Estimating the Effects of External Pollution on Indoor Air Quality

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The effect of external pollution levels on indoor air quality is a subject of growing interest, especially with the increasing application of natural ventilation in urban areas. The analysis described in this paper allows the effects of varying external pollution levels to be estimated for any configuration of ventilation system, natural or mechanical. The analysis takes into account filter efficiency and position, internal pollutant sources, degree of re-circulation and varying fresh air rates. By developing simplified dynamic equations rather than steady state formulations, the effects of varying "fresh" air rates based on the external pollution level can also be examined.

1 INTRODUCTION

Pollution in the outdoor air can have a significant effect on the quality of ventilation air, and thereby influence indoor air quality (IAQ). External pollution sources include

- General background pollution from industrial processes etc remote from the building location
- Local but widespread pollution sources, especially exhausts from vehicular traffic
- Specific local sources like boiler flues and ventilation exhausts.

There is an increasing body of knowledge about how pollution in urban areas is generated and dispersed and this has been summarised in a soon to be published CIBSE Technical Memoranda[1]. Methods outlined in that document provide a basis for estimating the concentration of the pollutant at the ventilation intake(s). In most cases, the building designer is concerned with indoor air quality, and so a method is needed to combine the effects of external pollution, air treatment in the HVAC plant and internal pollution sources. The paper describes the contaminant sources and sinks, and provides the basis of a simplified design method.

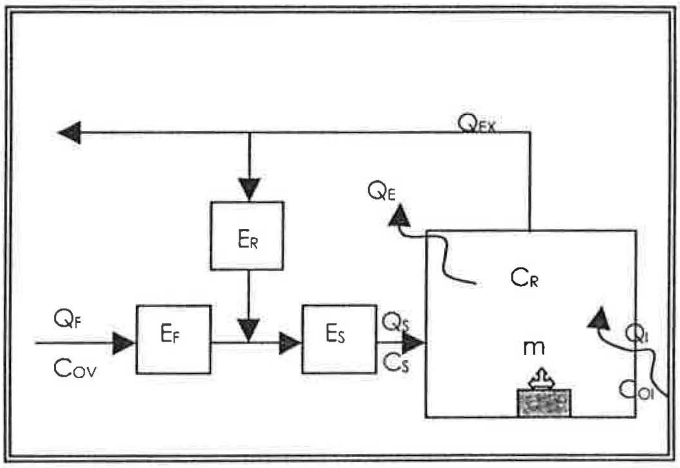

Figure 1 Schematic of generalised ventilation system

2 ANALYSIS OF ROOM IAQ

In order to estimate the IAQ under any operating regime, the following analysis is based on the generalised ventilation system shown in fig 1. Fresh air is supplied via a ventilation system at rate Q_F and with a concentration of pollutant C_{OV}. This air is passed through a cleaner/filter with efficiency E_F. Similar cleaner/filters are available in the recirculation path (efficiency = E_R) and in the final supply duct (efficiency = E_S). Air is extracted from the space at a rate of Q_{EX}. Air infiltrates into the space at a rate of Q_I and a concentration of C_{OI} and exfiltrates at a rate Q_E Although in many cases C_{OV} and C_{OI} will be the same, keeping the terms separate allows for pollution effects, either local to the ventilation system inlet (affecting C_{OV}) or to the exterior of the room (affecting C_{OI}). Pollutant is generated within the room at a rate of m.

Using the above general system, any specific configuration can be represented. For example, a 100% fresh air system would have $Q_F = Q_S$. If the filter/cleaners do not exist in any particular branch, their efficiency can be set to zero. A natural ventilation system would therefore be a 100% fresh air system with all filter efficiencies set to zero.

3 CONTAMINANT TRANSPORT

3.1 External Pollution

External airborne pollution is brought into the space via two routes.

3.1.1 Purpose provided ventilation inlets

The location of purpose provided inlets is, by definition, under the control of the designer. Subject to other design requirements, such inlets may be located to minimise the potential impact of local external pollutant sources. Because the location of the inlet and the route of the ventilation air is known, in a mechanical system, any appropriate air treatment (e.g. filtration) can be applied. The proper positioning of the inlet to a large centralised system is more critical than the localised inlet to a naturally ventilated space, since the air will serve a much larger proportion of the building population. Consequently an inappropriately located inlet will impair the IAQ experienced by much of the building rather than those just local to the pollution source (Kukadia & and Palmer [2]).

For each ventilation inlet, the pollutant load carried by the flow is simply given by -

$$p = \dot{V}_{out} * C_{out} \tag{1}$$

where p is the mass flow of pollutant (mg/s)

V_{out} is the volume flow of air (m^3/s)

C_{out} is the concentration of pollutant at the inlet position (mg/m3)

3.1.2 Building Leakage and Infiltration

Building leakage paths are outside the control of the designer, except in as much as minimum airtightness standards may be applied to components (doors and windows) or to the structure as a whole. Air is driven through the building from high pressure regions to low pressure. In general, this means the air will tend to flow from the windward to leeward side, and from bottom to top. This means that if there is a street level pollution source on the windward side of the building, pollutants can be spread through most of the building. If the building is leaky, this can have significant impact on IAQ. The other obvious but important factor with regard to infiltration is that it is continuous. Flowrates through purpose provided ventilation inlets can be varied depending on the prevailing "freshness" of outside air and the internal ventilation need. Infiltration rates are not controlled and are continuous over 24 hours. Consequently the background infiltration will influence the concentration that will exist in the occupied zone at the start up of the ventilation system.

Estimation of infiltration rates is an enormous subject in its own right. For the purposes of this paper, it is assumed that a reasonable estimate of infiltration rate has been made using techniques described elsewhere [3]. In the following analysis, the concentration of the infiltrating air can be different from the air being brought into the building through the ventilation system. This is to allow for the spatial variation in concentration around the building. For example, if the ventilation system inlet is at roof level, the concentration of traffic related pollutants will be different from that at street level (Ajiboye et al [4]). The pollutants brought into the space via infiltration is given by a similar expression to equation 1, but using Q_I and C_{OI}.

3.2 Filtration and cleaning

Most ventilation systems include filtration to some level. At the minimum, this may be wire screens to prevent birds or rodents entering the system. At the other extreme, it might include ultra-high efficiency filtration required in clean room applications. Specific chemical pollutants can also be removed using (e.g.) scrubbers or activated carbon. Guidance can be obtained from CIBSE Guide B3 [5].

In order to characterise the impact of filtration and/or cleaning on IAQ, the efficiency of this process is characterised by a simple efficiency term. This is not strictly true for some pollutants; for example, filters will have different removal efficiencies at different particle size ranges. For the purpose of this paper, such a simple efficiency relationship is adequate for a first level analysis. In such cases, the concentration downstream of the filter (C_{down}) is related to the upstream concentration (C_{up}) by

$$C_{down} = (1 - E) * C_{up} \qquad (2)$$

where E is the removal efficiency for the pollutant / particle size of interest.

The filter/cleaner may be positioned in a number of place(s) in the ventilation system -

- to treat the outside air coming into the building to remove a proportion of the pollutants that might exist in the outside air
- to treat the re-circulated air to remove a proportion of the pollutants that might be in the room air and which it is undesirable to recirculate.
- to treat the supply air (mixed outside and re-circulated air); this requires only one filter but it will have a higher loading.

3.3 Internal sources and sinks

Many of the important pollutants are generated inside the building. These internal sources may represent pollutants that exist in the outside air (e.g. metabolic CO_2 will add to the external CO_2

levels arising principally from the combustion of fossil fuels, traffic etc). Other pollutants will be almost entirely from internal sources (e.g. formaldehyde). Pollutants are often absorbed by materials in the space as well as acting as sources. Again, this subject is an enormous one in its own right and so for the purposes of this analysis, the nett emission rate (source minus sinks) is used. It is also assumed that the nett emission rate is a function of time only and is independent of the concentration of the pollutant and of any other variable (temperature, humidity etc) which is not included in the analysis.

The pollutant sources are also assumed to be in the room. In reality, in poorly maintained systems, pollutant sources may exist within the ventilation system itself, but these have been ignored in this present analysis.

3.4 Room Effects

3.4.1 Recirculation of room air

In many air conditioning systems, air is recirculated back from the occupied zone, mixed with fresh air and then supplied back to the zone again. This strategy is employed to provide an appropriate balance between indoor air quality and energy conservation.

3.4.2 Reservoir effect

Whenever the pollution levels in the outside air or the internal source strengths change, the pollution levels inside will take some time to reach a new steady state concentration. This reservoir effect can be a very useful mechanism to control IAQ.). It means that outside air rates can be temporarily reduced when external pollution levels are high (e.g. during peak rush hour periods). This could be based on a time schedule or by using air quality controlled fresh air dampers. These strategies are reviewed by Fletcher [6].

3.4.3 Ventilation effectiveness

Different ventilation strategies (e.g. mixing or displacement) and varying supply / extract configurations will influence the way in which contaminants are removed from the space. This is quantified by the ventilation effectiveness that relates the supply and exhaust contaminant concentrations to the concentration in the breathing zone.

$$\varepsilon = \frac{(C_{EX} - C_S)}{(C_R - C_S)} \qquad (3)$$

Where C_{EX} = concentration in the exhaust

C_S = concentration in the supply air

C_R = concentration in the breathing zone.

In a perfect mixing ventilation system, the ventilation effectiveness is 1.0; in practice, the value is between 0.9 and 1.0. For a displacement ventilation system, the stratification of the polluted air at high level results in ventilation effectiveness of 1.2 to 1.4. <u>These figures apply to evenly distributed internal pollution sources</u>. In the following analysis, the room is assumed to be perfectly mixed with a ventilation effectiveness of 1.0.

4 DEVELOPMENT OF EQUATIONS

By applying pollutant mass balances at each of the junctions in the above system, a generalised expression can be determined for the room concentration. For example, the mass balance around the room is given as

$$Q_s * C_s + Q_I * C_{Oi} + m = (Q_{EX} + Q_E) * C_R + V_{room} \frac{dC_R}{dt} \tag{4}$$

The concentration in the supply air can be obtained by applying pollutant mass balances at the mixing point and across the individual filters. Hence

$$C_S = \left[\frac{Q_F * C_{OV} * (1 - E_F) + (Q_S - Q_F) * C_R * (1 - E_R)}{Q_S} \right] * (1 - E_S) \tag{5}$$

An air mass balance around the room gives

$$Q_s + Q_I = Q_{EX} + Q_E \tag{6}$$

Combining these equations and integrating gives -

$$C_{R,t} = \alpha - \left[\alpha - C_{R,i}\right] \cdot e^{-\beta \cdot t} \tag{7}$$

Where $C_{R,t}$ = room concentration at time t

$C_{R,i}$ = room concentration at time 0

α,β = constants given by –

$$\alpha = \frac{Q_F \cdot C_{OV} \cdot (1 - E_F) \cdot (1 - E_S) + Q_I \cdot C_{OI} + m}{Q_S + Q_I - (Q_S - Q_F) \cdot (1 - E_R) \cdot (1 - E_S)} \tag{8}$$

$$\beta = \frac{Q_S + Q_I - (Q_S - Q_F) \cdot (1 - E_R) \cdot (1 - E_S)}{V} \tag{9}$$

5 APPLICATION OF EQUATIONS

Equation 7 can be used to assess the impact of different strategies on indoor air quality. For example, the following graphs show comparison between

- a naturally ventilated scheme – the ventilation is provided by background trickle ventilators apart form a period of rapid ventilation around midday when external pollution is lowest.
- a mechanically ventilated scheme – the ventilation rate is constant during the occupied period. Infiltration is constant for 24 hours and the mechanical ventilation operates between 7:00 and 18:00.

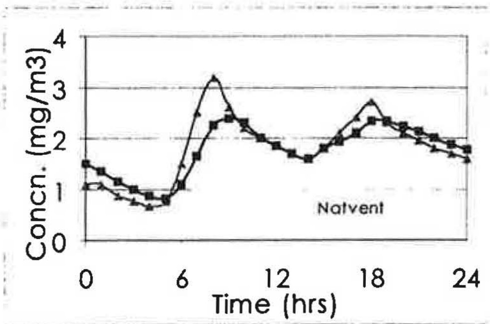

Figure 2 Natvent with no internal source

In each case, the graph shows the general external pollution level (the light line with the triangle marker) and the room concentration (the dark, heavier line with the square marker). The pollutant concentration in the infiltrating air and the natural ventilation air are assumed to be at the same level as the general external level. The concentration in the mechanical ventilation supply is taken as 15% lower than the general background level because the inlet has been positioned away from the dominant source. The first comparison shows the situation when there is no internal source of the pollutant in question. The average concentration in the two schemes is similar, but the swings about the mean are less pronounced for the naturally ventilated case. This is because of the variable ventilation rate that is out of phase with the varying external pollution load. This illustrates the potential of modulating outside air rates depending on outside air quality conditions.

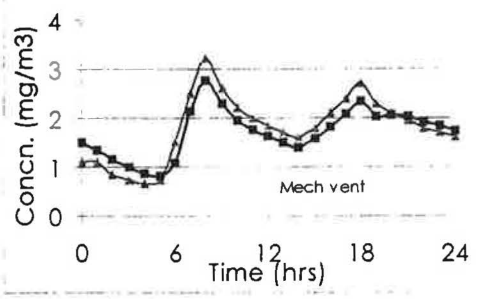

Figure 3 Mechvent with no internal source

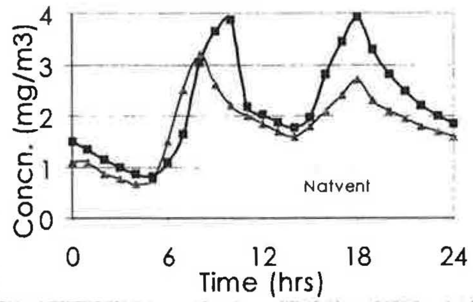

Figure 4 Natvent with internal source

The analysis has been repeated but with an internal source added. In this case, the naturally ventilated case performs less well because, for periods of time, the ventilation rate is lower than for the mechanically ventilated case and so the effect of diluting the internal source is diminished. This results in an increase in internal concentration. This highlights the importance of minimising internal pollution sources by specifying low polluting materials and processes, or by extracting pollutants at source.

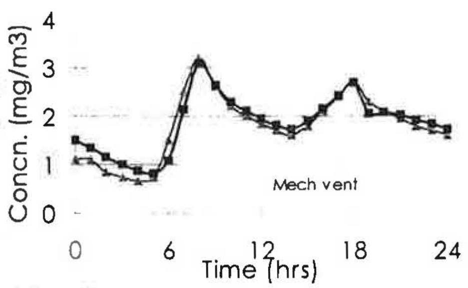

Figure 5 Mechvent with internal source

6 CONCLUSIONS

The paper has described a generalised method by which the effect of varying external air quality can be combined with a knowledge of the internal sources and the ventilation system strategy to predict the indoor air quality. This can be used to assess the ability of various system options to provide adequate IAQ. This is particularly important with respect to buildings in urban areas where the effects of traffic and other pollution sources may be a matter for some concern.

7 ACKNOWLEDGEMENTS

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