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Ventilation Effectiveness - The AIVC Guide

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1. SYNOPSIS

Sandberg and Skåret differentiate between the terms air change efficiency and ventilation effectiveness. Air change efficiency is a measure of how effectively the air present in a room is replaced by fresh air from the ventilation system whereas ventilation effectiveness is a measure of how quickly an air-borne contaminant is removed from the room. The AIVC guide covers ventilation effectiveness and related concepts. It shows the origins of the concepts used, provides proofs of essential formulae, and suggests standard symbols and definitions. It also recommends methods of measurement, and discusses the range of application of the concepts.

2. LIST OF SYMBOLS

Symbols		Units
t	time	s
τ_n	nominal time constant for the ventilation air	s
τ_n^c	nominal time constant for the contaminant	s
$\bar{\tau}_e^c$	local mean age of contaminant at the exhaust duct	s
$\bar{\tau}_p^c$	local mean age of contaminant at point p	s
$<\bar{\tau}^c>$	room mean age of contaminant	s
D_p	total dosage index	s
T_{pn}	transfer index	s/m^3
U_p	local purging flow rate	m^3/s
ε^c	ventilation effectiveness	
η^c	contaminant removal efficiency	
ε_p^c	local air quality index	
$C_p(t)$	concentration of contaminant at point p at time t	
$C_e(t)$	concentration of contaminant at exhaust duct at time t	
C_s	concentration of contaminant in supply duct	
$C(0)$	initial concentration of contaminant in the room	
$<C(t)>$	room mean concentration of contaminant	
C_i	concentration of contaminant in zone i	
V	room volume	m^3
V_c	equivalent volume of contaminant in the room	m^3
V_{ci}	equivalent volume of contaminant in zone i	m^3
Q	airflow rate from the supply duct	m^3/s
q_i	injection rate of contaminant in zone i	m^3/s
F_{ij}	air flow rate from zone i to zone j	m^3/s

3. INTRODUCTION AND OBJECTIVES

The concept of ventilation effectiveness is now well established in research literature as an index of the removal of contaminants from a ventilated space.

The theoretical background has been fully described by Sandberg [1,2,3], Skåret [4] and others, and many examples of its application have been described. The purpose of the AIVC guide on ventilation effectiveness is to encourage the use of the concepts outside the research field in the area of general practice, both as a design tool and as a means of measurement. In fulfilling this purpose, three objectives were identified. The first is the standardisation of the definitions and symbols used for the various indices which fall within the overall concept of ventilation effectiveness. The second is to provide examples of the application of the concept to the idealised cases of fully mixed flow and piston (or displacement) flow in a single zone, with further examples showing the effect of extending the representation of a ventilated space to more than one zone. The third is to give guidance on the interpretation of the values obtained, especially for ventilation effectiveness itself.

In preparing the guide, it was assumed that the principal readership would be practitioners who were wishing to use the concept for the first time, and that experts would wish to consult the document in order to use standardised definitions and symbols. Consequently, the only section of the guide which is in any way new is the section on the interpretation of ventilation effectiveness values, where it has been found that there is as yet insufficient evidence to suggest a common approach.

4. SELECTION AND DEFINITION OF VENTILATION EFFECTIVENESS INDICES

The two most fundamental indices are ventilation effectiveness and local air quality index. In addition to those, it was decided to include some other indices which provide a measure of the effect of a contaminant within a ventilated space, even though they may not be in general use at the present time. For example, the local purging flow rate has been included on the grounds that it is closely related to the local air quality index, and because it forms a link to the more important dosage index. Also, in forming the definitions, it was decided to use net contaminant concentration values rather than absolute values. In other words, the existing contaminant concentration in the outside or air supply is taken as zero, and concentration levels within the ventilated space are measured above this. This provides clearer and simpler definitions without any loss of generality. It was also considered important to choose the simplest and most obvious definitions. The definitions which have been included therefore are as follows.

Nominal Time Constant for the Contaminant (τ_n^c)

The ratio between the equivalent volume of contaminant in the room and the contaminant injection rate:

$$\tau_n^c = \frac{V_c}{q} = \frac{V.\langle C(\infty)\rangle}{q}$$

Ventilation Effectiveness (ε^c)

The ratio between the steady state concentration of contaminant at the exhaust duct and the steady state mean concentration of contaminant in the room:

$$\varepsilon^c = \frac{C_e(\infty)}{\langle C(\infty)\rangle}$$

Contaminant Removal Efficiency (η^c)

$$\eta^c = \frac{\varepsilon^c}{\varepsilon^c + 1}$$

Local Air Quality Index (ε_p^c)

The ratio between the steady state concentration of contaminant at the exhaust duct and the steady state concentration of contaminant at a point p in the room:

$$\varepsilon_p^c = \frac{C_e(\infty)}{C_p(\infty)}$$

Local Purging Flow Rate (U_p)

The ratio between the contaminant injection rate at a point p and the steady state contaminant concentration at that point:

$$U_p = \frac{q_p}{C_p(\infty)}$$

The Dosage Index (D_p)

The time integral of the contaminant concentration at a point p. If the integral is over all time, it is called the total dosage index:

$$D_p = \int_0^{\tau} C_p(t).dt$$

Transfer Index (T_{pn})

The transfer index at point p due to a sudden release of contaminant at point n is the total dosage index at p per unit volume of contaminant released at n:

$$T_{pn} = \frac{D_{pn}}{V_{cn}}$$

The defining equations for some of the indices can be cast in alternative forms, and the most useful alternatives are included alongside the original definitions. Provided certain conditions are met, it is also possible to write equations linking some of the indices, and these too have been included.

5. IDEALISED EXAMPLES

The value of the ventilation effectiveness, ε^c, has been evaluated for a series of idealised examples. There were three reasons for doing this. Firstly, it provides a simple demonstration of the evaluation process; secondly, it shows how the ventilation effectiveness depends on the distribution of contaminant injection; and thirdly, it provides a base of idealised values which can be used for comparison with ventilation effectiveness values in real situations. The strategy in presenting this in the guide has been to start by treating the ventilated space in the simplest possible way as a single zone. This is analysed in fully mixed flow and then in piston flow. Then the effect of improving the representation of the space, first as two zones (a model which appears frequently in the literature [1,4]), and then four zones is considered. Between them, the single zone, the two zone and the four zone models provide a useful indication of the range and pattern of values that may be expected for ventilation effectiveness. The possibility of using one of the CFD models which are now available is also mentioned but not described in detail; models of this type are reviewed in AIVC technical note 33. In evaluating these idealised cases, it has also been assumed that the contaminant is "passive", that is, it mixes immediately with the air without any momentum of its own. Although the indices are also valid for "active" contaminants, it is difficult to find a generalised way of dealing with them.

6. RESULTS OF THE IDEALISED EXAMPLES

Piston (displacement) flow is of particular interest because it is often considered to be the most efficient method of removing contaminants from a space. Figure 1 shows the results for true piston flow in a single zone for four different patterns of contaminant injection. The four patterns correspond to:

(i) uniform injection throughout the whole space,
(ii) localised injection accross a plane,
(iii) uniform injection in a region close to the inlet duct, and
(iv) uniform injection in a region close to the exhaust duct.

The results show the extent to which the ventilation effectiveness depends on the injection pattern; all values between unity and infinity are possible.

The results for the two zone model are shown in Figure 2, which is the well known plot of ventilation effectiveness versus recirculation factor. An interesting feature of this model is that it is capable of showing the effect of short-circuiting of ventilation effectiveness between the inlet and outlet ducts, a phenomenon which gives ventilation effectiveness values below unity. Also, as the recirculation factor increases, the properties associated with the fully mixed model become more dominant. When the recirculation factor exceeds approximately 4.5, the ventilation regime is essentially fully mixed.

The results for a four zone model have been included as an example of multizone modelling, and to illustrate the effect of greater model detail. The results, shown in Figures 3 and 4 are not very different from the two zone model, except for the case of an impermeable partition between two of the zones. Again, the model is similar to the fully mixed case when the recirculation factor is greater than about 4.5.

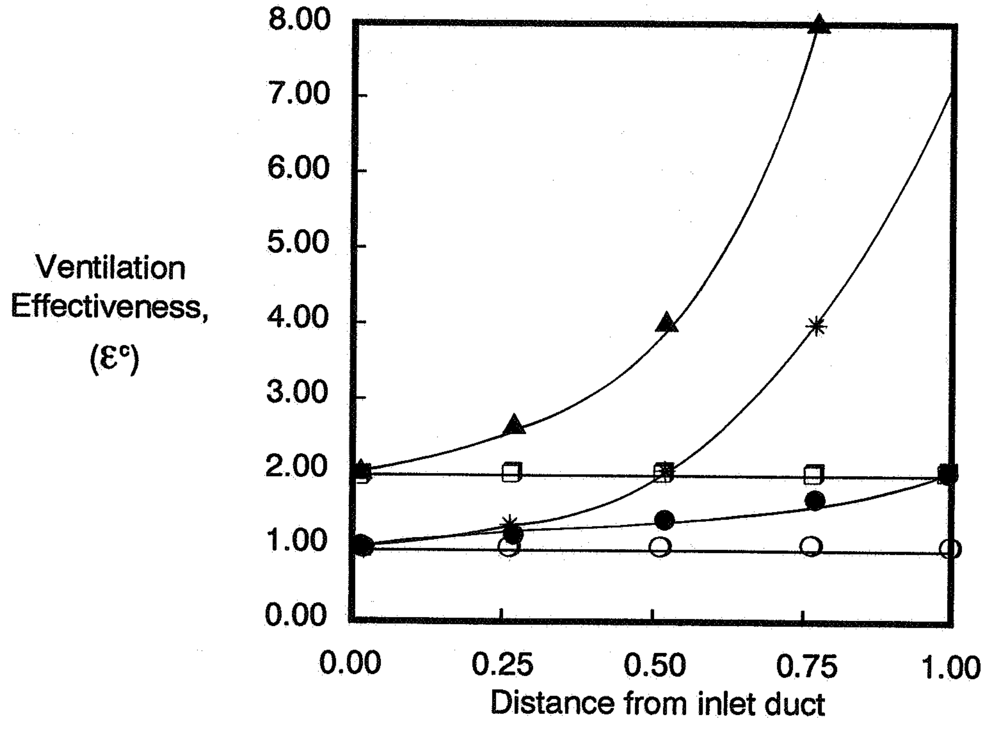

Figure 1 - Ventilation Effectiveness versus distance of contaminant source from inlet duct.

<u>Key</u>:

- —○— Fully mixed flow
- —□— Uniform injection throughout the whole space
- —✳— Localised injection accross a plane
- —●— Localised injection in a region close to the inlet duct
- —▲— Localised injection in a region close to the outlet duct

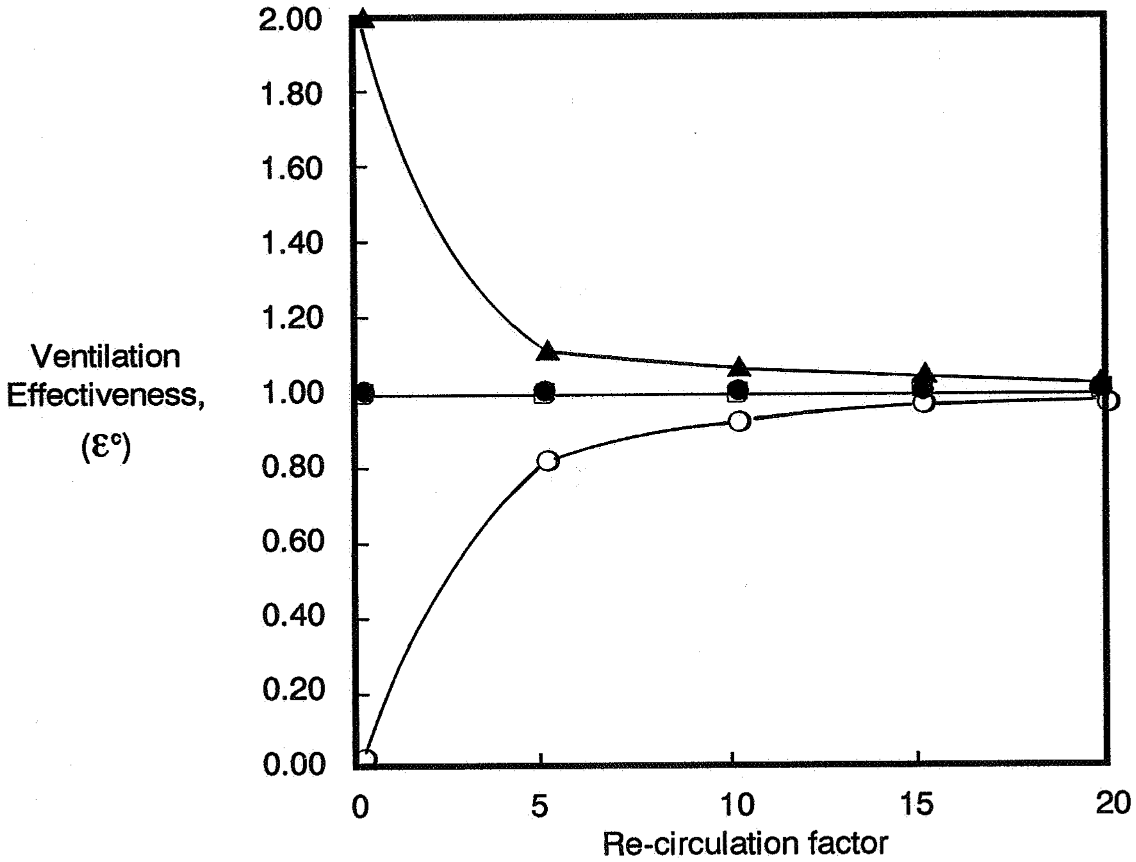

Figure 2 - Ventilation Effectiveness versus Re-circulation factor for a two zone model.

Key:

- —□— Injection in the unoccupied zone for a short-circuiting flow
- —●— Injection in the unoccupied zone for a piston flow
- —○— Injection in the occupied zone for a short-circuiting flow
- —▲— Injection in the occupied zone for a piston flow

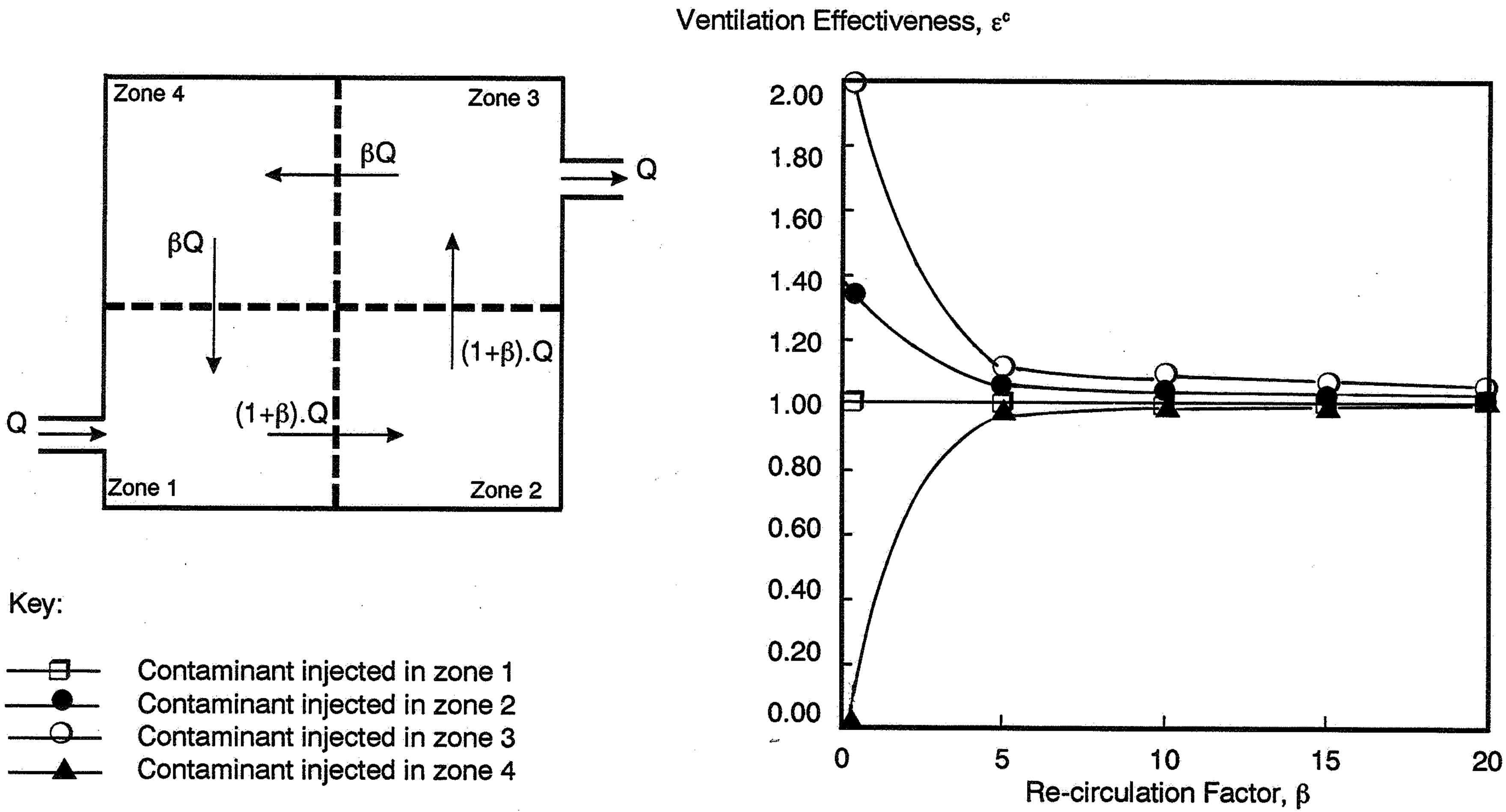

Figure 3 - Ventilation Effectiveness versus Re-circulation factor for a four zone partitioned model.

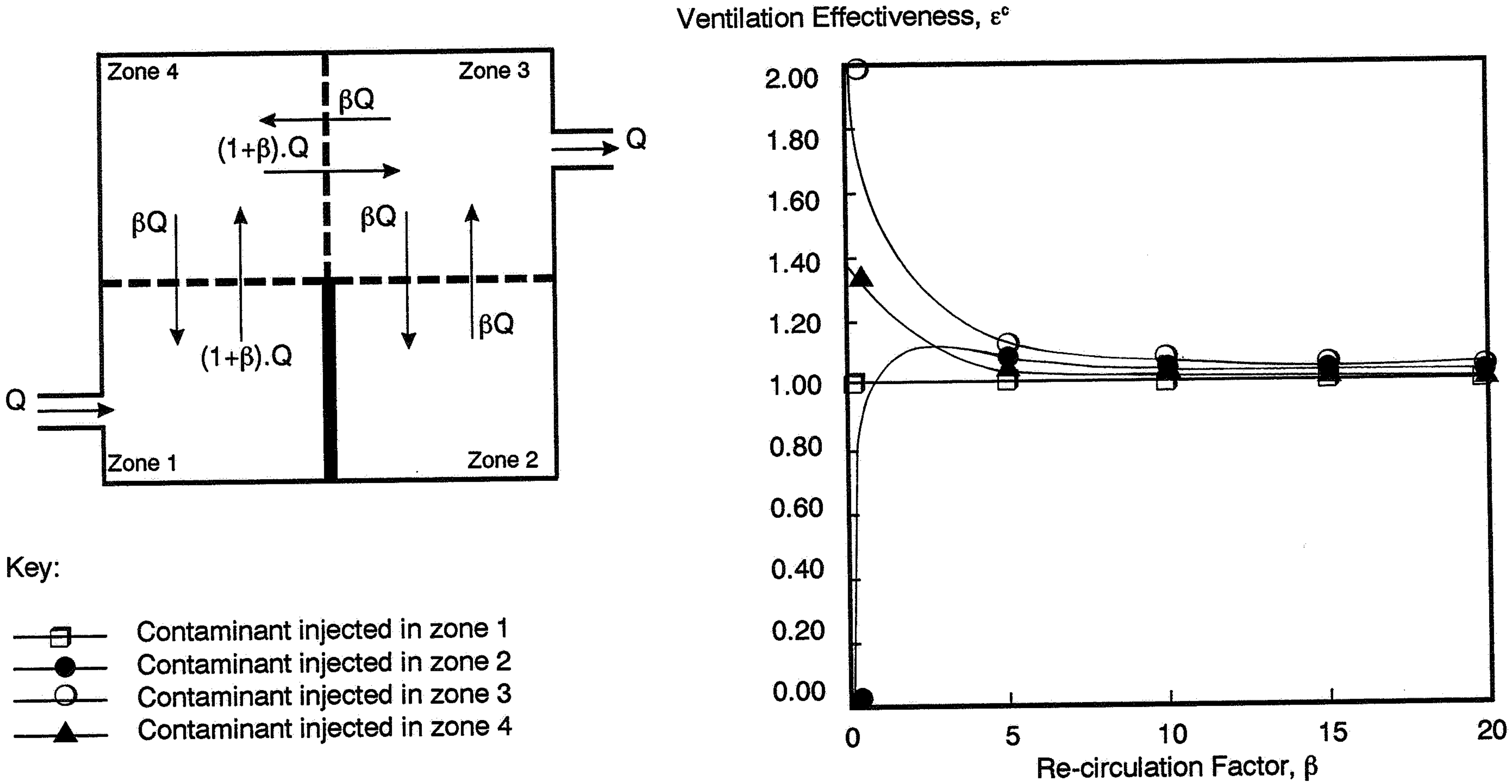

Figure 4 - Ventilation Effectiveness versus Re-circulation factor for a four zone re-circulation model.

7. METHODS OF MEASUREMENT

In order to determine any of the indices, it is necessary to measure the concentration of the contaminant at the appropriate points in the room. If it is not possible to use the contaminant itself, a tracer which imitates the behaviour of the contaminant may be used. All of the indices defined in paragraph 4 may be determined by direct measurement of the appropriate equilibrium contaminant concentration. However, there are two difficulties in using this method. Firstly, in some cases it is necessary to find the room average concentration, $\langle C(\infty) \rangle$, which may require measurements to be made at a large number of positions within the space. Secondly, if the time constant of the system is long, it may be necessary to continue measurements for an unacceptably long time in order to achieve equilibrium. Consequently, the guide suggests that it is often better to derive the required index from measurements of the time evolution of contaminant concentration.

8. INTERPRETATION AND APPLICATION

The indices fall in two groups. On the one hand, τ_n^c, ε^c, and η_c are indices of the whole space. On the other hand, ε_p^c, U_p, D_p, D_{pn}, T_{pn} all refer to a specific point. In the case of the whole space, it is a matter of choice whether to use ε^c or η^c. The former is immediately meaningful in terms of contaminant concentration ratios, whereas the latter has the advantage of always being within the range zero to unity. No recommendation is made as to which should be used.

The biggest problem with the ventilation effectiveness index is the interpretation of particular values. The results for the idealised examples showed that, except for fully mixed flow, the value is highly sensitive to the position and distribution of the contaminant source. Consequently, the value of the ventilation effectiveness taken on its own is not sufficient to make a judgement on the success of a ventilation system in removing a contaminant. There are several possible solutions to this problem. For example, if it is accepted that piston flow is the most efficient type of ventilation system, a value for ε^c could be compared with the value that would have been obtained if a piston flow had been installed. The comparison could be made with one of the four cases described above, presumably taking the idealised case whose contaminant distribution is most similar to the real case. One could then define a ventilation effectiveness ratio, r^c, such that:

$$r^c = \frac{\varepsilon^c(\text{real})}{\varepsilon^c(\text{piston})}$$

The value of r^c, which must lie in the range 0 to 1 (and could therefore be expressed as a percentage), gives a single figure indication of the performance of the system as a proportion of the best possible performance for the given contaminant distribution. It has also been suggested [5] that a critical feature of any ventilation system is its ability to sweep out a contaminant after injection has ceased. The nominal time constant of the contaminant is a measure of this, and again one could take the ratio between τ_n^c for the real system and τ_n^c for an idealised piston flow system in the same space. However, this leads to the same result as before, provided the nominal time constant for the ventilating air is the same in both the real and idealised cases, because:

$$r^c = \frac{\varepsilon^c(\text{real})}{\varepsilon^c(\text{piston})}$$

$$= \frac{\tau_n^c}{\tau_n}(\text{real}).\frac{\tau_n}{\tau_n^c}(\text{piston})$$

$$= \frac{\tau_n^c(\text{real})}{\tau_n^c(\text{piston})}$$

An alternative approach is to produce a simple parametric model. Most ventilation systems fall between the two extremes of fully mixed flow and piston flow. Indeed, whereas piston flow may be the ideal way of removing contaminants, mixing is necessary in order to provide uniform temperature and humidity. A simple three parameter model can be constructed by combining them, so that the parameters are the nominal time constant of the ventilating air for both types of flow, and the proportions in which they are mixed. The poster display gives some examples of the properties of such a model. The interpretation of the local indices follow directly from their definition. The local air quality index is the local equivalent of the ventilation effectiveness; the local purging flow rate is essentially measuring the same thing but in units of flow.

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