again relatively high outdoor concentrations of NO were recorded that fluctuated with time. Indoor NO concentrations followed those outdoors but with reduced response times.

- **West side, Floors 1 and 3 (Sampling locations 1-3, 1-4, 3-3, 3-4):** These sampling locations were on the same façade as sampling locations 1-1, 1-2, 3-1 and 3-2 and the pollutant source location, but situated laterally across the building towards the South side and hence away from the local source. Although outdoor sampling locations (1-3 and 3-3) showed elevated concentrations of NO, they were generally lower with less fluctuations than those recorded at locations 1.1 and 3.1. Indoor NO concentrations again broadly followed those outdoors, but with reduced response times.

- **East side, Floor 1 (Sampling locations 1-5 and 1-6):** For much of the time the indoor concentrations on the east side were higher than those outdoors. It is likely that this resulted from internal flows within the building, generated by the predominantly westerly wind at the time, driving the ingress of NO at the west façade, followed by inter-zonal airflow inside the building across to the indoor location at the east side of the building (Sampling Location 1-6).

- **North and South sides of the building:** The south façade seems to have followed the elevated external concentrations of the west façade to some extent. The north façade generally did not seem to have been affected by the emissions close to the west façade.

Figure 5 (from Kukadia and Palmer, 1998, BRE Study B), shows similar results to those of BRE Study A for NO_2 concentrations measured inside offices in a naturally-ventilated and a mechanically-ventilated building located adjacent to each other on a major busy road in Birmingham.

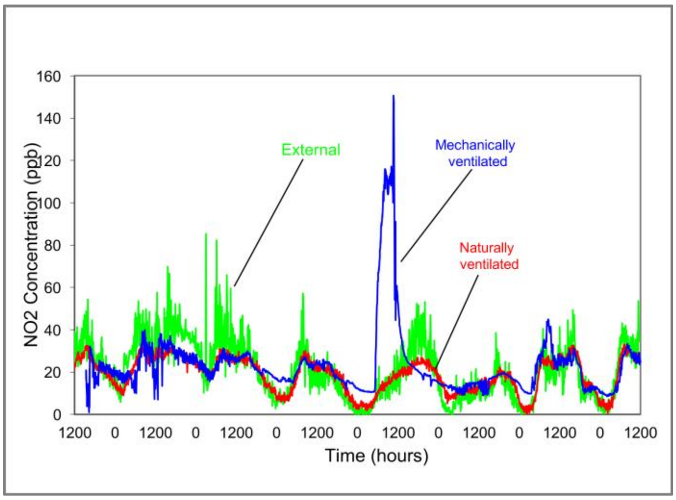

Figure 5: Nitrogen dioxide concentrations in adjacent mechanically and naturally ventilated buildings located on a major road in Birmingham, UK (from Kukadia and Palmer, 1998).

Traffic was the major ground-level source of NO_2. External concentrations of NO_2 were higher than internal concentrations, with the latter following the outdoor pollutant trends. The high concentration peaks in the outdoor environment were not seen in the indoor environment, again indicating the ability of a building to attenuate external pollutants.

The most prominent feature of the data is the exceptionally high level of NO_2 concentrations in the mechanically-ventilated building on one morning from about 06:00 to 12:30, coincident with the period between the start-up and shut-down of the building's ventilation system. The most likely cause was roof-level discharges from boiler plant being drawn into the roof-level ventilation inlet to the mechanically-ventilated building. This finding shows the importance of locating ventilation inlets away from high-level pollutant sources.

In the mechanically-ventilated building, the mean ventilation rate was 1.2 ach^{-1} (air changes per hour) and varied little whilst the system was operating. The ventilation rate in the naturally-ventilated building was 1.6 ach^{-1} and more variable and was dependent upon the occupants opening windows and weather conditions. Over the period of the tests, wind speeds were recorded at the nearby meteorological site as being higher than normal, ranging from 5 ms^{-1} to 10 ms^{-1} with gusts of about three times the mean wind speed.

Figure 6 (BRE Study C) shows an example of indoor and outdoor concentrations of carbon monoxide (CO) levels monitored in a naturally-ventilated building in London. The façade facing the roadside was mostly sealed and had unopenable windows. Ventilation air was drawn in from the courtyard side which was located away from the road and hence less polluted, and ducted through to the offices located towards the roadside.

Measurements of indoor concentrations were made in four offices, whilst outdoor concentrations were measured at one point at the roadside. All four offices showed similar concentrations since they shared a common air intake from the courtyard side of the building. Low external carbon monoxide levels over the weekend period indicate little vehicular activity in comparison with the working week.

Comparison of indoor and outdoor concentrations showed that the high levels measured at the roadside were reduced and did not occur inside any of the offices. In particular, the high peak of about 12 ppm seen on the roadside (due to a bus idling at a bus stop) was not seen in the roadside offices. This indicated that there was little pollutant infiltration through the fabric of the building and that placing ventilation inlets away from the source was effective in reducing pollutant ingress.

It is clear that for this building, by using supply air from the courtyard side, the high concentration peaks of CO (12 ppm) in the outdoor environment were avoided, leading to CO concentrations with a mean of about 0.4 ppm inside the building.

During the monitoring period (in winter) air change rates of between 1 and 2 ach^{-1} were measured in the offices.

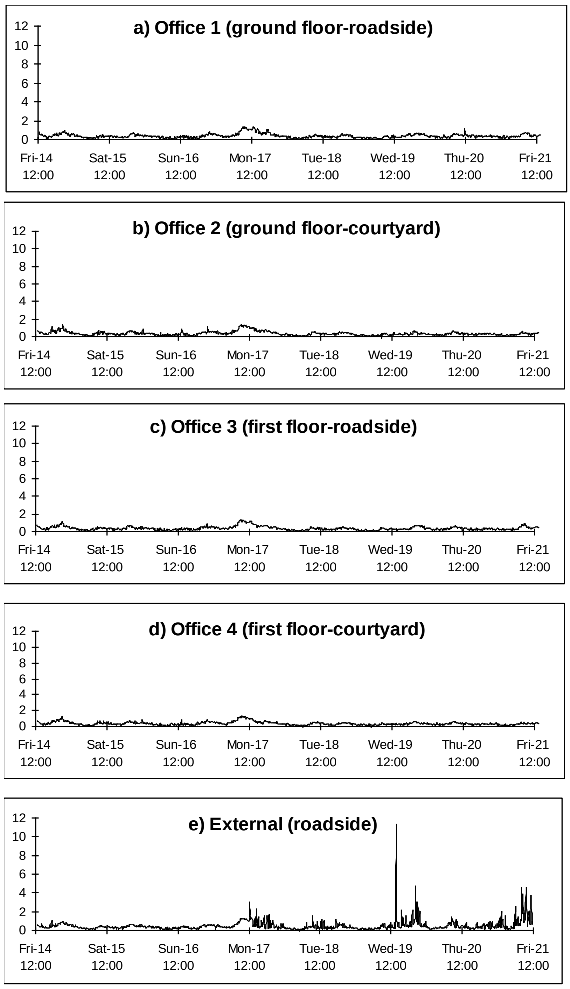

Figure 6: Carbon monoxide concentrations in a naturally ventilated building, London, UK (from Kukadia et al. 1999).

Returning to BRE Study A, Figures 7 and 8 (from Kukadia et al. 2011), show the variation of indoor to outdoor pollutant concentration ratios (R_{IO}) with the type of pollutant monitored and the seasonal ventilation characteristics of the building. The major variations occurred primarily from occupants opening windows in the summer and markedly altering the ventilation rate, thereby increasing pollutant ingress.

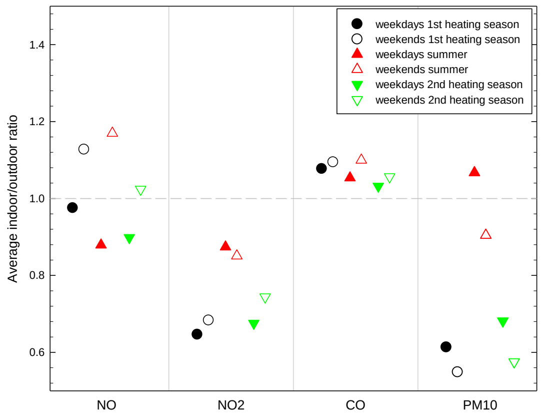

Figure 7: Seasonal averages of indoor to outdoor concentration ratios (R_{IO}) for gaseous pollutants and PM_{10} mass fraction (from Kukadia et al. 2011).

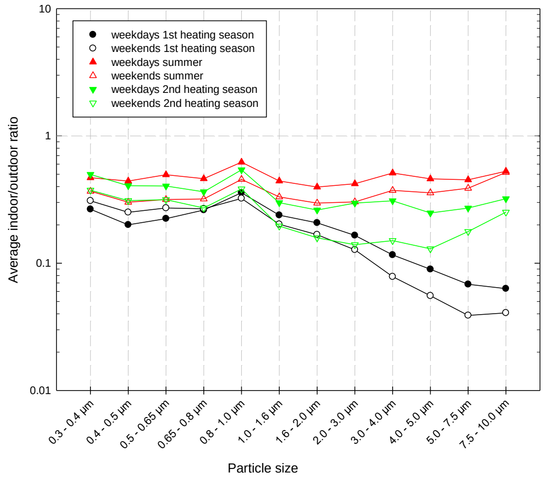

Figure 8: Seasonal averages of indoor to outdoor concentration ratios (R_{IO}) for particle size bands (from Kukadia et al. 2011).

- For gases of low chemical reactivity (NO and CO), although there were short-term differences between the outdoor and indoor concentrations arising from the building time-lag, the indoor concentration usually retained a long-term mean equilibrium with the outdoor concentration, $R_{IO} = 1$ (Figure 7).
- The chemically reactive gas (NO_2), gave $R_{IO} < 1$, primarily due to its deposition to surfaces, and the ratio varied with the ventilation rate and ventilation pathways. For example, during the heating seasons, with windows closed, $R_{IO} = 0.65$, while during the summer, with windows open during the working day, $R_{IO} = 0.85$ (Figure 7).
- Figure 8 shows that for particle measurements indoors, both the PM_{10} mass-fraction and particle size distributions were affected by the presence and activities of the building occupants. These effects were greater for larger particle sizes (>3 µm), which were rarely present indoors when the building was unoccupied. The attenuation of particles passing from outside to inside was noticeable, due mainly to losses in transit through the building fabric, and varied with the particle size.
- Measurements when rooms were unoccupied with windows closed provided the most reliable information on indoor to outdoor ratios as follows.
    - Based on the PM_{10} mass fraction, $R_{IO} \approx 0.60$.
    - Based on particle number concentration:
        - For particles 0.3 µm to 1 µm, $R_{IO} \approx 0.20$ to 0.30.
        - For particles 1 µm to 3 µm, $R_{IO} \approx 0.15$ to 0.30.
        - For particles >3 µm, $R_{IO} \approx 0.05$ to 0.10.

Figure 9 shows graphs of indoor to outdoor concentration ratios (left y-axis) and ventilation rates (right y-axis) against time. Ventilation rates were generally between approximately 0.3 and 1 ach^{-1} over the year. Opening windows in the summer, effectively altering the air permeability of the building envelope, had a greater effect on ventilation, and thus pollutant ingress, than variations in ventilation driving forces due to internal and external temperature differences (buoyancy) and wind-induced pressure differences.

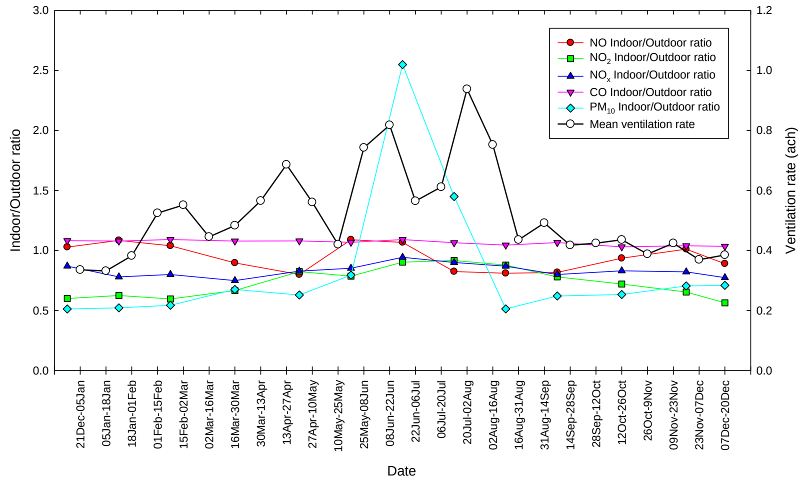

Figure 9: Two-week means of indoor:outdoor concentration ratios and ventilation rates over the monitoring period (from Kukadia et al. 2011).

Ventilation rates varied with types of room and their use, with closed rooms having much lower rates as expected. Further, during June indoor concentrations of PM_{10} were higher than those outdoors. This was related to the activities of new staff now working in the room which had previously only housed the monitoring equipment.

4 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be made from the studies reported here.

1. Since people spend typically 90% or more of their time indoors, there is greater concern over human exposure to air pollution indoors and its adverse effect on health, comfort, well-being and productivity. The demand for buildings with good indoor air quality is increasing as people become more aware of the likely effect of air pollution on their health. Thus, air quality is becoming an important issue, both in terms of outdoor air and indoor air quality.

2. In all the buildings monitored in the studies discussed here, the peak concentrations of the external pollutants were attenuated by the building fabric and the transient peak concentrations measured externally reduced considerably as a result. This indicates the ability of the fabric of the building to reduce the ingress of outdoor pollutants.

3. Concentrations of pollutants from sources far from the building monitored resulted in greater pollutant dispersion before reaching the building. This, in turn, resulted in the building being enveloped in relatively uniform pollutant concentrations. Therefore, the results showed minimal variation of pollutant concentrations both vertically and laterally.

4. The possibility of drawing combustion products into buildings from local short-range pollutant sources at ground-level (such as diesel-engined vehicles and generators) and

roof-level (such as boiler flues) has been shown. The findings highlight the real danger of cross-contamination between ventilation exhausts and intakes at roof-level and contamination from other sources.

5. Placing air intakes away from pollutant sources such as in courtyards can be successful in providing a greater damping effect of the high concentration peaks that occur in the outdoor air.

6. Knowledge in the area of the effect of outdoor air pollution and ventilation on IAQ is now increasing through research. However, there is still a lack of detailed information on, and hence understanding of, how outdoor pollutants impact on different types of buildings in urban areas, the ingress characteristics of the building fabric and ventilation requirements, and hence the effects on IAQ.

7. It is therefore important that further, in-depth studies are carried out to investigate a greater range of building types, and also ventilation systems and designs. This will promote a greater understanding of the area, and, in turn, will enable effective industry guidance to be developed to provide improved IAQ in buildings of all types.

5 ACKNOWLEDGEMENTS

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