THE ROLE OF AIR EXCHANGE RATE AND SURFACE REACTION RATES ON THE AIR QUALITY IN MUSEUM STORAGE BUILDINGS

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ABSTRACT

Museum storage buildings often have low air exchange rates. For such buildings, the indoor level of air pollution is primarily dependent on the air exchange rate, and the sorption capacity of indoor surfaces. This paper illustrates the effect of the air exchange and the sorption reactions, as well as mechanical ventilation with active filtration, by using data from pollution measurements in three Danish museum and archive buildings. Typically indoor ozone levels will increase when the air exchange rate increases, as ozone enters buildings from outside. Pollutants generated indoors, such as organic acids, will dilute in concentration as the air exchange rate increases. However, the source strength and the surface sorption capacity are dominating influences when the air exchange rate is below about 1 h^{-1}. Active filtration is an efficient method for pollution removal, especially by internal re-circulation units.

INTRODUCTION

Many museum storage facilities are located in buildings with little human activity; there are usually no permanent work places within the storage areas, and they are only visited when an object is picked up or delivered back. For the rest of the time the room or entire building is kept closed, which results in very stagnant conditions for the indoor environment. If the building lacks mechanical ventilation there can be very little exchange between the rooms and the ambient air. This will retard outdoor air from entering collection area, but will allow internally generated compounds to accumulate inside the rooms.

AIR POLLUTANTS AND MATERIAL DAMAGE

Gaseous air pollutants attack materials by chemical reactions: some by acid hydrolysis (e.g. acetic acid), and others by direct oxidation (e.g. ozone). The more pollutant that is available to be deposited on an object, the faster the reaction. Some pollutants acts in synergy, and also the interplay between pollutants and moisture is an important factor in deterioration processes such as hydrolysis. The main deterioration effect from particulates is soiling, which especially is a problem with the fine fraction (<1µm diameter). The key pollutants causing material damage include ozone, oxides of nitrogen, oxides of sulphur, reduced sulphur gases, organic acids, and fine particles. Ozone, nitrogen oxides, and sulphur oxides originate entirely from outdoor sources. Reduced sulphur gases may have both outdoor and indoor sources, whereas organic acids in any significant level are generated indoors. Fine particles may have sources both outdoors and indoors; however, their chemical content may differ. A general introduction to air pollution in museum environments is given, for example, in [1-4].

POLLUTION CONTROL IN BUILDINGS

The leakier a building is, the more air pollutants will infiltrate from outdoors. This is especially true for large, open-plan buildings, such as museum galleries. In such buildings the indoor level of outdoor-generated pollutants will typically be in the range of 30-80% of the outdoor concentration.

At the other extreme, indoor-generated pollutants are especially abundant in small, confined air volumes such as display cases, safes, and storage cabinets. With an almost airtight room made from polluting materials, the pollutants which are generated inside cannot escape and the concentration can reach a very high level. If it doesn't, there must be fast reaction with the stored treasures. Somewhere between the open gallery building and the display-case we have storage and archive buildings. Climate control for such buildings is focussed mainly on the relative humidity (RH); on avoiding extremes of dry or humid conditions, and minimizing the amplitude of RH variations.

Traditionally, climate control in buildings is carried out by mechanical means using heating, ventilation and air-conditioning systems. Such systems can be equipped with filters for gaseous and particulate pollution. However, recently there has been increased focus on passively climatized

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buildings, where the building materials and structure contribute temperature and humidity stability. To obtain the highest buffering effect, such buildings must be relatively airtight, which is fine for storage buildings without human comfort requirements (no need for a constant intake of "fresh" air). Such storage facilities can have an air exchange rate of 0.5 h^{-1} or less, driven by natural ventilation only. See for example [5] in this publication. However, what this means for the air quality is not clear, as so far only few investigations have been conducted in museum buildings with low air exchange rates.

This paper describes different factors which define the air quality inside museum storage buildings. Results from air quality monitoring in three Danish museum and archive buildings are used to illustrate this. This monitoring was carried out in storage rooms within the National Museum of Denmark, the Danish Museum for Photographic Art, and the Arnamagnæan Institute's archive at Copenhagen University. These locations were used for an investigation of different ventilation strategies for museum storage buildings, which will be published in full elsewhere [6]. More than 20 three-month monitoring campaigns were carried out at 11 locations within the three buildings. Some locations had two or more measurement periods following each other but under different ventilation conditions. The storage rooms ranged in volume between about 120 and 500 m^3, and most had low air exchange rates (<0.5 h^{-1}) although this was changed for some of the measuring periods. Most of the locations had no mechanical ventilation. The rooms were highly loaded with furniture and collection objects; typically the surface-to-volume ratio was about 4 m^2/m^3.

METHODS

Air pollutants were measured at all locations by passive sampling. Organic acids (formic + acetic) were sampled using a Palme's diffusion tube sampler system provided by Oxford Brookes University. Ozone was sampled using the Analyst diffusive sampler system, provided by the Italian Institute for Atmospheric Pollution CNR-IIA. The reported pollution concentrations, or the I/O ratios based on pollution measurements, are three month average values.

Particles were measured as the concentration of ultrafine particle in air (0.02-1 µm diameter) using a TSI P-Trak Particle Counter. The particle count was taken once per minute during a 6-8 hour period.

The air exchange rates were determined by measuring the concentration decay rate of a tracer gas (freon 134a) at one minute intervals during a one hour period, using a photo-acoustic sensor (Innova Multigas Monitor 1302).

Both indoor and outdoor conditions were measured at all sites. The indoor monitoring apparatus was set up near the centre of each room. The outdoor environment was monitored at the National Museum from a Stevenson Screen located on a lawn near the building, and for the two other buildings from roof-top weather stations.

INDOOR/OUTDOOR POLLUTION RELATIONS

Air pollutants from outdoors will infiltrate buildings through holes or cracks in the building envelope, through open windows, or via the ventilation system. During the infiltration process the pollutants will deposit on surfaces that the air flow passes, thus constantly reducing their concentration. Ozone is an example of a highly reactive compound, which normally will be much reduced indoors compared to outdoors. Typical indoor/outdoor ratios (I/O) for ozone are below about 0.3, although I/O ratios as high as 0.8 have been reported in museum buildings [7,8].

When such sorption reactions are the dominant pollution removal factor, then the steady-state I/O relation of ozone (and of other outdoor pollutants) can be described by the deposition mass balance [9]:

$$\frac{I}{O} = \frac{n}{n + v_d\left(\frac{S}{V}\right)} \tag{1}$$

Where:

I = indoor concentration of pollutant [ppb or μgm^{-3}]
O = outdoor concentration of pollutant [ppb or μgm^{-3}]
n = air exchange rate [h^{-1}]
v_d = deposition velocity [mh^{-1}]
S = inside surface area of room [m^2]
V = volume of room [m^3]

The surface removal rate $v_d(S/V)$ is a central factor of expression 1. This removal rate is defined as the deposition velocity of a pollutant times the surface-to-volume ratio of the room. The deposition velocity is defined as the flux of a pollutant to a surface

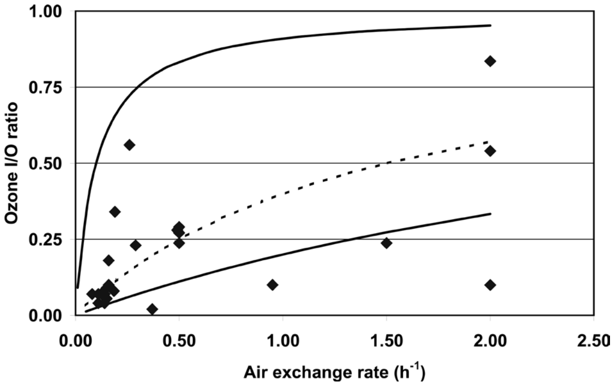

Figure 1. The indoor/outdoor ratio for ozone at different air exchange rates. The relation is modelled for three different environments: a highly reactive room with the ozone surface removal rate of 4 h^{-1} (low curve), a normal room with the ozone surface removal rate of 1.5 h^{-1} (dotted curve), and a slightly reactive room with the surface removal rate of 0.1 h^{-1} (upper curve). The data points represent measurements from real museum stores.

divided by its concentration in air, which gives it the unit of velocity. For highly reactive pollutants such as ozone, removal by surface reaction, rather than reaction in the air, is a significant part of the total pollution loss indoors. The surface removal rate is directly comparable to the air exchange rate: if, for example, a room has the surface removal rate of 1 h^{-1}, then pollutants will deposit on the indoor surfaces in a rate equal to what would be ventilated away at one air changes per hour.

Fig. 1 shows how the air exchange rate and the surface removal rate will influence the I/O ratio of ozone within a building, based on equation 1. A typical room with an ozone removal rate of 1.5 h^{-1} is illustrated by a broken line. The model lines are compared with 25 measurements from different museum stores. A few measurements falls outside the area defined by the model lines (which indicates normal indoor environments); however, these specific measurements are from locations where extra control measures such as air filters were installed. Fig. 1 shows that the most efficient way to retard outdoors pollutants from infiltration is a combination of a low air exchange rate and a high surface removal rate.

INDOOR POLLUTION GENERATION

For compounds which are released to the environment indoors, as emission from building materials and even the collection itself, the steady state concentration inside a building is dependent on both the air exchange rate, and the re-sorption onto the interior surfaces. In general; the higher the air exchange rate, the lower the concentration of indoor generated pollutants.

A mass balance similar to that of equation 1 can be expressed for indoor generated pollutants (assuming the outdoor concentration = 0):

$$I = \frac{\left(\frac{G}{V}\right)}{n + v_d\left(\frac{S}{V}\right)} \qquad (2)$$

Where: G = generation rate of pollutant [µg/h]

Fig. 2 shows how the air exchange rate and the surface removal rate will influence the indoor concentration of a pollutant which is generated inside a building (assuming a constant generation rate of pollutants).

A typical room with an organic acid removal rate of 0.5 h^{-1} is illustrated with the dotted line. The 16 data points represent measurements of organic acid concentrations (the sum of acetic and formic acid) from different museum stores. We see that both an increase in air exchange or in the surface removal rate will lower the pollution concentration, however, the surface removal rate is the dominant factor when the air exchanges is below about 1 h^{-1}, while at higher air exchanges it is mainly the air exchange rate which controls the pollution concentration. Note that internally generated pollution can have a much higher concentration within a porous object, such as a book, than in the free air space of the room,

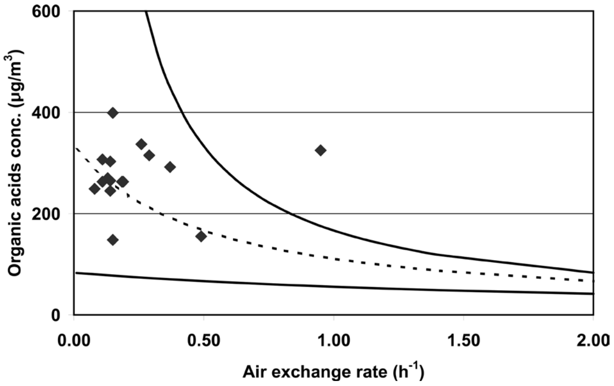

Figure 2. The concentration of organic acids (µg/m^3) at different air exchange rates, modelled for a 120 m^3 room. The internal emission of organic acids – emission from furniture, building materials, or the collection itself - is assumed constant at 20 mg/h. The relation is modelled for three different environments: a highly reactive room with the acid surface removal rate of 2 h^{-1} (low curve), a normal room with the acid surface removal rate of 0.5 h^{-1} (dotted curve), and a room with no surface removal at all (upper curve). For the latter model ventilation is the only removal mechanism. The single data points represent measurements from real museum stores similar to the model room.

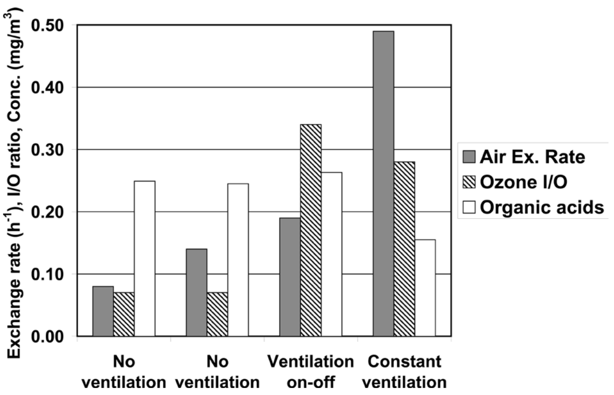

Figure 3. The air exchange (h^{-1}), ozone indoor/outdoor ratio, and organic acids concentration (mg/m^3) for four different monitoring periods at the Arnamagnæan Institute's archive with four different ventilation rates.

whereas pollution coming from outside will always have a higher concentration in the air space than in the pore spaces of the book.

The desire to keep a low air exchange rate for a building in order to maintain a stable indoor climate may conflict with the need to keep a clean air quality if emissive materials are present in the room. The use of 'passive sorption' where the air pollutants are re-sorbed onto walls will only work to the rate of 2, maybe 3 h^{-1}, for normal rooms. Instead an efficient way to further increase the rate of pollution removal is by the use of filter units, through which the room air is constantly re-circulated.

THE EFFECT OF AIR EXCHANGE

The relation between the rate of air exchange and pollution levels is illustrated in fig. 3, using measurements from the Arnamagnæan Institute's archive as an example. The trend for the ozone I/O ratio is that it increases when the air exchange increases. On the other hand; the internal generated organic acids were only significantly decreased in concentration when the ventilation was constantly on. For the organic acids it would have been expected that a more significant concentration decrease would take place as the air exchange rate increased. However, this is based on the assumption that the acid emission was constant over time, which it maybe in fact was not.

Also, particles do infiltrate buildings from outdoors, and are being reduced in concentration on their route indoors due to deposition on surfaces. Fig. 4 shows ultrafine particle measurements from a storage room during half a day. The indoor particle concentration followed the outdoor particle concentration closely, constantly keeping the I/O ratio at about 0.25. For this example the air exchange rate was about 1 h^{-1}, so according to equation 1 the surface removal rate for particles was then 3 h^{-1}.

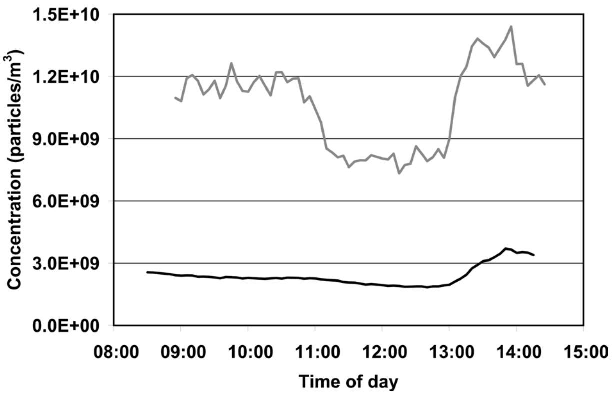

Figure 4. The concentration of ultrafine particles outdoors (grey upper curve) and inside a storage room (black low curve).

THE EFFECT OF SORPTION

As fig. 1 and 2 suggest, the amount of reactive surface available inside a room is one of the main means of pollution removal at low air exchange rates. It can, however, be difficult to add enough extra wall surfaces into a normal room without disturbing the original functions of the room, such as providing storage space for collection items. One way to get around this is to use ventilation filters, which are constructed so that they expose a large surface area within a relatively small volume. The air is forced to pass through the filter media by a mechanical fan, rather than by passively diffusing to the wall surfaces. This ensures that large volumes of air are being filtered at a high rate. Fig. 5 show how the ozone I/O ratio for the Photographic Museum archive was lowered by passive sorption onto

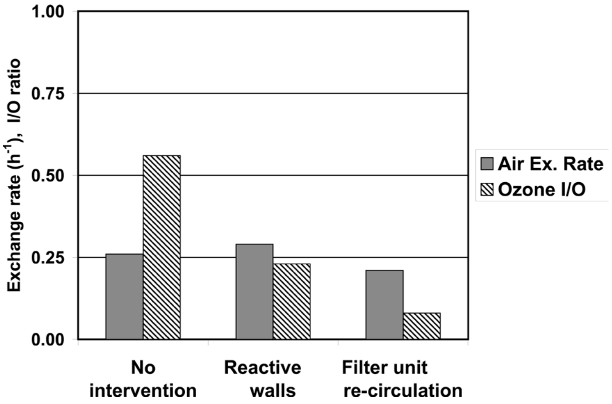

Figure 5. The ozone indoor/outdoor ratio for the Photo Museum archive. The I/O ratio was measured during three different situations: For the room itself without any control measures (left), with reactive wall paper (centre), and with a re-circulating filter unit (right). The reactive paper was from MicroChamber® with a core of activated carbon. 102 m^2 of paper was used inside the 158 m^3 archive. The filter unit (Kemfilter Maximus 700) re-circulated the room air at a rate of 3.7 room volumes per hour.

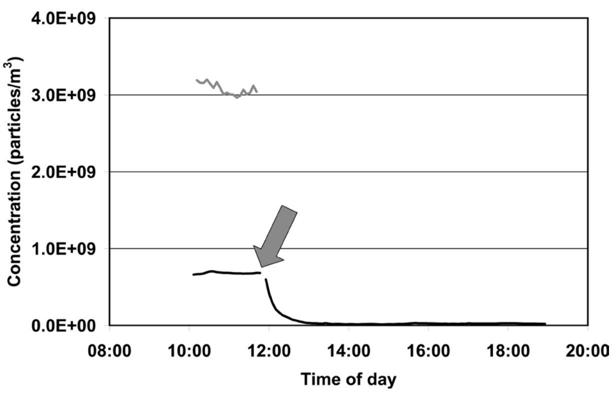

Figure 6. The concentration of ultrafine particles outdoors (grey upper curve) and inside (black low curve). The arrow points to the time when a re-circulation filter unit inside the room was turned on (Kemfilter Maximus 700).

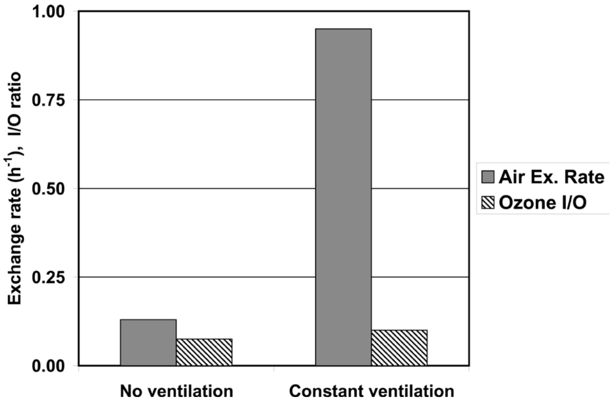

Figure 7. The ozone indoor/outdoor ratio for a storage room at the National Museum. The I/O ratio was measured during a low (left) and a higher (right) air exchange rate. The higher air exchange rate was forced by the use of a fan, pressing the air through a carbon filter.

reactive wall paper, but was even better removed when the air inside the archive was constantly being re-circulated through an internal filter unit. During the three measurement periods the air exchange rate was more or less uniform, so the indoor decrease in ozone must primarily be attributed to the increased amount of reactive surface materials inside the archive, either as the reactive wall paper, or the filter media inside the re-circulation unit. For the room alone the surface removal rate was about 0.2 h^{-1}, which was comparable to the air exchange rate, indicating negligible absorption by the walls and furniture. The reactive wall paper raised the surface removal rate to 1.0 h^{-1}, and the filter unit to 2.4 h^{-1} – more than 10 times the removal rate of the room alone.

The recirculation unit was equipped with filters both for gaseous pollutants and ultrafine particles. Fig. 6 show how effective the internal recirculation was on the particle level; within 90 min from activating the re-circulation unit the particle I/O ratio fell from 0.23 to 0.01, and this ratio was maintained during a three month test period.

THE EFFECT OF VENTILATION

Ventilation with ‘fresh’ air, where outdoor air is taken inside by the force of a mechanical fan is commonly used also in museum buildings. Based on equation 1 it is clear that by increasing the ventilation rate the inflow of air pollutants will also increase, unless a filter is used. For a fresh air ventilation system these filters must be placed in the incoming air stream. However, if the main reason for choosing mechanical ventilation for a storage room is to control the air pollution [10] then care must be taken that the chosen filters remove all air pollution. Fig. 7 illustrates this point: In a storage room with no mechanical ventilation and a low natural air exchange rate of about 0.1 h^{-1} the ozone I/O ratio was 0.08. When a ventilation system with a carbon filter was installed the air exchange rate was forced up to almost 1 h^{-1}, however the I/O ratio remained almost unchanged at 0.10.

What happened here was that while the filter did remove a large amount of ozone from the air, the total mass of air which was forced through the room was also increased. The surface removal rate while no ventilation took place was about 1.6 h^{-1}, according to equation 1. When the fan and filter was installed the total removal rate (of room + filter) became much higher, 12 h^{-1}, which reflects that the filter did indeed remove a lot of ozone. However, the net result for the environment inside the room was unchanged, and the collection was still exposed to the same level of ozone.

SUMMARY

Surface reactions are the main destruction mechanism for air pollutants. Keeping in mind that surface deposition on the collection items is part of the deterioration route for these objects, it is important to keep as much ‘sacrificial’ surface material as possible (on walls, or in filters) compared to the surface area of the collection itself. Passive surface removal, by the use of reactive wall paper, can provide a surface removal rate equal to the pollution dilution provided by several air exchanges per hour, however, by the help of mechanical filter units this can be increased by a factor of 10. A building, which has a low exchange rate with the ambient air combined with an internal active pollution control, will provide a high degree of protection from pollutants in air coming from both outside and inside the room.

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