AIR POLLUTION LEVELS IN AIR-CONDITIONED AND NATURALLY VENTILATED MUSEUMS: A PILOT STUDY

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Abstract

An air-conditioned and a naturally ventilated museum in a highly polluted part of London were compared for effectiveness of pollution control. Nitrogen dioxide, sulphur dioxide and hydrogen sulphide concentrations were measured inside and outside using diffusion tubes. Airborne particles were measured using a Grimm laser counting device. It was found that the benefits normally attributed to air-conditioning with filtration were not as great as might be thought. Only nitrogen dioxide and particle levels were significantly lower in the air-conditioned museum than in the naturally ventilated museum.

Keywords: preventive conservation, pollution, particles, natural ventilation, air-conditioning

Introduction

There is an accumulating body of evidence that, from the conservation standpoint, relative humidity and temperature conditions in air-conditioned buildings are no better, and may in some cases be worse, than those achievable in naturally ventilated buildings (Oreszczyn et al. 1994). However, little is known in museums about the comparative behaviour of other important environmental parameters, namely pollutants and particles, under these different ventilation methods.

This study is a pilot investigation of these issues, the aim being to determine the effectiveness of pollution control in an air-conditioned and a naturally ventilated museum building in a polluted urban environment. The air-conditioned Museum of London and the naturally ventilated National Museum of Childhood at Bethnal Green, also in London, were monitored for nitrogen dioxide, sulphur dioxide and hydrogen sulphide. These gaseous pollutants were selected because they had been identified as causes of object deterioration (Brimblecombe 1990) and were suitable for passive monitoring. Particle concentrations and fresh air ventilation rates were measured at the same time as the gaseous pollutants. Monitoring was carried out at internal and external locations so that indoor/outdoor ratios could be calculated. The aim was to obtain a snapshot of the effects of different ventilation regimes on gaseous and particulate pollution.

Measurement Methods

Concentrations of nitrogen dioxide, sulphur dioxide and hydrogen sulphide were measured using diffusion tubes. These passive samplers contain a pollutant-specific chemical reagent which reacts with the pollutant to form a non-volatile compound that can later be analysed quantitatively in the laboratory. Diffusion tubes were exposed in triplicate sets at locations at each museum, for one month. The diffusion tube methods used have all been described in the literature. See for example, Shooter (1993), Hargreaves et al. (1991) and Shooter et al. (1995).

A Grimm particle counter was used to measure airborne particles. This uses a laser scattering technique to monitor the mass of particles in the size range 0.75–15µm, per cubic metre of air. In still air particles >15µm settle out whereas smaller particles can remain indefinitely suspended until they deposit on a surface. Particles in the range 0.1–2µm are normally considered the most important for museums (Thomson 1986), as this range normally contains the combustion-related particles which include sulphates and nitrates. This type of laser scattering technique is not generally considered accurate for absolute measurements of particle mass. However it is reliable, the equipment is portable and relatively unobtrusive, and so it is ideal for taking measurements to compare one location with another.

Measurements of the fresh air ventilation rate were carried out using the tracer gas technique (Liddament 1996). Sulphur hexafluoride, an inert gas not normally present in the atmosphere, was released into the museum air and its decay sampled at several locations.

Museum of London monitoring and results

Gaseous pollution monitoring tubes were exposed at ten locations, between February and March 1997, with a subsequent batch of tubes (at the external air intake of the air-conditioning system and by the roadside) exposed between March and April 1997. Particle measurements were taken over three days in May 1997 at internal and external locations where gaseous pollutant measurements had previously been carried out. The locations are marked on the site map (Fig. 1).

Gaseous pollution

At the Museum of London there was an average external nitrogen dioxide concentration of 31ppb (Table 1), typical of a highly polluted urban location. The highest individual value, 37ppb, was measured at the roadside, closest to vehicle traffic which is the principal source of nitrogen dioxide in urban areas. Inside the museum the average concentration was 6ppb, only 19% of the average external concentration. Sulphur dioxide concentrations also showed a large decrease from 8ppb externally to 1ppb internally, which was also only 19% of the external concentration. In contrast to the behaviour of these two gases, hydrogen sulphide occurred at much more widely varying concentrations within the museum (ranging between 41 and 111ppt), and on average the internal concentration of hydrogen sulphide was slightly greater than the external.

Particles

High external particle concentrations, comparable with those measured by the Government's tapered element oscillating microbalance (TEOM) monitor in central London, were found outside the Museum of London (Fig. 3). These appeared to correlate with traffic activity around the Museum. Concentrations began to rise in the early morning rush-hour period from 07.00 onwards. A steady concentration was maintained through the morning, rising in the afternoon to a peak level of around $100\mu gm^{-3}$ between the hours of 17.00 and 19.00. By 20.00 hours concentrations had fallen off considerably, and then declined further to a background level of less than $25\mu gm^{-3}$ which was maintained until the following morning.

Whilst external particle concentrations seemed closely associated with traffic levels, inside the Museum of London (Fig. 4) they seemed to depend more on the number of visitors and the level of human activity. In the early morning, from 04.00 to 07.00 the internal particle concentration was below $10\mu gm^{-3}$. As daytime employees started arriving for work, and the Museum was cleaned prior to opening, concentrations began to rise. There was a sharp rise just after 10.00, when the Museum opened to the public and concentrations picked up quite rapidly from then to around $40\mu gm^{-3}$. Between 14.00 and 16.00 concentrations were at their highest, with a maximum of $84\mu gm^{-3}$ between these hours. From 16.00 levels fell slowly until 18.00, after which time there was a rapid decrease to less than $10\mu gm^{-3}$. Thus, the internal particle concentration had already reached a low level whilst the external concentration was still quite high. Although data were not collected in the Museum between 19.00 and 04.00 because of a power failure, it seems likely that the concentration remained below $10\mu gm^{-3}$ throughout this period, when there was minimal activity in the Museum.

This air-conditioned museum had a measured fresh air ventilation rate of 1.3 air changes per hour (ach^{-1}). However, as approximately 80% of the air is recirculated, the overall ventilation rate was probably close to $6.5ach^{-1}$. This means that there was considerable air movement within the galleries and that this quantity of mixed fresh and recirculated air passed through the filters. The level of fresh air (20%) is considered to be high for such a large building which may be good in terms of dissipating pollutants generated by the visitors but results in high energy consumption. Given the age of the services at the Museum of London, the system is considered to be a well-maintained and well-run system, which incorporates both high specification particle and gaseous filtration.

Bethnal Green Museum monitoring and results

Pollution monitoring tubes were exposed at seven locations, between March and April 1997. Particle measurements were taken over three days in May 1997 at internal and external locations where gaseous pollutant measurements had previously been carried out. The locations are marked on the site map (Fig. 2).

Gaseous pollution

The Bethnal Green Museum is located 3km east of the Museum of London, in a similarly urban and highly-polluted environment. The average monitored external nitrogen dioxide concentration at the Bethnal Green Museum was 27ppb (Table 2). This only decreased slightly inside the building to an average value of 23ppb, representing 84% of the external concentration. External sulphur dioxide was higher at this site than the Museum of London, with an average level of 23ppb. However, this showed a pronounced decrease inside the museum where the average concentration was only 4ppb, representing 16% of the external concentration. No hydrogen sulphide was detected at this museum.

Particles

External levels of particles were again high during the day (Fig. 5) and remained at a steady level throughout the day. The working day average concentration was 62μgm^{-3}, compared with 53μgm^{-3} at the Museum of London. Because data were only collected during the daytime, it was not possible to say with certainty that external particle concentrations correlated with diurnal traffic flow, though given the similarity of the external environment to that of the Museum of London, this seems probable.

Inside the Bethnal Green Museum (Fig. 6), it appeared that particle concentrations could again be correlated with visitor numbers. Concentrations began to rise sharply after the Museum opened at 10.00, and reached a peak of 303μgm^{-3} between 14.00 and 16.00, declining gradually thereafter. There was no evidence of a similar peak on the previous day, a Friday (time 1741, at the very beginning of the graph), when the Museum was closed to the public. This confirmed the view that particles in the Museum happened to correlate with visitor numbers.

The Bethnal Green Museum air exchange rate measured 0.3ach^{-1}. This is a low level of ventilation for a domestic-scale, old, naturally ventilated building. However, the measurements were taken when the windspeed was low and there was little temperature difference between outside and inside. This would result in the ventilation rate being close to its lowest value. The actual ventilation rate during the gaseous pollution monitoring may have been higher because there was a greater temperature difference between inside and outside and possibly higher wind speed. These factors tend to increase the ventilation rate, especially in a naturally ventilated building. Ideally, several air exchange measurements would have been made under a variety of temperature and wind conditions, to determine the range of the air change rates that occur in this Museum.

Discussion

One of the most notable aspects of this study was the difference in nitrogen dioxide concentrations inside the two museums. At the Bethnal Green Museum the average internal concentration was 84% of the external concentration. This result is typical of naturally ventilated museum buildings (see e.g. Blades 1995). At the Museum of London the average internal nitrogen dioxide concentration was only 19% of the external concentration, indicating that the museum's air-conditioning and filtration system was effective at removing nitrogen dioxide.

The sulphur dioxide concentration at the Bethnal Green Museum followed a typical pattern for a naturally ventilated building, in that the high external concentration fell rapidly as measurements were taken further into the interior of the building. This is thought to occur because sulphur dioxide is more reactive than nitrogen dioxide, more readily reacting with surfaces such as interior walls and floors, and objects on open display. So, the further into the interior the gas penetrates, the more opportunity it has to react with a surface, and hence the lowest concentrations should occur at the heart of the building. This is apparent from the Bethnal Green Museum data, where the highest internal value occurs close to the main entrance, with reduced concentration at the far end of the gallery and in store room 24. At the Museum of London there is a similar pattern of high sulphur dioxide externally and very low values of about 1ppb internally.

Although the absolute levels of sulphur dioxide were higher at Bethnal Green Museum (around 25ppb), compared with those at the Museum of London (around 8ppb), there was very little difference in the internal/external ratios, which were 16% and 14%, respectively. While it is possible to attribute the Museum of London's reduction in concentration to the air-conditioning system, this is only of the same order as that achieved by the building fabric and reduced air exchange rate at the Bethnal Green Museum. Studies of other similar naturally ventilated museums have found internal sulphur dioxide values at 20-40% of the external (Leissner et al. 1997).

Whereas nitrogen dioxide and sulphur dioxide have mainly external sources, such as motor vehicle emissions and fossil fuel combustion respectively, hydrogen sulphide can originate from a wider range of sources, external and internal, such as motor vehicles, standing water, decay of biological matter and other biological processes, construction and decorative materials. This fact is reflected in the behaviour of hydrogen sulphide measured at the Museum of London. In contrast to the fairly uniform nitrogen dioxide and sulphur dioxide concentrations in the gallery, hydrogen sulphide occurred at varying concentrations throughout the galleries, suggesting that indoor point sources for the gas were important. The average internal hydrogen sulphide concentration exceeded the external concentration, indicating that the air-conditioning and filtration system is not effective at reducing the hydrogen sulphide concentration to below the external level, despite both fresh and recirculated air being passed through activated carbon filters.

High concentrations of external particles were measured at both museums, with daytime averages of $53\mu gm^{-3}$ at the Museum of London and $62\mu gm^{-3}$ at the Bethnal Green Museum (Table 3). It was apparent that the Museum of London's air-conditioning and filtration system was effective at reducing internal particle levels: the daytime internal concentration was $29\mu gm^{-3}$, which was 55% of the external value. The particle size distribution inside the Museum of London was different from that outside, with a lesser proportion of small particles and a higher proportion of large particles. The air-conditioning's filtration system may be less effective at removing larger particles because these tend to be generated locally, rather than carried in with external air (Weschler et al. 1996). At the Bethnal Green Museum the average daytime internal particle concentration ($93\mu gm^{-3}$) was 1.5 times greater than the external concentration, and the ratio of small to large particles was approximately the same inside and outside the Museum. In both museums, once the visitors had departed, the particle levels fell back rapidly to overnight concentrations of less than $10\mu gm^{-3}$.

Conclusion

The Bethnal Green Museum is a well sealed naturally ventilated building, with a low air exchange rate of $0.3ach^{-1}$, albeit measured under conditions favouring low values. The Museum of London has a well-maintained and well-operated air-conditioning system incorporating both chemical and particle filtration, producing a fresh air exchange rate of $1.3ach^{-1}$, which is high for an air-conditioned building. It would be reasonable therefore, to consider both buildings as good examples of their respective type, that is, producing the most favourable conditions for pollutant removal.

What then were the relative merits of their different ventilation regimes, from the point of view of pollution control?

Both museums in this study are located in one of the most highly polluted areas of the United Kingdom. Yet, it is apparent that the benefits of the air-conditioning/filtration system were not as great as might have previously been thought. The main pollution benefit of air-conditioning system with carbon filtration was in the reduction in nitrogen dioxide concentrations. The limit suggested by Thomson (1986) of $10\mu gm^{-3}$ (5ppb) for this pollutant was not exceeded at the Museum of London, but was exceeded at the Bethnal Green Museum. Damage effects attributed to nitrogen dioxide include decolourisation of pigments (Whitmore and Cass 1989), weakening of textiles and synergistic effects with metal tarnishing-pollutants (Brimblecombe 1990, Fiaud and Guinement 1986). However, with the exception of large metal objects and large textiles, these objects are likely to be displayed in cases which are known to achieve large reductions in external pollutant concentration (Leissner et al. 1997), usually below the Thomson limit. It should be stated that whilst this limit is a useful guide, as yet there is no international agreement as to what level of pollutant would constitute an acceptable level of damage.

Thomson (1986) also suggests a limit of $10\mu gm^{-3}$ (4ppb) for sulphur dioxide. The Museum of London's internal locations all had values well below this level. However, this standard was also achieved at three of the four internal locations at the Bethnal Green Museum, the exception being the location closest to the main entrance. This suggests that from the point of view of reducing sulphur dioxide concentrations, the Museum of London's air-conditioning system did not represent a significant advantage. It is true that inside the Bethnal Green Museum some sulphur dioxide deposition will take place on object surfaces, but the surface area of objects on open display represents only a small fraction of the total interior surface area, and so only a small fraction of internal sulphur dioxide will be deposited on museum objects.

Hydrogen sulphide did not appear to be controlled by the filtration system at all. Theoretically, carbon filters should be able to trap hydrogen sulphide, but they may fail to do so for a number of reasons. The measured ambient hydrogen sulphide concentrations, although able to tarnish metals, were all extremely low - in the parts per trillion range - some 100 times lower, than the nitrogen dioxide and sulphur dioxide concentrations. It may be difficult to design a filter that is efficient at removing such a low concentration from the large volumes of air that are being filtered. Even if this was achieved, gallery air-conditioning may not solve the problem of sulphide tarnish which is frequently caused by hydrogen sulphide emissions from inside display cases.

These conclusions are further substantiated by comparing the monitored results from this study with a similar study of internal/external pollutant levels measured in a naturally ventilated office and air-conditioned office without carbon filtration (Kukadia and Palmer 1996). The naturally ventilated building in this study has lower sulphur dioxide and nitrogen dioxide levels than Kukadia (Table 4) because of the lower ventilation rate. For gases which are less reactive such as nitrogen dioxide, ventilation rate has a smaller impact. The data from the office study and from this study, show less reduction in sulphur dioxide, in the building without recirculation or filtration. An even greater impact can be seen with nitrogen dioxide where the conventional air-conditioned office building with no recirculation or carbon filtration reduces the external pollution concentration by only 20% whereas recirculation plus carbon filtration in the museum reduces the external concentration by 60%.

The Museum of London's filtration system reduced particle concentrations significantly. The air-conditioned building was able to mitigate short-term peaks in particles much better than the naturally ventilated building. However, at both museums particle concentrations declined quickly once the visitors had departed. This may have implications for the management of public areas in museums. Storage areas and less visited parts of the building may maintain low particle concentrations without air-conditioning, whatever the external environment. It may be possible to develop strategies that reduce particle concentrations by changing cleaning regimes and using floor surfaces or coverings that do not retain dust.

As a results of this pilot study, further research is under way to verify and expand on these conclusions. A wider sample of museum buildings are being studied, ozone will be monitored, and controlled interventions carried out in an attempt to improve pollution control in naturally ventilated and air-conditioned museums.

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Figure Captions

Figure 1. Sampler Locations at the Museum of London: (14) Eighteenth Century Gallery, (6) Prehistoric Gallery, (12) Stuart Gallery, (11) Tudor Gallery, (A) External, by entrance, (B) External, roadside, (C) External, a/c intake. Map reproduced by kind permission of the Museum of London.

Figure 2. Sampler locations at the Bethnal Green Museum: (A) Store Room 24, (B) Main Gallery upper floor, (C) Main Gallery far end, (D) Main Gallery by front entrance, (E) External, south side, (F) External, east end, (G) external, north side. Map reproduced by kind permission of the Bethnal Green Museum.

Figure 3. External particle concentrations at the Museum of London, 28-29 May 1997.

Figure 4. Internal particle concentrations at the Museum of London, 27-28 May 1997.

Figure 5. External particle concentrations at the Bethnal Green Museum, 30 May 1997.

Figure 6. Internal particle concentrations at the Bethnal Green Museum, 30 May - 1 June 1997.

Table 1. Gaseous pollution measurements at the Museum of London, February - April 1997. Values are given as the mean result of three tubes exposed at each location. Detection limits (2-sigma) were NO_2 0.1ppb, SO_2 0.4ppb and H_2S 25ppt.

Location	Nitrogen dioxide (ppb)	Sulphur dioxide (ppb)	Hydrogen sulphide (ppt)
18th Century Gallery Ambient	6.2	1.4	41
Death and Burial Case			107
Pawnbrokers Shop Case 1 (with charcoal cloth)			37
Pawnbrokers Shop Case 2			84
Prehistoric Gallery Ambient	6.1	1.3	102
Prehistoric Gallery, Case T6 (vented)	1.8	<0.4	71
Prehistoric Gallery, Case T9 (unvented)	2.5	0.9	228
Stuart Gallery Ambient	5.2	0.6	111
Stuart Gallery Case 6	4.4	0.4	<25
Stuart Gallery Case 7 a	4.4	0.5	117
Stuart Gallery Case 7 b (near archaeological material)			250
Tudor Gallery Case T22			<25
External (under main entrance canopy)	27.9	8.8	86
External (roadside)	37.2	6.4	82
External (by air-conditioning intake)	26.7		< 25
Average indoor	5.8	1.1	85
Average outdoor	30.6	7.6	84
Average indoor concentration as % average outdoor	19	14	101

Table 2. Gaseous pollution measurements at the Bethnal Green Museum, March - April 1997. Values are given as the mean result of three tubes exposed at each location. Detection limits (2-sigma) were NO_2 0.1ppb, SO_2 0.4ppb and H_2S 25ppt, nd = not detected.

Location	Nitrogen dioxide (ppb)	Sulphur dioxide (ppb)	Hydrogen sulphide (ppt)
Store Room 24	19.8	2.5	nd
Main Gallery, upper floor, top of Sleep case	25.2	3.3	nd
Main Gallery, far end, top of Puppet Theatre	22.7	2.3	nd
Main Gallery by front entrance, above Dolls case	22.8	6.6	nd
External - East End	26.2	19.2	nd
External - South Side	28.6	26.3	nd
External - North Side	25.7	23.1	nd
Average indoor	22.6	3.7	
Average outdoor	26.8	22.9	
Average indoor concentration as % average outdoor	84	16	

Table 3. Summary of particle monitoring data.

Particle size range		Bethnal Green Museum Concentration (μgm^{-3})	Museum of London Concentration (μgm^{-3})
Data from daytime (9am-5pm) only:			
<3.5µm	Average indoor	8	2
	Average outdoor	6	13
>10µm	Average indoor	42	17
	Average outdoor	27	16
Total particles	Average indoor	93	29
	Average outdoor	62	53
All data:			
Total particles	Average indoor	26	12
	Average outdoor	62	41

Table 4. Average indoor concentrations as percentage of average outdoor concentrations for two different studies

Study	Ventilation method	Air exchanges per hour	Sulphur dioxide	Nitrogen dioxide
This study	Natural ventilation	0.3	16%	84%
Kukadia and Palmer	Natural ventilation	1.6	40%	90%
This study	a/c with recirculation and carbon filtration	1.3	14%	19%
Kukadia and Palmer	a/c with no recirculation or carbon filtration	1.2	40%	80%